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RAPID COMMUNICATION

Triboelectric nanogenerator for harvesting pendulum oscillation energy

Sangmin Lee[a,1], Yean Lee[b,1], Dongseob Kim[c], Ya Yang[a], Long Lin[a], Zong-Hong Lin[a], Woonbong Hwang[c], Zhong Lin Wang[a,d,*]

[a]*School of Material Science and Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0245, USA*
[b]*Department of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0245, USA*
[c]*Department of Mechanical Engineering, Pohang University of Science and Technology, San 31, Hyoja, Namgu, Pohang, Gyungbuk 790-784, South Korea*
[d]*Satellite Research Facility, MANA, International Center for Materials Nanoarchitectonics, National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan*

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KEYWORDS
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Abstract
There is abundance of lost mechanical energy that can be harvested and recycled from our living environment. Here we developed a pendulum motion based triboelectric nanogenerator (TENG) that sustains its motion with low maintenance providing multiple output peaks from a tiny-scale single mechanical triggering. The triboelectric effect of our device is enhanced by the surface structure of the PDMS that is composed of micro roughness with nanowires. We demonstrated lighting up a commercial LED light bulb by harvesting lost mechanical energy of the pendulum oscillation of a wall clock. Our approach can be a promising platform of developing a sustainable, low maintenance system to harvest lost mechanical energy.

Introduction

Harvesting wasted energy is likely a key solution for energy crisis and environmental health. There is abundance of ambient energy such as solar, thermal, wind, and mechanical energy in our daily life. Of the list, harvesting mechanical energy is most desired as it is not limited by the weather, day/night, season, temperature and/or location, as is the case for solar and wind energy. Recently, emerging nanotechnologies for harvesting mechanical energy using nanogenerators (NGs) have attracted a lot of attention for its potential to build cost-effective, self-powered system [1-9]. Several methods have been developed based on piezoelectric and triboelectric effects. Piezoelectric NG utilizes piezoelectric potential generated in nanowires (NWs) under dynamic strain. It can effectively convert mechanical energy into electrical current, harvesting energy from

*Corresponding author at: School of Material Science and Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0245, USA.

E-mail addresses: sangmin.lee@mse.gatech.edu (S. Lee), zlwang@gatech.edu (Z.L. Wang).

[1]These authors contributed equally to this work.

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human motion, vibration and wind [10,11]. On the other hand, triboelectric nanogenerator (TENG) relies on the coupling of triboelectrification and electrostatic induction; when two materials with oppositely polarized triboelectric charges are subject to the periodic contact and separation either by press and release motion or planar sliding motion, the induced potential difference between the two electrodes can be changed cyclically, thus driving the alternating current flowing

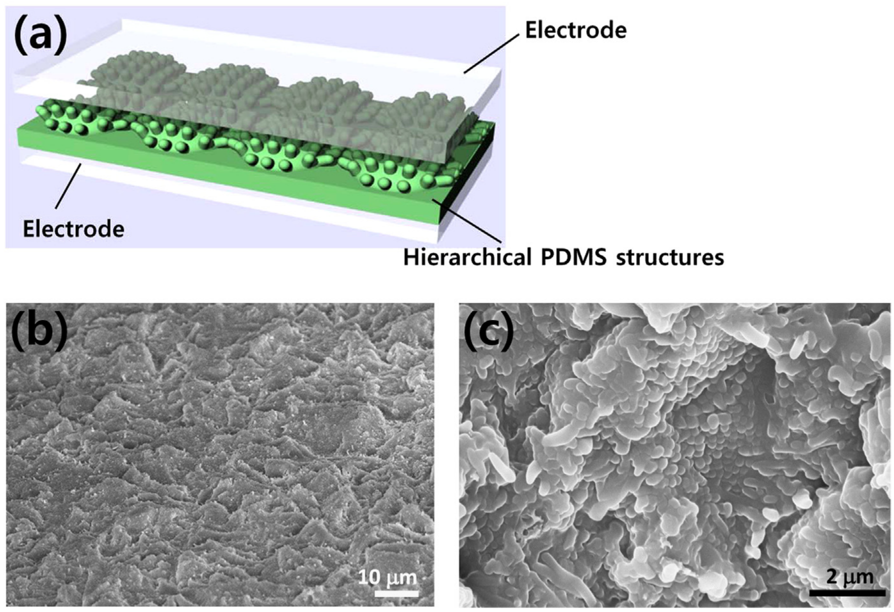

Figure 1 Schematics and SEM images of TENG with hierarchical PDMS structures. (a) Scheme of TENG with PDMS with micro-nano roughness on its surface. (b) SEM image of PDMS surface with micro structure and NWs. (c) Magnified SEM image of PDMS NWs on micro structures.

