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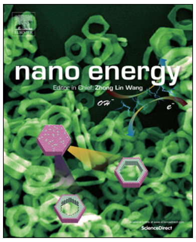

RAPID COMMUNICATION

Multi-layered disk triboelectric nanogenerator for harvesting hydropower

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Abstract

New technologies that can scavenge ambient environmental energy have attracted increasing interest in the past decades. Recently, triboelectric nanogenerator (TENG) has been demonstrated as a powerful approach for harvesting various forms of mechanical energies. In this work, a newly designed TENG is demonstrated by coaxially integrating multiple layers disk TENGs into a whole system, which transforms the fluid flow into rotation motion of multiple layers disks and generates a multiplied electrical output. To achieve the effective structural integration and output multiplication, a D-shape shaft is adopted to facilitate the synchronized relative rotation of all the segmentally-structured disk layers and light weight and low stiffness springs are employed to ensure the intimate contact of the tribo-surfaces. With the above design, the nanogenerator delivers an open-circuit voltage up to ~470 V and a short-circuit current density of 90.6 mA/m^2, corresponding to an instantaneous maximum power density of 42.6 W/m^2 (2.68 kW/m^3) at a rotation speed of 1000 rpm. By combining the TENG with a water turbine, the device can be effectively driven by a water flow from a common household faucet. This technology represents an important advance of TENGs toward practical applications and shows great potential in hydroelectric power and wind power industries.

Introduction

With the increasing threat of environmental pollution and energy crisis, it is becoming an increasingly urgent necessity to develop novel and efficient technologies for harvesting

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energy from ambient environment [1-3]. Among various energy sources, mechanical energy is one of the most effort-attracting candidates because it universally exists in our living environment, but usually goes to waste. In this regard, nanogenerator (NG), which utilize nanostructures for converting environmental mechanical energy into electricity, has been developed as a very effective and practically-applicable technology since 2006 [4-6]. Recently, along the progressive track of this area, triboelectric nanogenerator (TENG) has emerged as a promising subcategory based on the conjunction of triboelectrification and electrostatic induction [7-10]. With the numerous advantages such as simple fabrication, low cost, light weight, small volume and high efficiency, TENGs are not only becoming unprecedented technology for mechanical energy conversion, but also showing a great potential as self-powered active sensors [11-14]. Until now, two fundamental working modes have been established for TENGs – vertical contact-separation mode and in-plane sliding mode with distinct characteristics and different application areas [15-18]. Compared with the vertical contact-separation mode, the in-plane sliding mode enables more compact structures, and is more effective for triboelectric charge generation and transfer, thus more efficient for charging energy storage units. Moreover, the electricity generation efficiency based on this mode can be easily enhanced by introducing segmental or grating design to achieve multi-cycles of charge transfer in one sliding motion. As a typical structure, disk-based TENG was demonstrated to be a promising structure for harvesting rotation energy [19]. Since most types of irregular motions can be transformed into rotations by certain mechanisms, such disk TENGs are applicable for scavenging different forms of mechanical energy, similar to the electromagnetic-induction-based turbine engines. However, in the first design of the disk TENG, only one pair of triboelectric layers were driven to slide by rotation motion, which is inefficient for fully utilizing the input energy. Thus, it is highly desirable to realize multi-layered integration [20] on the disk TENGs, which requires two critical issues resolved in the structure design in order to reach a multiplied output performance: intimate contacts between any two adjacent triboelectric layers maintained during the rotation, under a minimized pressing for a small resistance; strictly synchronized rotation of all the segmentally-structured disk pairs so that the output from each pair can be perfectly added-up.

