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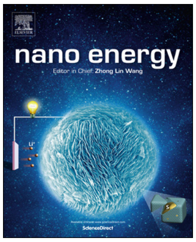

RAPID COMMUNICATION

Rotating-disk-based hybridized electromagnetic-triboelectric nanogenerator for scavenging biomechanical energy as a mobile power source

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Abstract
Scavenging biomechanical energy from human motions as a mobile power source has potential applications for driving some personal electronics, especially in the remote areas. A critical issue is how to obtain high efficient electric energy from one mechanical motion. Here, we report a rotating-disk-based hybridized nanogenerator that consists of an electromagnetic generator (EMG) and a triboelectric nanogenerator (TENG) for simultaneously scavenging biomechanical energy from one rotating motion. Operated at a rotating rate of 200 r/min, the EMG and TENG can produce an output powers of about 8.4 mW (in correspondence of power per unit mass/volume: 24 μW/g and 56 W/m^3) at a loading resistance of 12 Ω and 8.6 mW (in correspondence of power per unit mass/volume: 119 μW/g and 261 W/m^3) at a loading resistance of 0.2 MΩ, respectively. The generated electrical energy of the hybridized nanogenerator is about two times larger than that of individual energy harvesting unit (EMG or TENG) under the same working time. The hybridized nanogenerator can be utilized to effectively harness the biomechanical energy from a human hand induced rotating motions for sustainably driving a commercial globe light with an intensity of illumination up to 1700 lx.

Introduction

With the rapid growth of mobile electronic devices, human increasingly depends on these devices for communication,

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security and sensing [1,2] Currently, all of these devices require to be powered by an external power source such as Li-ion batteries, which have a limited energy storage capacity and the environmental pollution problem. To solve the high electricity demands of individuals in remote areas such as in developing countries and field scientists or explorers on the expedition process where the conventional electric power is unavailable, it is critical to develop renewable human motion-driven mobile power source. Several methods have been demonstrated for scavenging biomechanical energy from human motions as a long-lasting power source to drive some personal electronic devices, where most of them are based on piezoelectric and electromagnetic generators [3-6].

By using the conjunction of triboelectrification and electrostatic induction through the periodic contact/separation between two triboelectric materials, triboelectric nanogenerator (TENG) as a new type of mechanical energy harvesting technology has been extensively reported, which exhibits a small size, a low weight, and a low cost [7-10]. Although some TENGs have been integrated in a commercial shoe to scavenge biomechanical energy from human walking for directly lighting up some LEDs, [11-14] the output of TENG is still rather limited so that it cannot be utilized to sustainably power some larger power devices such as a commercial globe light. By integrating two kinds of mechanical energy harvesting units, a hybridized mechanical energy harvesting technology has been used to largely increase the total output power of the energy device, [15-17] where the core idea of this technology is based on how to extract more electricity from one mechanical motion. It is possible to integrate a TENG and an electromagnetic generator (EMG) for simultaneously harvesting mechanical energy from one rotating motion, where the weight of the EMG can be decreased by integrating the TENG in the hybridized nanogenerator, and the total output power can be enhanced to realize more potential applications.

Here, we demonstrated the first rotating-disk-based hybridized nanogenerator that integrated an EMG and a TENG for simultaneously scavenging biomechanical energy from one rotating motion as a mobile power source. The hybridized nanogenerator with a planar structure and a diameter of 14 cm can produce output powers of 17 mW for TENG and 50 mW for EMG through scavenging the human-hand-induced biomechanical energy. The hybridized nanogenerator has a much better charging performance than that of individual energy harvesting unit (EMG or TENG) for charging a capacitor of 6600 μF. A commercial globe light can be sustainably powered by using a prototype of the hybridized nanogenerator to charge a capacitor in outdoor, which gives an illumination intensity of 1700 lx. The hybridized-nanogenerator-based mobile power source has the potential applications in sustainably driving some mobile electronic devices.

Experimental section

Fabrication of the hybridized nanogenerators

The hybridized nanogenerator consists of a planar-structured TENG and an EMG. An circular acrylic disk was used as a substrate with a diameter of 140 mm and a thickness of 5 mm by utilizing a laser cutter. Six magnets with a magnetic alternating manner have been fixed in the acrylic disk, where the corresponding six coils were fixed in alignment with magnets for producing the output current/voltage signals. The TENG is composed of a layer of radial-arrayed metal Cu strips on a flexible substrate, a layer of PA film, and two sets of complementary radial-arrayed electrodes by using a printed circuit board (PCB) technology. The PA film was covered on the complementary radial-arrayed electrodes, which were connected to two wires for producing the output current/voltage signals when the relative motion appears between the radial-arrayed metal Cu strips and the complementary radial-arrayed electrodes. The mass and the volume of TENG part are about 72 g and 3.3×10^{-5} m^3, respectively, where the layers 2–4 in Figure 1 were included in the calculation. The mass and the volume of EMG part are about 350 g and 1.5×10^{-4} m^3, respectively, where the layer 1 and the coils in layer 5 in Figure 1 were included in the calculation.

Measurement of the hybridized nanogenerators

The output voltage and current of the hybridized nanogenerators were measured by low-noise voltage preamplifiers (Keithley 6514 System Electrometer and Stanford Research SR570).