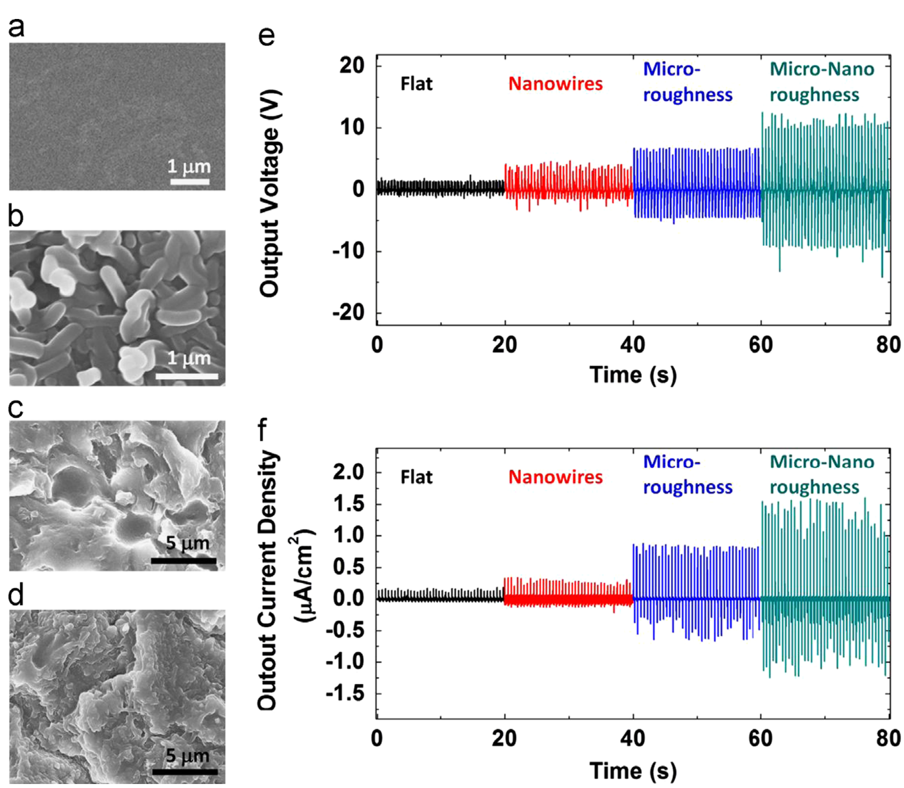

Figure 2 Comparison of TENG performance respect to different surface roughness. SEM image of (a) flat, unaltered surface of PDMS, (b) PDMS surface containing only NWs, (c) PDMS surface with micro structure only, and (d) PDMS surface with both micro structures and NWs. Experimental results of (e) output voltage and (f) current density with different surface roughness measured under the same experimental conditions.

through the external load [12-16]. Due to its high output, several studies successfully demonstrated TENGs directly lighting up hundreds of LED bulbs [13,16].

In this study, we report a sustainable TENG based on the pendulum motion of a wall clock. Since the pendulum motion is subjected to a restoring force due to gravity that will accelerate it back toward the equilibrium position, the motion can not only generate power output multiple times but also maintain the motion with only low-input energy. The TENG was fabricated based on polydimethylsiloxane (PDMS) with micro-nano structured surface to enhance surface contact area and friction during the contact and the separation of two triboelectric materials. The generated open-circuit voltage and short-circuit current were about 6 V and 0.6 μA/cm^2 under the pendulum motion, respectively, and did not vary significantly as the oscillatory amplitude of the pendulum decreased. Furthermore, we demonstrated the potential of the TENG to work as a self-powered device capable of scavenging mechanical energy from the pendulum motion of a wall clock.