Here in this work, we developed an effective strategy for the multi-layer integration of the disk TENGs, with the above two issues resolved. In this design, a D-shape shaft was introduced to coaxially transmit the rotation motion onto each rotor (rotating part in each pair of triboelectric layers), with the segmental phase synchronized. On the other hand, to maintain intimate contact of the tribo-surfaces, light weight and low stiffness springs were adopted to fix the stators at the four corners and provide a gentle and adjustable pressing force. Through a parallel connection of four integrated units into one multi-layered disk TENG, the device is capable of generating an enhanced short-circuit current density (J_{sc}) of 90.6 mA/m^2 with a peak power density of 42.6 W/m^2 (2.68 kW/m^3), under an input rotating speed of 1000 rpm. Furthermore, when the device is coupled with a water turbine, the multi-layered TENG can effectively harvest water flow energy, producing a maximum short-circuit density of 26.3 mA/m^2 by scavenging the water flowing from an ordinary household faucet, which can be used as a direct power source for instantaneously lighting up hundreds of serially connected light-emitting diodes (LEDs). This work provides a significant progress for the power improvement and applicability of triboelectric nanogenerators for harvesting large scale mechanical energy, such as hydroelectric power and wind power.

Results and discussion

The multi-layered disk TENG is mainly composed of two groups: rotors with Al film as the attached triboelectric layers, and stators with the purposely chosen polytetrafluoroethylene (PTFE) film as the other triboelectric layers. They are coaxial with the input rotation motion, as schematically depicted in Figure 1a. For achieving flat surfaces, acrylic sheets were used as template substrates for both of them. At first, they were processed by laser cutting to form eight-sector structures with through-holes in the center for the shaft connection, which were of the same shape as the attached triboelectric layers. For the rotor templates, the center-hole is of D-shape, strictly matching the D-shaft we used, so that they can be led by the shaft to rotate with little angular variations (Figure 1b). Both sides of a rotor substrate were deposited with Al films by e-beam evaporation, which serve as one side in a disk TENG unit. As for the stators, the center-hole is in round-shape, with the diameter a bit larger than the D-shape shaft. In this way, the stators will not rotate with the spinning shaft. On their surfaces, 50-μm-thick PTFE films with aluminum electrodes on the back side were securely attached. For the four-layer integration as depicted in Figure 1, the stator placed in the middle was double-side coated with PTFE. The multiple-layered structure was obtained by stacking three stators and two rotors in an alternating sequence, with the D-shape shaft going through all the center-holes. Each pair of PTFE film and aluminum film next to each other constitutes a disk-TENG unit. The stators were fixed together by 4 screws going through the holes in their four corners, with one screw fastened to a bracket to ensure their stationary during operation. In order to maintain intimate surface contact between adjacent tribo-layers, low-stiffness springs were installed on these screws to apply a well-controlled gentle pressing force between the plates. When the D-shape shaft is connected to a rotating object, e.g. a rotary motor in the experimental measurement, all the Al layers on the rotors will be driven to rotate with the same phase, while the PTFE layers on the stators will stay still. In this manner, the relative rotation between the adjacent layers enables periodic contact-separation cycles of the opposite triboelectric charges, and thus generates electricity in each layer. When all of the four layers of the multi-layered disk TENG are connected in parallel, the current with the same phase can be added up, contributing to a multiplied power output. It is worth noting that, in order to enhance the surface roughness and promote the triboelectrification intensity, the aluminum films on the rotor part were coated with silver nanoparticles [21]. Figure 1c shows the SEM images of the assembled silver nanoparticles on Al film,