Results and discussion

Figure 1a illustrates a schematic diagram of a hybridized electromagnetic-triboelectric nanogenerator, which consists of an EMG including the top and bottom layers (1 and 5) and a TENG including the middle layers (2, 3, 4) with the planar structures, where the rotator and the stator are composed of layers 1–2 and layers 3–5, respectively. For the rotator of EMG (layer 1) at the top, six magnets uniformly distribute in an acrylic substrate with the magnetic poles in alternating arrangement manner. For the stator of EMG (layer 5) at the bottom, the corresponding six groups of coils were integrated on a substrate in series connection at the same positions of the magnets. The rotator of the TENG consists of radially-arrayed sectors separated by equal-degree intervals in between, where each sector unit has a central angle of 1 degree (layer 2). The stator of TENG includes a layer of triboelectric material (polyamide film, layer 3) and a layer of complementary-patterned electrode networks that are separated by trenches in between (layer 4). Figure 1b displays the corresponding photographs of each layer, where the detailed fabrication process is discussed in experimental section.

The operation of the hybridized nanogenerator is based on the relative rotation between the rotator and the stator, which can be divided into two parts: the TENG and EMG. Due to Faraday electromagnetic induction, the EMG can deliver an alternating current through a periodic change of magnetic flux in coils. Figure 2a depicts a schematic diagram of the hybridized nanogenerator that works in a 1/3 whole period. The distribution of magnetic field was calculated via COMSOL. At the initial state, magnets are in alignment with coils and there is no current in the coils under the magnetic field with a positive direction. When the rotator counterclockwise spins for 30° to reach an intermediate state, the magnetic flux through the coils decreases in this process, resulting in an induced positive current in the coils (process 1). When the rotator continually

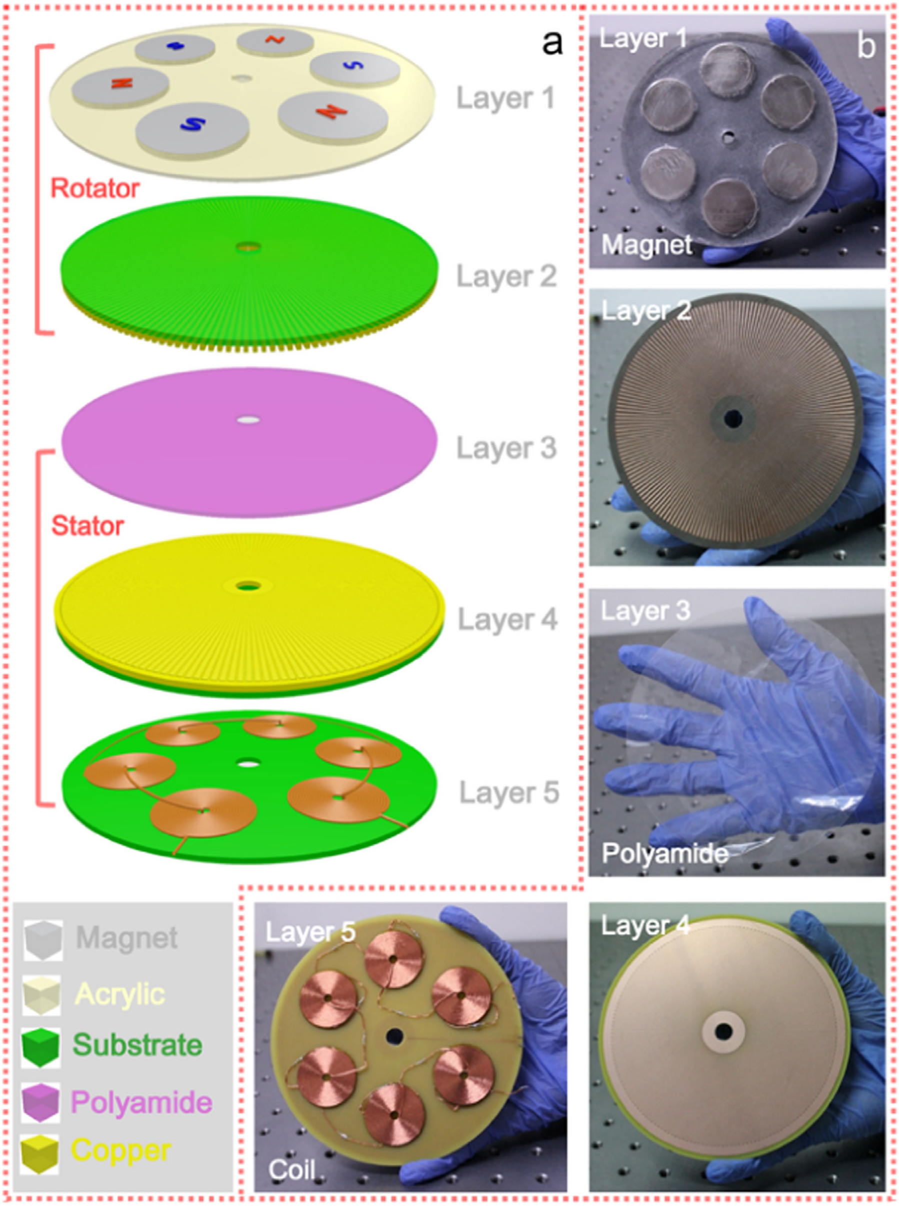

Figure 1 (a) Schematic diagram of the designed hybridized nanogenerator. (**b**) Photographs of the hybridized nanogenerator.