Results and discussion

The principal mechanism of TENG involves building of triboelectric and electrostatic potentials between different materials. Hence, we carefully considered both materials in the triboelectric series with different tendency to gain or lose electrons and their surface contact area when designing our TENG. The basic structure of the NG is composed of micro-nano structured PDMS in contact with the lower Al electrode and the upper Al electrode, as shown in Figure 1a. The upper Al electrode plays dual roles of being the electrode and the contact surface. According to the tendency of the material in triboelectric series, electrons are injected from the upper Al electrode into the PDMS, leading to surface triboelectric charges on the PDMS [12,17]. The roughness of the PDMS was fabricated by using micro-nano structured Al as a nanoimprinting template [18]. First, in order to create micro-roughness of Al substrate, sand particles with the diameter of about 50 μm were ejected from a nozzle using compressed air. The pressure of the compressed air is about 6 kgf · cm^{-2}, and the sandblasted Al substrates were rinsed with deionized water. Afterwards, the nano-scale holes were formed on the plate by anodizing the Al substrate for 1 h in 0.1 M phosphoric acid at a constant voltage of 165 V using direct current DC power supply (Digital electronics Co., DRP-92001DUS). During the anodization, the solution was maintained at 2 °C by a circulator (Lab. Companion, RW-0525G). After the anodization, a widening process was performed in 0.1 M phosphoric acid solution for 100 min at 30 °C to enlarge the diameter of the nanoholes. Then, in order to facilitate peeling of the PDMS polymer from the Al substrate, the surface energy of the anodized Al substrate was lowered based on a self-assembled monolayer using a heptadecafluoro-1,1,2,2-tetrahydrodecyl trichlorosilane (HDFS), which can reduce the surface adhesion between them [19,20]. Once the PDMS monomer is mixed with its curing agent, we applied the PDMS on top of the Al substrate and vacuumed it thoroughly in order to remove all air trapped within the micro-nano structure and thus created finely defined patterns on PDMS. The sample was then placed in an oven at 100 °C for

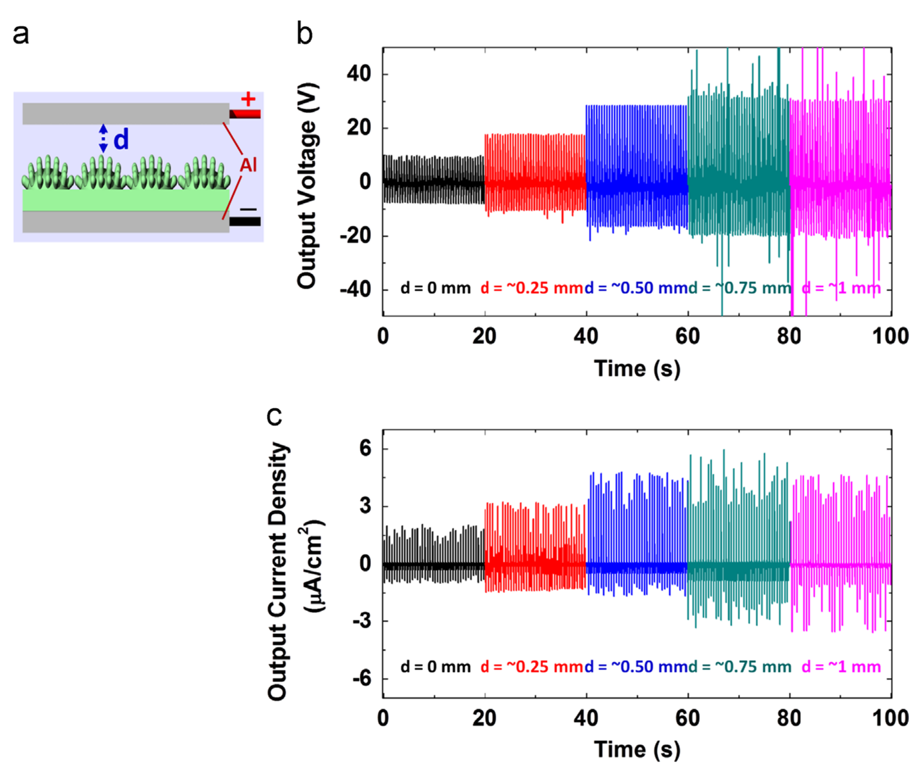

Figure 3 TENG performance comparison respect to separation distance. (a) Schematics of TENG with a separation distance between PDMS with micro-nano roughness and the top Al electrode. (b) Open circuit output voltage comparison. (c) Short circuit output current density comparison.