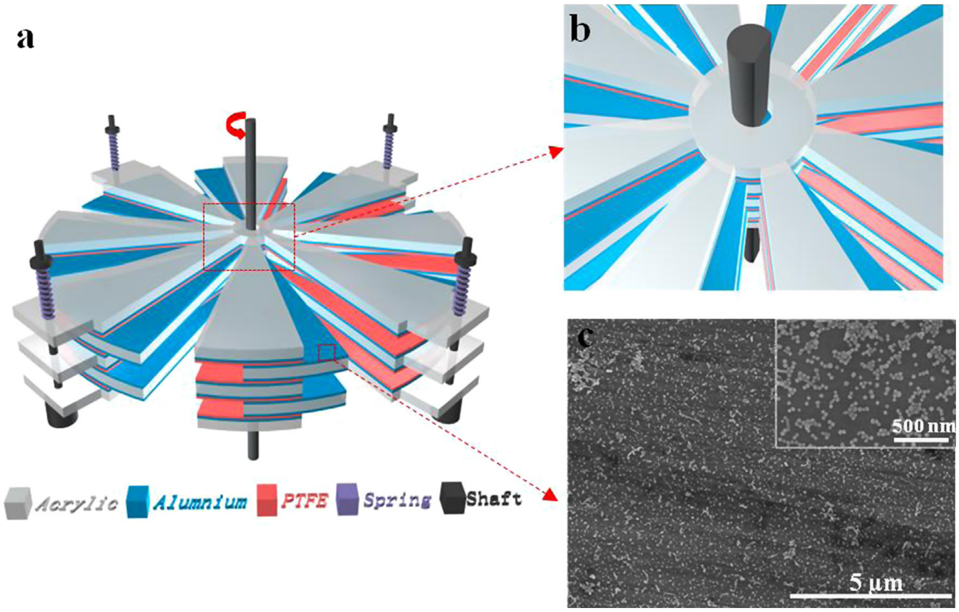

Figure 1 Device structure of the multi-layered disk triboelectric nanogenerator (TENG). (a) The schematic diagram showing the structure design of the multi-layered disk TENG. (b) The enlarged picture showing the D-shape shaft going through all the center-holes. (c) The SEM image of the silver nanoparticles coated on the aluminum electrode of the rotor part, the inset is the SEM image in higher magnification.

which uniformly distribute across the whole surface with an average diameter of 50 nm. In this experimental demonstration, the projected surface area of the TENG device is 34.2 cm^2. In the following discussion, this value will be used to calculate the transferred charge density, current density, and power density of the multi-layered device.

The operation mechanism of the multi-layered disk TENG can be explained as the coupling of the contact electrification and the relative-rotation-induced charge transfer. For simplicity, we adopted a structure with two triboelectric units to illustrate the multi-layer integrated electricity generation process, as shown in Figure 2a. For a parallel integration, the aluminum films in the two layers of units are connected together, while the two PTFE's electrodes are also connected as the other common electrode. In the first state (Figure 2a_1), the rotor and the stators are at the overlapping position where the triboelectric surfaces are in closely contact. Since the PTFE is a more triboelectrically negative material than aluminum [22], electrons will be injected from Al surfaces to PTFE, leaving the PTFE surfaces negatively charged and the Al surfaces positively charged with equal density. But there is little electric potential drop across the two electrodes, thus no electron flowing through the external circuit at this state. When the rotor is driven to rotate and slide against the stator surfaces (stage a_2), the overlapping area starts to decrease, resulting in an in-plane separation of the opposite tribo-charges in both of the two layers. This induces a higher potential at the aluminum common electrode of the rotor part in reference to the common electrode of PTFE, which will drive a current flow from the rotor part to the stators in order to screen this induced potential difference. This electricity generation process will last until the two parts rotate to a complementary position without overlap in contact area, which fully separates the opposite tribo-charges, as shown in Figure 2a_3. In this state, all of the mobile tribo-charges on the Al films have been transferred to the common electrode of PTFE, which doubles the amount of transferred charges as driven by the one-layer structure. As the rotor continues spinning, the aluminum films will gradually get contact with adjacent sector of PTFE films (stage a_4), resulting in an increase in the overlapping area, and thus a decrease in the tribo-charge-induced potential difference. As a result, the transferred charges on the PTFE electrodes will flow back to the aluminum film through external load in order to re-establish the electrostatic equilibrium, which contributes to the second cycle of current in reverse direction. When the rotor reaches the fully overlapping position with the stators again (stage a_1), all the positive tribo-charges will flow back from the PTFE electrode to the Al films. Therefore, in each individual cycle, triboelectric charges from each layer of TENG element will contribute to the electrical output of the whole device, which means that the amount of transferred charges in the multi-layered TENG will theoretically equal to the summation of the charge transfer from each single triboelectric unit. This will lead to the multiplied current signal and thus the multiplied power output, compared to the single-layered disk TENG.

In order to verify this output enhancement from multilayer integration, we employed finite element simulation (FEM) to compare one-layer structure (Figure 2b) with two-layer integration (Figure 2c) in their generated potential difference between the two electrodes at the open-circuit condition and the transferred charge density at the short-circuit condition when both of them are at the fully displaced state. For the simplicity, the 2-dimensional models were utilized. Each tribo-charged surface has the same area of 10 mm × 1 mm and is assigned with a charge density of $\pm 8\ \mu\mathrm{C/m}^2$ (positive for Al and negative for PTFE).