spins for another 30°, the magnetic field with a negative direction appears in the coils (process 2). With the rotator spinning for 30° again, the magnetic flux through the coils decreases in this process, inducing a negative current in the coils (process 3). Finally, the rotator continues to counter-clockwise spin for 30° to reach a new state that is equivalent to the initial state (process 4). The schematic diagram of the current change in above operating processes is illustrated in the middle of Figure 2a, indicating that the EMG has an AC output current/voltage.

Figure 2b illustrates the electricity generation process of TENG. When the top Cu gratings slides along the surface of PA film, electrons are injected from PA film to Cu since Cu is much more triboelectrically negative than PA, [18] where the charge density on the Cu gratings is twice as high as that on PA film according to charge conservation. At the initial position, the adjacent two electrodes have the same quantity of positive and negative charges due to electrostatic induction effect of top Cu grating, respectively. Once there is a relative sliding between the top Cu grating-1 and PA film, the electrons will flow from electrode 1 to electrode 2, resulting in a positive current signal (process 1), where the current can last until the top Cu grating moves on the top of the electrode 1 (process 2) and an equilibrium state can be created with no current signal. When the Cu grating-1 goes on sliding and the Cu grating-2 appears on the top of electrode 2, the electrons can flow from electrode 2 to electrode 1, resulting in a negative signal (process 3). The produced current can last until the Cu grating-2 fully moves on the top of electrode 2 that is equivalent to the initial state (process 4). Thus, the TENG also delivers an AC output during the continuous relative rotation. The working frequency of the TENG can be expressed as

$$f_{TENG} = \frac{360}{2\Delta\theta} \cdot \frac{\upsilon}{60} = \frac{3\upsilon}{\Delta\theta} \quad (1)$$

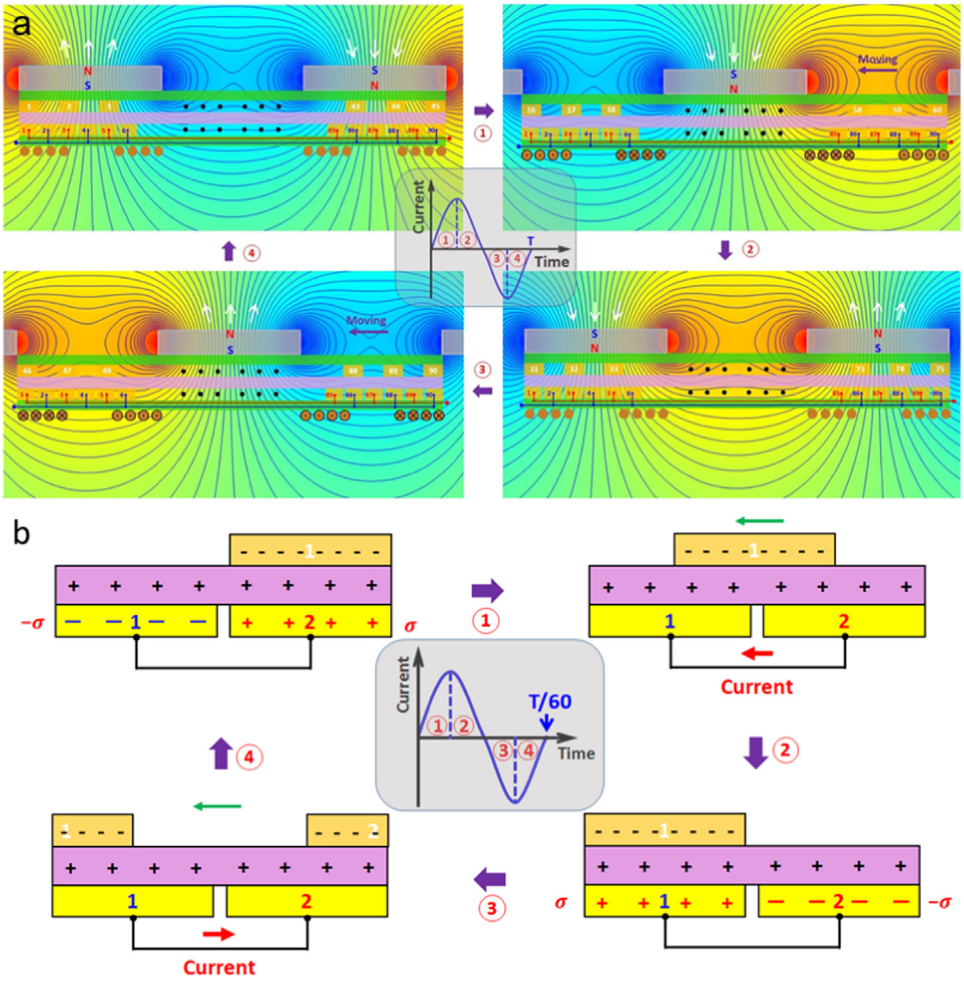

Figure 2 (a) Schematic diagram of working principle of EMG under the relative rotation between the rotator and the stator in an angle degree of 120, where the symbols ⊙ and ⊕ represent the output currents that flow out of and in the plane, respectively. (b) Schematic diagram of working principle of TENG under the relative rotation between the rotator and the stator in an angle degree of 2. The four processes illustrate the charge distribution and electricity generation in short-circuit condition.