1 h to finish curing process of the PDMS. As shown in Figure 1b and c, the PDMS NWs are clearly visible apart from the micro roughness.

To investigate the effect of the surface roughness, we prepared four different PDMS samples to compare their performance; one without any modification, one with only NWs, another one with only micro-roughness, and finally, one with NWs on the micro roughness, as shown in Figure 2a–d. The performance of the TENGs was characterized by a controllable trigger setup, which could periodically press and release at frequency of 2 Hz. In order to guarantee the measurement for each TENG is under the same condition, the trigger in contact with the TENG is standardized with the same material and contact area of 10-mm diameter. As shown in Figure 2e and f, the flat PDMS produced the lowest output with open circuit voltage of $\sim$1.5 V and the short circuit current density of $\sim$0.2 $\mu A/cm^2$. The PDMS with only NWs showed second lowest output with the open circuit voltage reaching merely $\sim$5 V and the short circuit current density of $\sim$0.4 $\mu A/cm^2$. The next highest output was achieved with micro roughness surface with the open circuit voltage of $\sim$7 V and short circuit current density of $\sim$0.9 $\mu A/cm^2$. The micro roughness with NWs produced the highest output, as expected, with the open circuit voltage of 12 V and the short circuit current density of 1.6 $\mu A/cm^2$. As the surface roughness of the PDMS layer increased, the generated output became larger. In order words, under the same experimental condition, the increased surface roughness results in increased contact area between two triboelectric materials and thus a larger amount of triboelectric charges.

The triboelectric effect also depends on the separated distance of the materials [14,16]. Hence, we examined the optimum distance by measuring micro-nano structured sample with different thickness of spacers (See Figure 3a). Figure 3b and c show the result of the voltage and current density corresponding to the separation distance. We found a steady increase in the output as the space in between the PDMS and the Al electrode increased up to $\sim$0.75 mm in which the maximum open circuit voltage of $\sim$30 V was reached and further separation did not enhance the output. It means that the output is saturated over a distance of $\sim$0.75 mm due to the almost maximum potential difference generated between two triboelectric materials.

Since our device was aimed toward the TENG capable of scavenging the mechanical energy from pendulum motion, the pendulum driven TENG was composed of two major parts; one oscillating part and another one part fixed at the center of the base. As shown in Figure 4a, for the oscillating part, the micro-nanostructured PDMS of 1 cm^2 was attached at the end of a 125 μm-thick Kapton film. A 50 nm-thick Au electrode was coated between the PDMS and the Kapton film to enable the transfer of the induced charges. The device was positioned at the center of the moving pendulum. Only one side is coated with gold and attached with PDMS while the other side is left