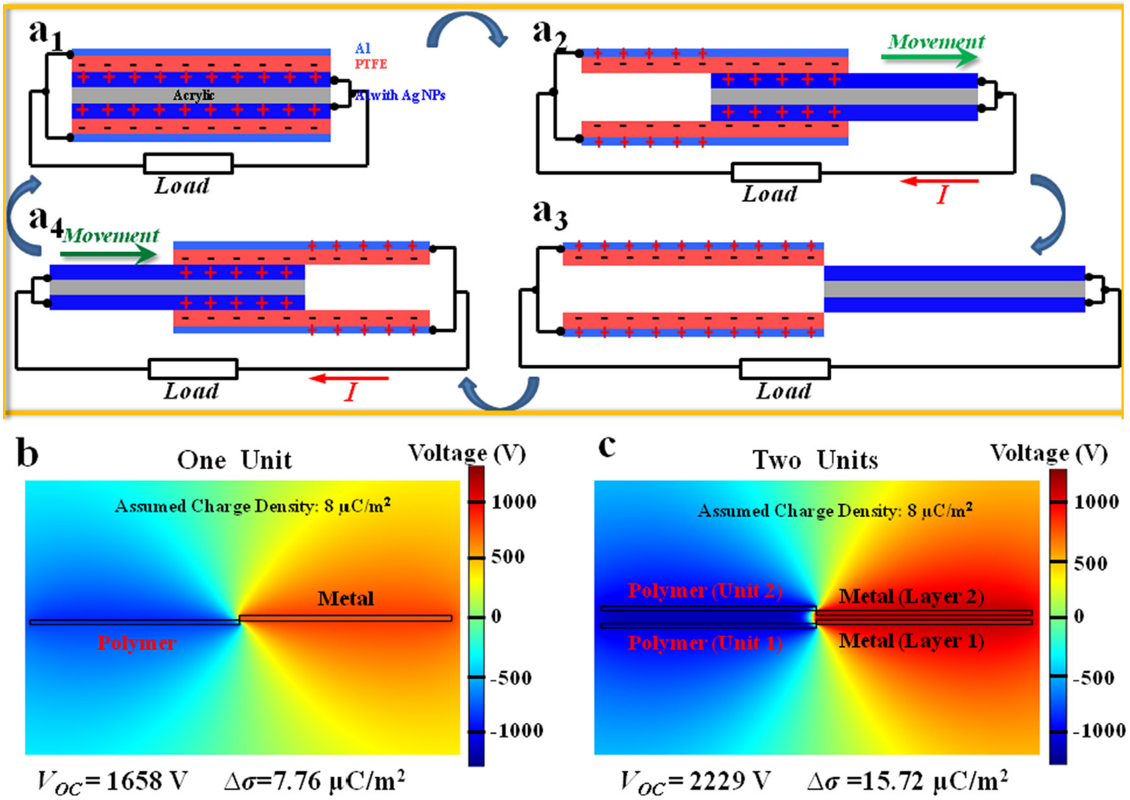

Figure 2 Working mechanism of the multi-layered disk TENG. (a) A full cycle of electricity generation process of the TENG. (b) Finite element simulation of the potential difference and transferred charge density for the disk TENG with one tribo-charged unit. (C) Finite element simulation of the potential difference and transferred charge density for the disk TENG with two tribo-charge units.

According to the Figure 2b, the calculated open-circuit voltage (V_{oc}) and transferred charge density ($\Delta\sigma$) from the single-layered TENG structure are 1658 V and 7.76 μC/m^2, respectively. When another layer of the same structure is integrated adjacently, which has a synchronized in-plane displacement (Figure 2c), the V_{oc} and $\Delta\sigma$ between the two groups of parallelly-connected electrodes will increase to 2229 V and 15.72 μC/m^2, respectively. By comparing these two groups of results, the transferred charge density is doubled through this multi-layer integration, as expected from the theoretical discussion. On the other hand, the elevation of the V_{oc} should come from the superposition of the electric fields generated by the two groups of separated tribo-charges, which are located close to each other [23,24]. Therefore, the numerical simulation results clearly illustrate that the multi-layer integration of the disk TENG is a very effective approach to get multiplied electrical outputs, and hence improved efficiency than the single unit one, as long as all the layers rotates at the same phase.