where $\upsilon$is the rotating speed (rpm) of the rotator, and $\Delta\theta$ is the center angle of a single Cu grating strip. The working frequency of the EMG can be given by

$$f_{EMG} = \frac{n}{2} \cdot \frac{\upsilon}{60} = \frac{n\upsilon}{120} \tag{2}$$

where $n$is the number of magnets. In this study, $\Delta\theta$ is equal to 1 degree and n is 6 so that the working frequency of TENG is 60 times larger than that of EMG.

Under a rotation rate of 200 r/min, the output voltage and current of TENG can reach about 75 V and 0.33 mA, respectively, as depicted in Figure 3a and b. Under the same rotation condition, the output voltage and current of EMG are about 0.62 V and 57.8 mA, respectively, as displayed in Figure 3c and d. By the analysis of the output voltage/current curves, the corresponding working frequencies of TENG and EMG are about 600 Hz and 10 Hz, respectively, which is completely consistent with the calculated results by using Eqs. (1) and (2). Figure 3e and f displays the resistance dependence of both the output current and the corresponding output power of the TENG and EMG, respectively. The output currents of both the TENG and EMG decrease with increasing the loading resistance, while the instantaneous powers of both the two generators increase in the initial stage and then decrease under the larger loading resistances. The largest instantaneous powers of TENG and EMG are about 8.6 mW (powers per unit mass/volume: 119 μW/g and 261 W/m^3) at a loading resistance of 0.2 MΩ and 8.4 mW (powers per unit mass/volume: 24 μW/g and 56 W/m^3) at a loading resistance of 12 Ω, respectively. To exactly compare the output performances of the TENG, EMG, and hybridized nanogenerator, Figure 3g and h shows the generated electrical energy and the output current signals of TENG and EMG at the loading resistances of 0.2 MΩ and 12 Ω, respectively. Here, the generated electric energy $E_{electricity}$ can be expressed as:

$$E_{electricity} = \int_{t_1}^{t_2} I^2 \cdot R \cdot dt \tag{3}$$

where I is the output current of the nanogenerator, and R is the loading resistance. Under the same time interval between t_1 and t_2 (100 ms), the produced electrical energies of TENG and EMG are the same (0.4 mJ), suggesting that the efficiency for converting the mechanical energy into electricity can be enhanced 100% by using the hybridized