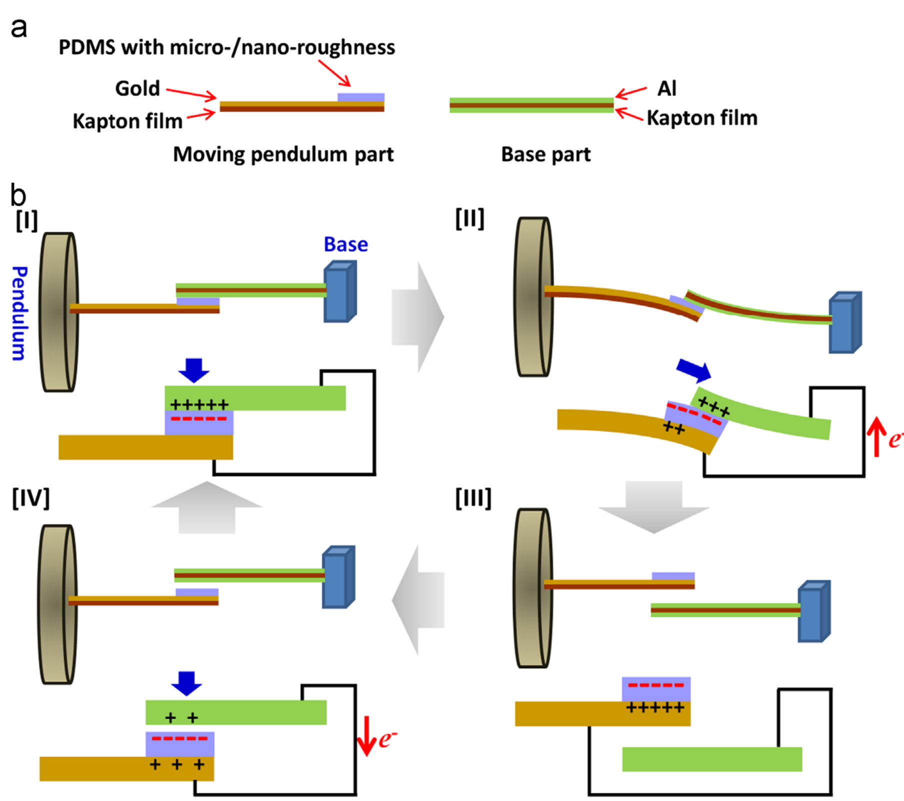

Figure 4 Mechanism of pendulum motion driven TENG. (a) Moving pendulum is composed of Au coated Kapton film with PDMS on top, and the base part is composed of Al coated Kapton film. (b) Illustration of TENG mechanism in one cycle of energy generation: ($b_{[I]}$) Triboelectric effect generates surface charge the moment PDMS comes in contact with Al surface, ($b_{[II]}$) sliding motion decreases the overlapping area between the PDMS and the Al surface leading to the difference of electrical potential which drives the current, ($b_{[III]}$) once separated, the PDMS surface remains negative while Al surface is electrically neutral, ($b_{[IV]}$) as the PDMS comes in contact with the Al surface again, electrons are driven from Al to Au surface in order to reach electrical equilibrium.

untouched. For the base part, a 40 nm-thick Al electrode was coated on both sides of a 125 μm-thick Kapton film. As schematically shown in Figure 4b, the TENG under the pendulum motion shows a hybridized electric generation of pressing contact and sliding separation process, demonstrated from a rotary triboelectric nanogenerator recently [21]. When the PDMS comes in contact with the Al electrode, due to its tendency to gain electrons, there will be a generation of surface charges caused by triboelectric effect. At that time, there is little electric potential difference in the space as both surfaces of opposite charges have equal density and are in contact with each other (Figure $4b_{[I]}$). However, as the PDMS slides away, the overlapping area between tribo-charged surfaces decreases causing in plane charge separation as shown in Figure $4b_{[II]}$. This results in the difference of the electrical potential, which drives electrons from the Au electrode to the Al surface in order to reach an equilibrium. Then, the Al surface is electrically neutral while the Au electrode has positive charges with equal density of the negative tribo-charges on the PDMS surface. (Figure $4b_{[III]}$). Finally, when the PDMS comes in contact with the aluminum electrode again (Figure $4b_{[IV]}$), the electrons travel from Al to Au electrode in response to offset the potential difference.

The electrical output of the TENG was measured under the pendulum motion depending on the initial amplitude of the motion (see Figure S1 in Supporting Information). As shown in Figure 5a, the measured output voltage was about 6 V and was not changed little as the amplitude of the motion increased from 2.2 to 5.1 cm, however higher amplitude naturally resulted in greater number of oscillation. For initial input height of 2.2 cm, we measured about 15 oscillations and at 5.1 cm, 28 oscillations. The number of oscillations linearly increased at about 4 oscillations per 1 cm increase in initial amplitude. This indicates that the pendulum motion based TENG produces multiple outputs from a single input force unlike previously introduced TENGs which produce a single output signal per input force. Furthermore, the oscillatory amplitude did not significantly alter the output performance. This shows that the pendulum motion based TENG only requires small input force to maintain the low amplitude oscillation to continuously produce multiple output signals. On the other hand, during one oscillation motion, the output is higher when the pendulum swings forward where the PDMS comes in contact with the Al electrode as opposed to when it swings backward where plain Kapton surface hits the Al electrode (See Figure 5b). This is because the micro-nano roughness structured PDMS has a larger contact area and friction and thus, the output was significantly larger. Thus, if the micro-nano structured PDMS are attached on both sides of the Kapton film coated with Au electrode, high outputs can be generated regardless of the moving direction of the pendulum motion. Then, the measured maximum short-circuit current density was about 0.6 μA/cm^2, and also the value