The electrical outputs of the four-layered disk TENG, as structurally described in Figure 1, were measured by connecting the shaft to a spinning motor with a rotation speed of 10 rpm (Figure 3). The rotors were driven to make a relative rotation movement against the stators. At first, the V_{oc}, short-circuit current density (J_{sc}), and $\Delta\sigma$ of each individual units (named as Unit 1-4, respectively) were measured separately. Figure S1 shows the measured results for all the four layers (the outputs from Unit 1 are shown in Figure 3a as typical results). It is observed that each layer of disk TENG provides the electric outputs on the same level: V_{oc} of ~400 V; $\Delta\sigma$ of ~65 μC/m^2, and J_{sc} of ~0.5 mA/m^2, with only a little variation. Thus, such a multi-layer integration can help the input rotation motion to enable effective electricity generation in these four layers. By connecting the layers in parallel, the obtained output from each layer can add up to give a multiplied output. As shown in Figure 3b, when two triboelectric units were connected, the transferred charge density was increase to 110 μC/m^2 with an enhanced J_{sc} of 0.9 mA/m^2, both of which are about twice of the one-layer results, while there is very little change on the V_{oc} (427 V). If three units were integrated, the $\Delta\sigma$ and J_{sc} were triply enhanced to 169 μC/m^2 and 1.2 mA/m^2, respectively, and V_{oc} still stayed comparable to that from an individual layer. After connecting all of the four units together, the $\Delta\sigma$ and J_{sc} were further scaled up and reached the highest values of 234 μC/m^2 and 1.5 mA/m^2, respectively. At this time, the V_{oc} only had a small increase to 470 V. From the above results, we can conclude that the multi-layered integration with parallel electric connection gives transferred charge density and short-circuit current density a good superposition relationship, while the open-circuit voltage will remain on the same level, which are in good agreement with the simulation results. Furthermore, based on the output enhancement trend from increased layers, we should be able to further improve the electrical outputs by integrating more