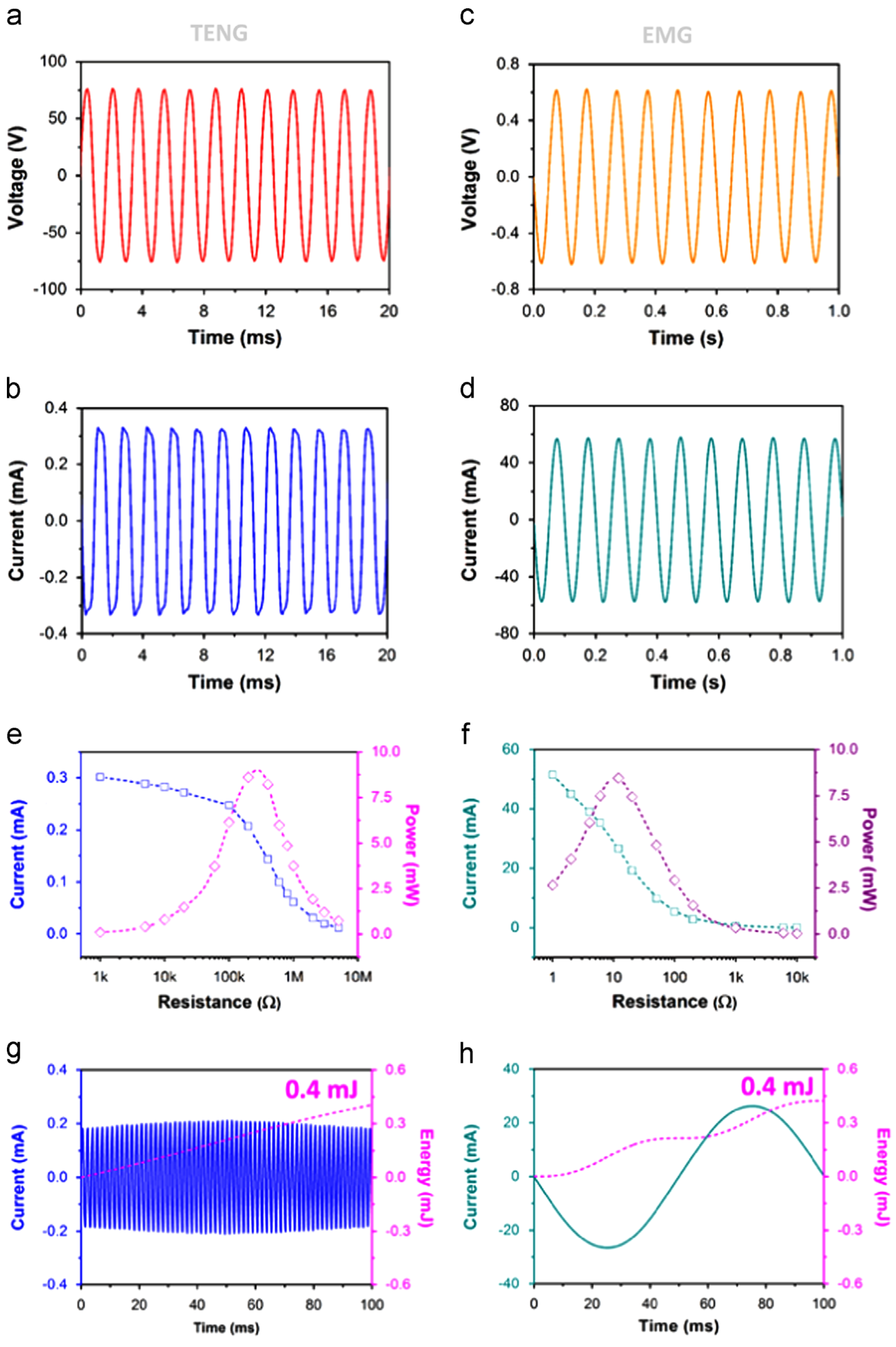

Figure 3 (a,b) Open-circuit voltage (a) and short-circuit current (b) of TENG under a rotation rate of 200 r/min. (c,d) Open-circuit voltage (c) and short-circuit current (d) of EMG under a rotation rate of 200 r/min. (e,f) The relationships between the output current/power and the loading resistance of TENG (e) and EMG (f). (g,h) The generated electrical energy of TENG (g) and EMG (h) in 100 ms.

nanogenerator technology as compared with the individual energy harvesting unit (TENG or EMG).

To solve the impedance mismatch issue of the TENG and EMG, two transformers were used to decrease and increase the impedances of the TENG and EMG, respectively. As illustrated in Figure 4a and b, the output voltage of the TENG can be decreased to about 5.5 V, while the corresponding output current of the TENG can be increased to about 3.87 mA. Figure 4c and d displays that the output voltage and the output current of EMG are about 4.3 V and 4.3 mA after using a transformer, respectively. Figure 4e and f depicts the dependences of the output current and the

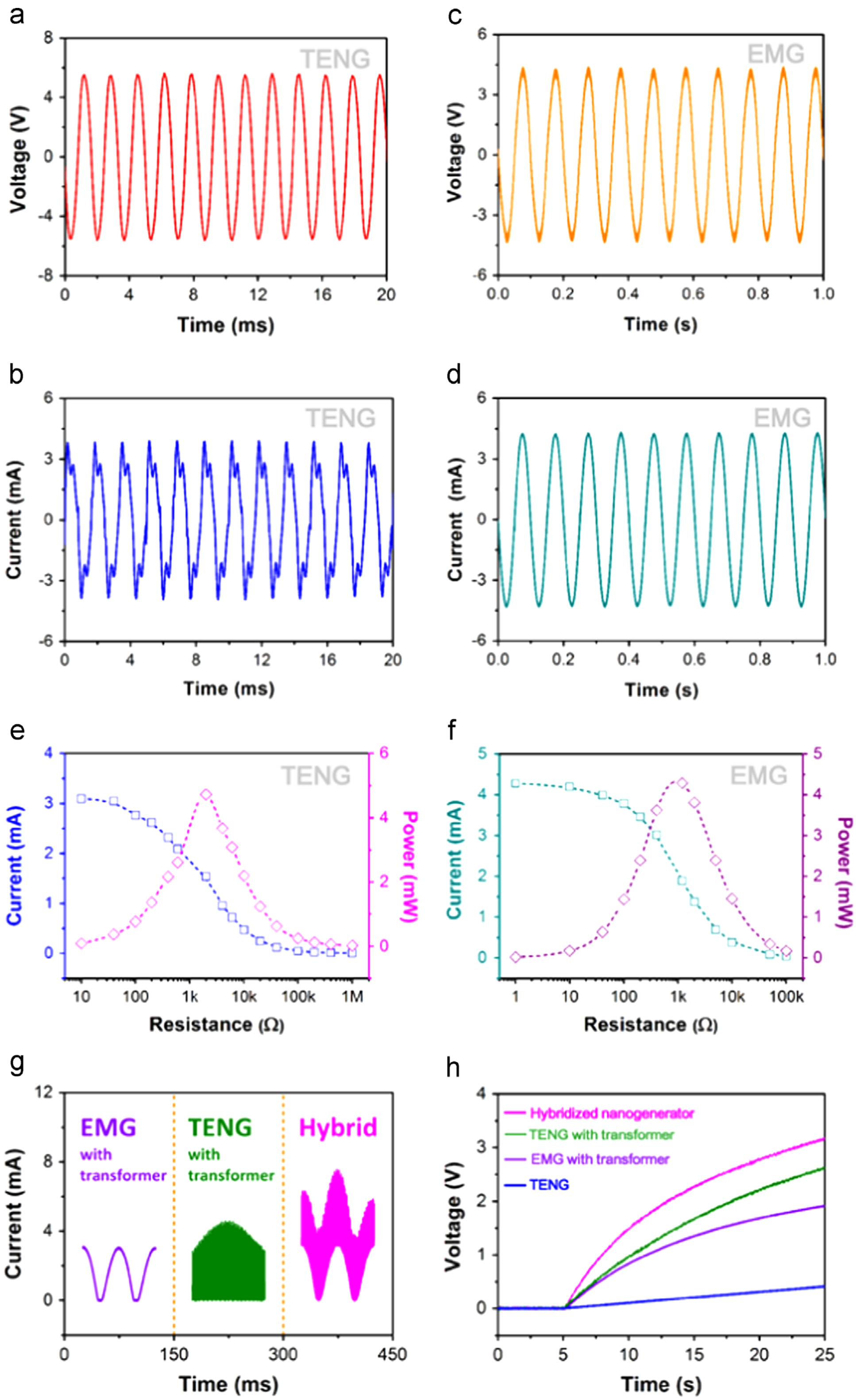

Figure 4 (a,b) Open-circuit voltage (a) and short-circuit current (b) of TENG after using a transformer. (c,d) Open-circuit voltage (c) and short-circuit current (d) of EMG after using a transformer. (e,f) The relationships between the output current/power and the loading resistance of TENG (e) and EMG (f) after using the transformers. (g) The comparison of short-circuit current for the EMG with transformer, TENG with transformer, and the hybridized device. (h) Measured voltages of a 6600 μF capacitor charged by the TENG, TENG or EMG with transformer, and the hybridized nanogenerator (EMG and TENG with transformer in parallel).