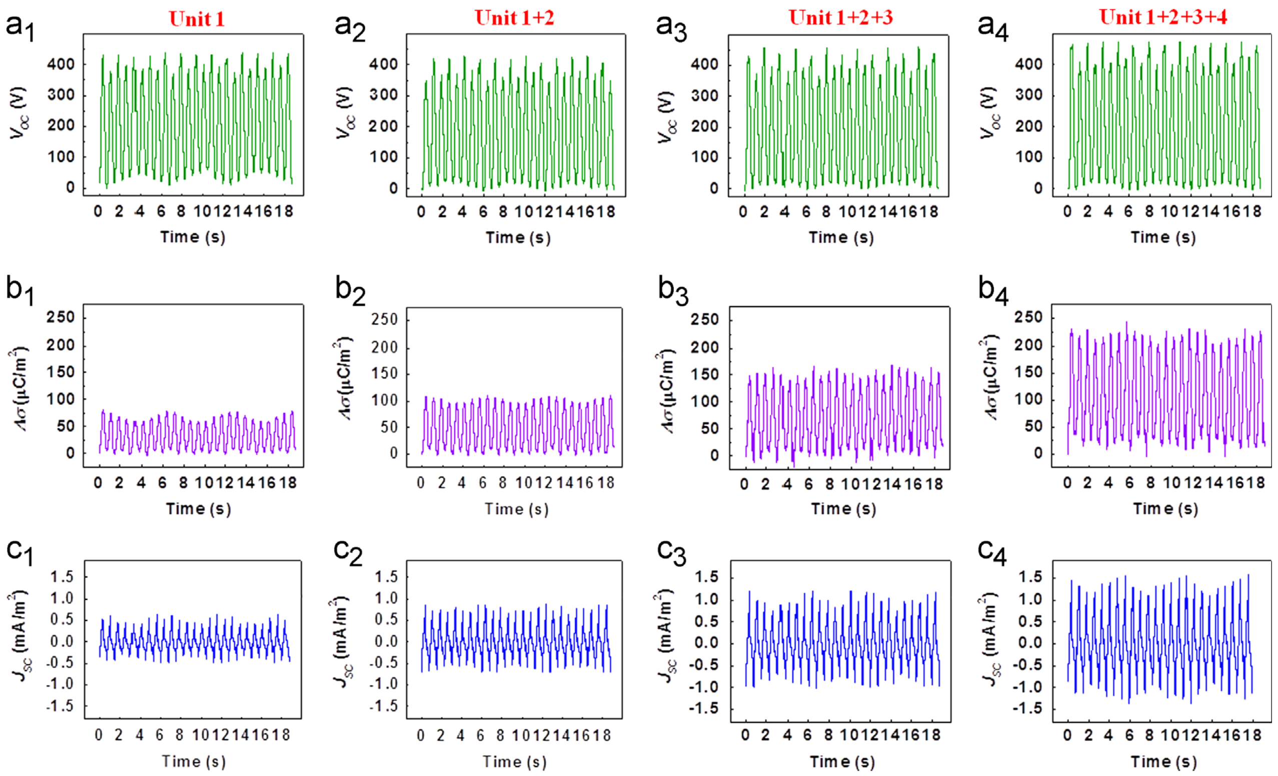

Figure 3 Electrical output of the disk TENG with different configurations under the rotation speed of 10 rpm. (a_1-a_4) The open-circuit voltage (V_{oc}), (b_1-b_4) the transferred charges density ($\Delta\sigma$), and (c_1-c_4) the short-circuit current density (J_{sc}) of the disk TENG with one, two, three, and four tribo-charged units.

units into a whole device. Therefore, the multi-layered parallelly-connected structure is an effect and indispensable method to achieve high electrical output, especially large current density.

With the integration of four layers disk-TENG units, the electrical output of the device can reach a high level at an increased rotation speed of the rotors, since a larger rotation speed will lead to a faster tribo-charge transfer process, which increases the current density and thus the output power density. As shown in Figure 4a, when the rotation speed was set at 1000 rpm, the J_{sc} of the TENG reached 90.6 mA/m^2, which is about 4 times as large as the previously-reported single-layered disk TENG [19]. To characterize the power output of the device, we also measured the V_{oc} under the rotation speed of 1000 rpm. As shown in Figure 4b, the voltage remains the same value with that at low-speed condition (10 rpm), which implies that the indispensable intimate contact of the triboelectric surfaces during rotation is not affected by the high rotary speed. In practical applications, the energy harvester is usually connected to external loads with different resistances, so that we systematically studied the voltage and current outputs on a series of different resistances, from 100 Ω to 150 MΩ. As depicted in Figure 4c, the current density drops with the increase of the external resistance, while the voltage across the load shows a reversed tendency. Figure 4d illustrates the power density as a function of load resistance. The power density initially rises at a low resistance region and then declines significantly at a higher resistance region, showing a peak value of ~5 W/m^2 at ~1 MΩ (Figure 4d). To investigate the relationship between the rotation speed and current output of the multi-layered device, we carried out a set of systematic measurements under different rotation speed condition. As illustrated in Figure S2, with the rotation speed being raised from 100 rpm to 1000 rpm, the J_{sc} gradually increased from 6.16 mA/m^2 to 90.6 mA/m^2. The variation tendency can be fit in a good linear relationship (Figure S3), indicating its potential application in self-powered active rotation speed sensor.