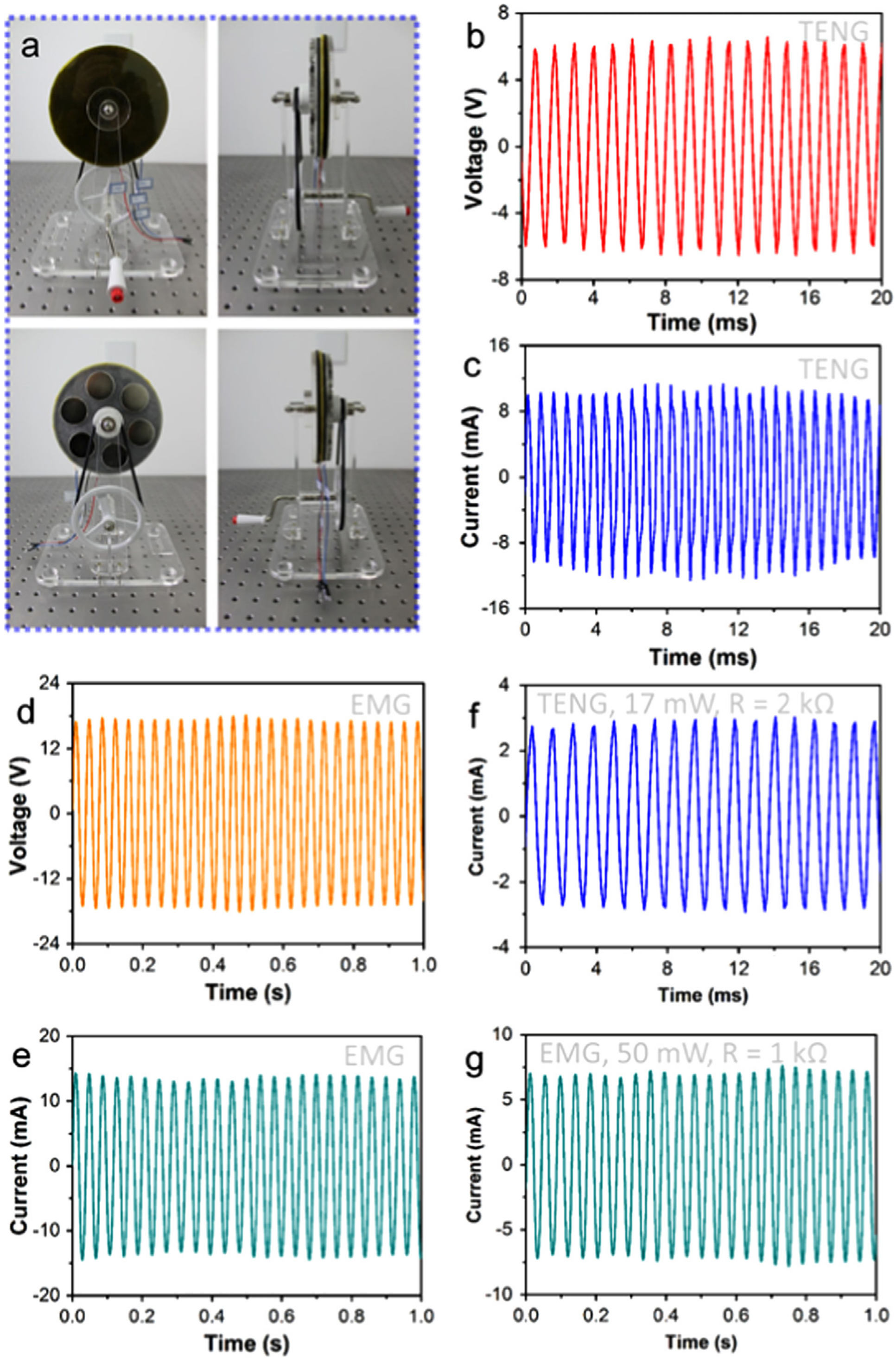

Figure 5 (a) Photographs of the human-hand rotation driven hybridized nanogenerator. (b,c) Open-circuit voltage (b) and short-circuit current (c) of TENG after using a transformer under the rotation driven by human hand. (d,e) Open-circuit voltage (d) and short-circuit current (e) of EMG after using a transformer under the rotation driven by human hand. (f,g) Output current signals of TENG (f) and EMG (g) under the loading resistances.

corresponding power of TENG and EMG on the external loading resistance after using the transformers, respectively, indicating that the output current decreases with increasing the loading resistance and the largest output powers of both the TENG and EMG appear under the loading resistances ranging from 1 kΩ to 5 kΩ. Thus the impedance match of the TENG and EMG can be achieved by using transformers although the loss can be significant.

To increase the total output current of the hybridized nanogenerator, two bridge rectification circuits were utilized to convert the AC signals of TENG and EMG into DC output, and the obtained current signals were then connected in parallel.