The disk TENG is a promising structure to harvest different types of mechanical energies existing in the nature. Moreover, it has been demonstrated recently that this type of device can produce a larger output power and more advantages than a traditional electromagnetic induction generator (EMIG) [25]. Therefore, the multi-layered disk TENG, which delivers a multiplied electrical output, may be an important alternative to traditional EMIG for power generation. In practical application, through the coaxial design in this work, the multi-layered disk TENG can be easily coupled with a turbine or a windmill. Then, irregular flow motions of fluid, such as water flow or wind, can be effectively transformed to rotary motion of the shaft and hence enable the electricity generation of the device. As an example, the nanogenerator was demonstrated as a practically applicable structure for harvesting the energy of water flow. Through connecting the shaft with a water turbine, the water flowing through the turbine can effectively drive the rotation of the disk TENG (Figure 5b). As shown in Figure 5a and Video S1, when the water flow that comes from an ordinary household faucet was turned on, the rotors of the multi-layered disk TENG were driven to spin against the stators. In this manner, the mechanical

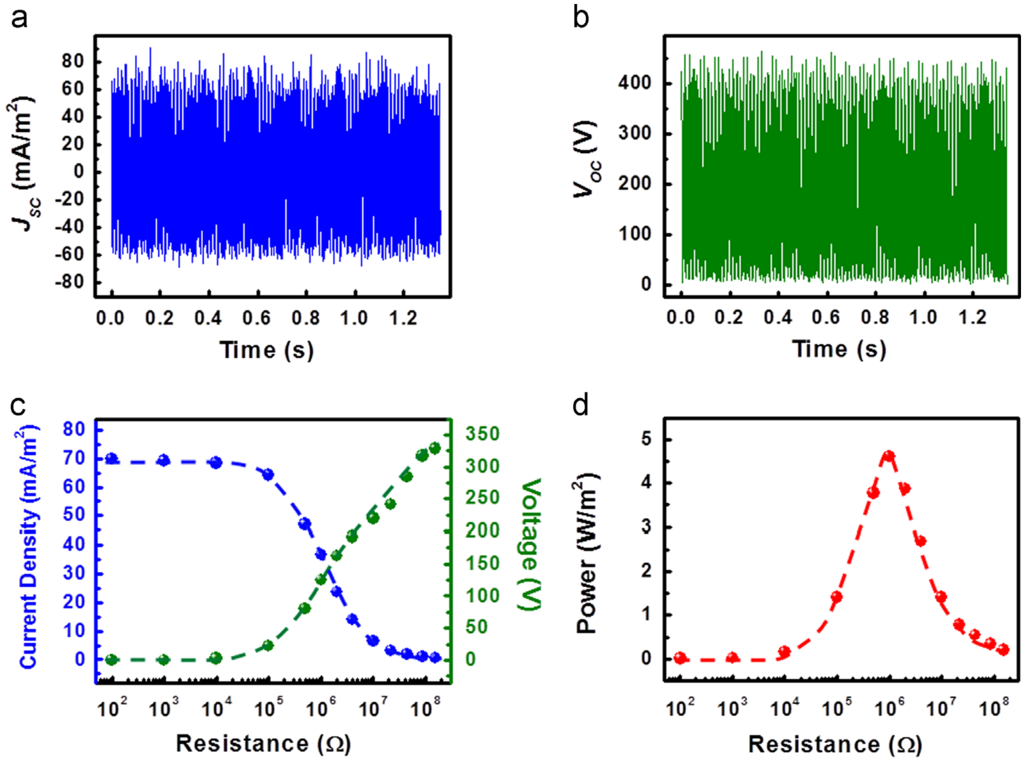

Figure 4 Output performance of the four-layer disk TENG at 1000 rpm. (a) The J_{sc}, and (b) V_{oc} of the device. The dependence of (c) the output voltage (green) and current (blue) and (d) the power density on the resistance of the external load.