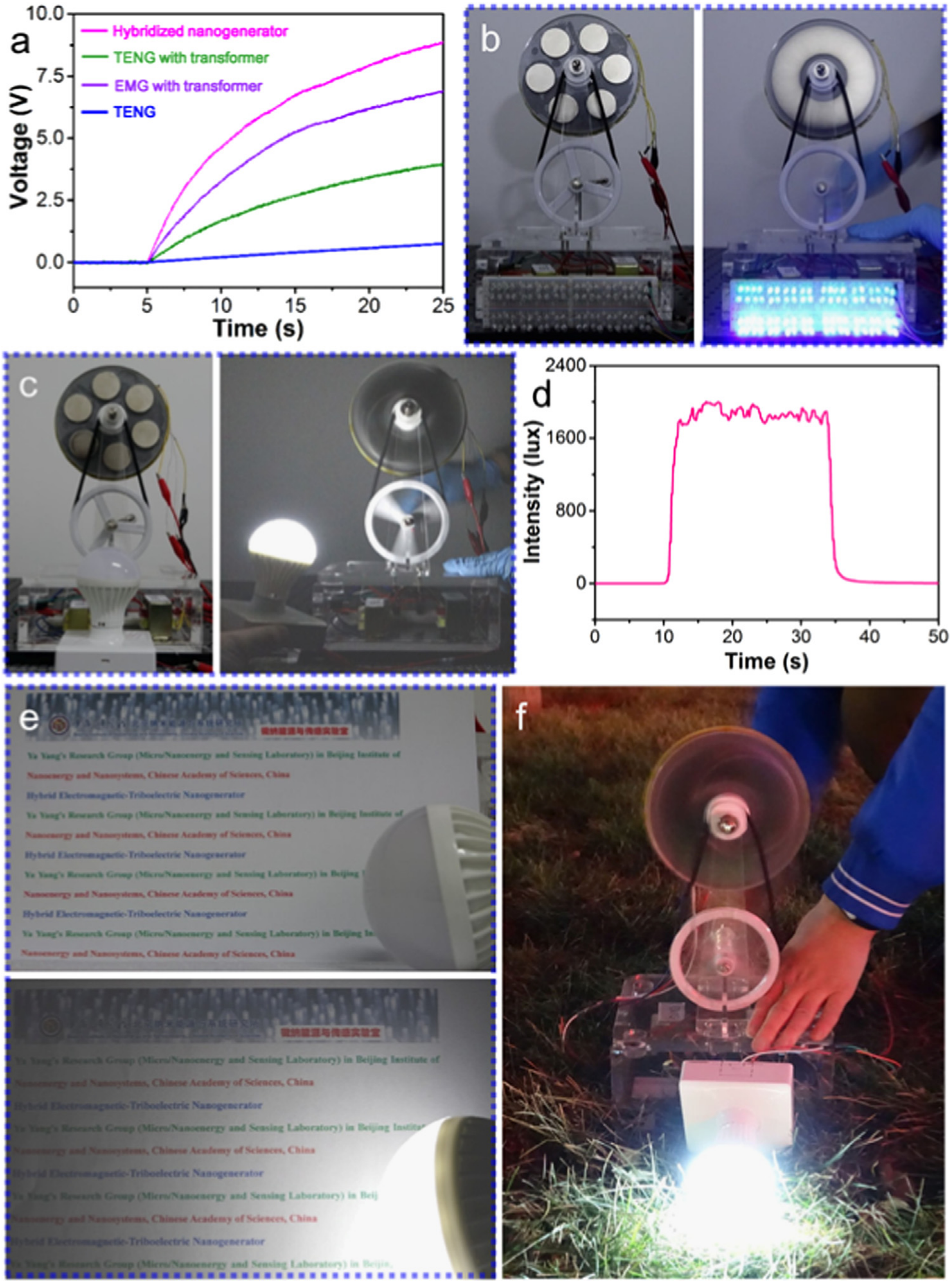

Figure 6 (a) Measured voltages of a 6600 μF capacitor charged by the TENG, TENG or EMG with transformer, and the hybridized nanogenerator (EMG and TENG with transformer in parallel) driven by human hand rotation. (b) Photographs of 40 LEDs lighted up by the hybridized nanogenerator. The top and bottom 20 LEDs were connected to the TENG and EMG, respectively. (c) Photographs of a globe light that can be directly powered by the hybridized nanogenerator with a capacitor of 6600 μF. (d) The illumination intensity of the globe light in (c). (e) Photographs of the hybridized nanogenerator driven globe light that can be used for providing the illumination to read the printed text in complete darkness condition. (f) Photograph of a globe light that can be directly powered by the human hand rotation driven hybridized nanogenerator in the wild.

As shown in Figure 4g, the obvious enhancement of the output current signals can be observed for the hybridized nanogenerator as compared with that of individual energy harvesting unit (TENG or EMG). The output current of TENG is not constant, which is due to the local change of the distance between rotator and stator in the rotating process. To demonstrate that the hybridized nanogenerator has a better output performance than individual energy harvesting units, the different nanogenerators were used to charge a capacitor of 6600 μF under a rotation rate of 200 r/min. As displayed in Figure 4h, the hybridized nanogenerator has the better chaging performance than that of the individual energy harvesting unit, where the TENG without the transformer has the lowest charging performance than that of other generators.

To demonstrate that the hybridized nanogenerator can be utilized as a mobile power source, we fabricated a prototype device of the human hand-driven hybridized nanogenerator. As illustrated in Figure 5a, human hand-driven rotation can induce the relative motion between the rotator and the stator of the hybridized nanogenerator, where the total weight of the device is 1.2 kg. Figure 5b and c presents that the open-circuit voltage and the short-circuit current of TENG are about 6.3 V and 10.7 mA after using a transformer under the rotation of human hand, respectively. The open-circuit voltage and the short-circuit current of EMG are about 17.4 V and 13.8 mA, respectively, as depicted in Figure 5d and e. f displays that the output current of TENG is about 3 mA under a loading resistance of 2 kΩ, where the corresponding output power of TENG is about 17 mW. Moreover, the output power of EMG can reach 50 mW under a loading resistance of 1 kΩ, as displayed in Figure 5g. Figure 6a depicts that the different generators were used to charge a capacitor of 6600 μF under the rotation of human hand, clearly showing that the hybridized nanogenerator has much better charging performance than that of individual energy harvesting unit (TENG or EMG).

To demonstrate the capability of the hybridized nanogenerator as a mobile power source, the TENG and the EMG were connected to two groups of LEDs (TENG for top 20 LEDs, EMG for bottom 20 LEDs), respectively. As illustrated in Figure 6b, these LEDs can be lighted up at the same time under the human hand driven rotation motion of hybridized nanogenerator (see the movie file-1). Figure 6c shows that a white globe light can be continually lighted up by the hybridized nanogenerator (movie file-2), where a capacitor of 6600 μF was utilized to connect both the nanogenerator and the white globe light. The corresponding intensity of illumination is up to 1700 lx, as displayed in Figure 6d. The obtained illumination was sufficient for reading the printed texts in complete darkness condition (Figure 6e, movie file-3). The mobile characteristic of the hybridized nanogenerator was also demonstrated by using the nanogenerator to sustainably power a globe light in the wild, as depicted in Figure 6f (movie file-4).

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.nanoen.2015.03.012.

Conclusion

In summary, we have demonstrated a rotating-disk-based hybridized nanogenerator including an EMG and a TENG for simultaneously scavenging biomechanical energy from human hand induced rotating motions as mobile power source. Under a rotating rate of 200 r/min, the EMG and TENG can produce the output powers of about 8.4 mW at a loading resistance of 12 Ω and 8.6 mW at a loading resistance of 0.2 MΩ, respectively, where the generated electrical energy of the hybridized nanogenerator is more than double of that generated by individual energy harvesting units. At the best matched loading resistances for each, the EMG and TENG can produce an output power per unit mass/volume of 24 μW/g and 56 W/m^3, and 119 μW/g and 261 W/m^3, respectively, indicating the unique advantages that can be offered by TENG owing to its light weight, low-cost and the potential for large-scope applications together with EMG. By charging a capacitor, the hybridized nanogenerator exhibited better charging performance than that of the individual energy harvesting units. A commercial globe light can be sustainably lighted up by scavenging the biomechanical energy from human hand induced rotating motions, which has an illumination intensity up to 1700 lx. This invention of the hybridized nanogenerator may push forward a significant step toward the practical applications of biomechanical energy harvesting units as a mobile power source in the wild.

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