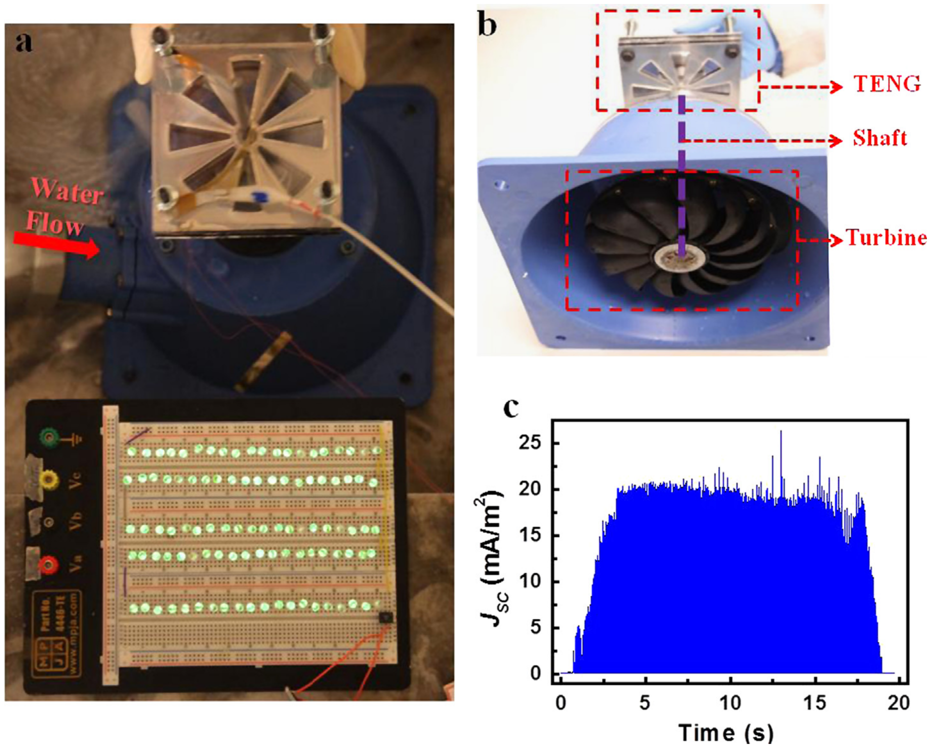

Figure 5 Application of the four-layer disk TENG for harvesting energy from water flow. (a) The picture of the multi-layered disk TENG coupled with a water turbine for harvesting water flow energy and lighting up 100 commercial LEDs. (b) The picture of the energy harvesting system showing the detailed structural design. (c) The real-time measurement of the current signal of the system.

energy of the water flow was effectively converted into electricity, which is capable of instantaneously lighting up 100 commercial LEDs. Through a real-time measurement of the current signal (Figure 5c), the J_{sc} generated by the water flow can be as high as 20 mA/m^2. From this demonstration, the similar methodology can be expanded to the applications of harvesting energies from ocean wave and wind power, which will make the multi-layered TENG an effective approach to harvesting large-scale mechanical energies.

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.nanoen.2014.03.015.

Conclusions

In summary, we demonstrated a new TENG structure by coaxially integrating multiple layers disk TENGs, which can harvest mechanical energy to drive the rotation motion of multiple layers disks and generate a multiplied electrical output. To realize an effective structural integration and output multiplication, we adopted the following two strategies. First, a D-shape shaft was used to realize the synchronized relative rotation of all the segmentally-structured disk layers so that the output from each layer can be perfectly added-up. In addition, to achieve intimate contact of the tribo-surfaces, light weight and low stiffness springs were adopted to fix the whole structure and provide a gentle pressing force. Through systematical performance characterization, the power superposition from every single layer of the multi-layered disk TENG was clearly demonstrated. With the above rational design, the nanogenerator, when operating at the rotation speed of 1000 rpm, can produces an open-circuit voltage up to $\sim$470 V and a short-circuit current density of 90.6 mA/m^2, corresponding to an instantaneous maximum power density of 42.6 W/m^2 (2.68 kW/m^3) at a rotation speed of 1000 rpm. After combining the TENG with a water turbine, a water flow from a common household faucet can drive the device to generate high-output electricity, which is capable of instantaneously driving 100 commercial electronics (LEDs). Owing to the vast applicability of the disk-structured TENG and the effective power enhancement from the multi-layer integration, the multi-layered disk-TENG we demonstrated in this paper represents an important advance of TENGs toward practical application and shows great potential in hydroelectric power and wind power industries.

Acknowledgments

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.nanoen.2014.03.015.

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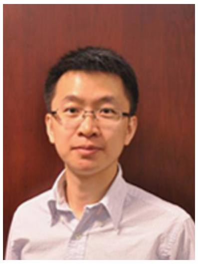

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