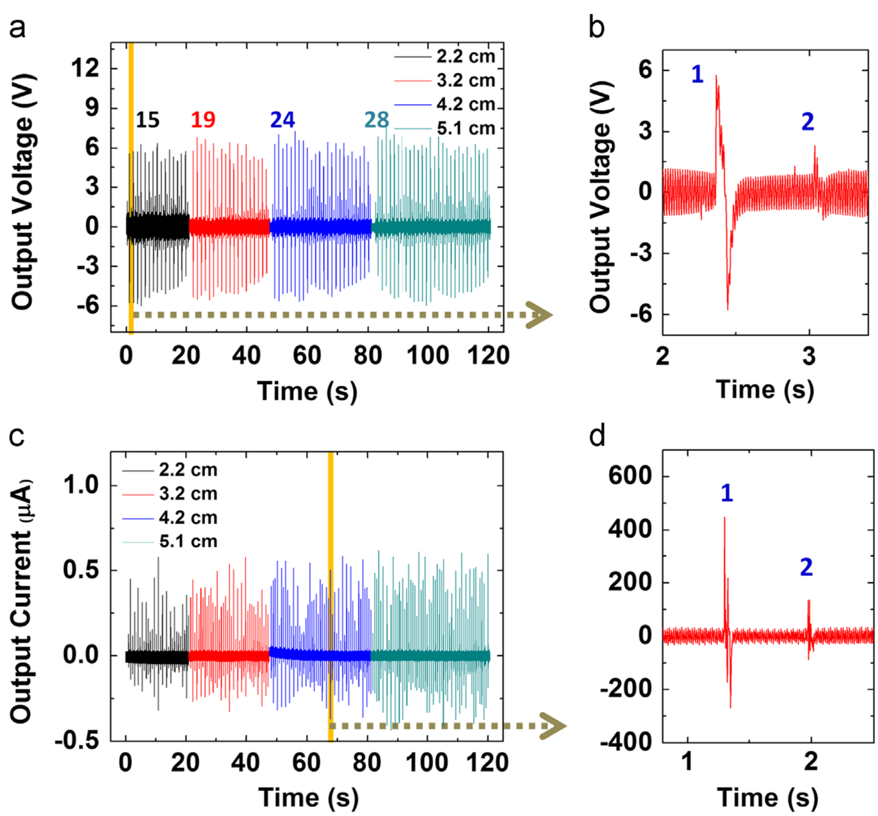

Figure 5 TENG performance under pendulum motion. (a) Measurement of the open-circuit output voltage depending on input height. The number indicates the number of free oscillation at the specific input height. (b) Comparison of the open-circuit voltage between forward and backward direction of the pendulum motion. (c) Measurement of the short-circuit output current of different input height and the free oscillation number. (d) Comparison of the short-circuit current between forward and backward direction of the motion.

did not vary significantly depending on the initial amplitude like the output voltage, as shown in Figure 5c and d.

In order to demonstrate the practical application of the TENG under the pendulum motion, we attached it to a battery run wall clock with a swing pendulum (Walnut Hollow, TQ800P). The schematic is illustrated in Figure 6a. The micro-nano structured PDMS was adhered on both sides of the Kapton film coated with Au electrode to fully utilize the oscillation under the pendulum motion, and the device was fixed at the center of the swing pendulum of the wall clock. The opponent Al electrode was coated on the 25 μm-thick Kapton film, and the device was positioned at a fixed part of the wall clock. The AC output was rectified to a DC output by a full-way rectifying bridge. The rectified output voltage was measured to be about

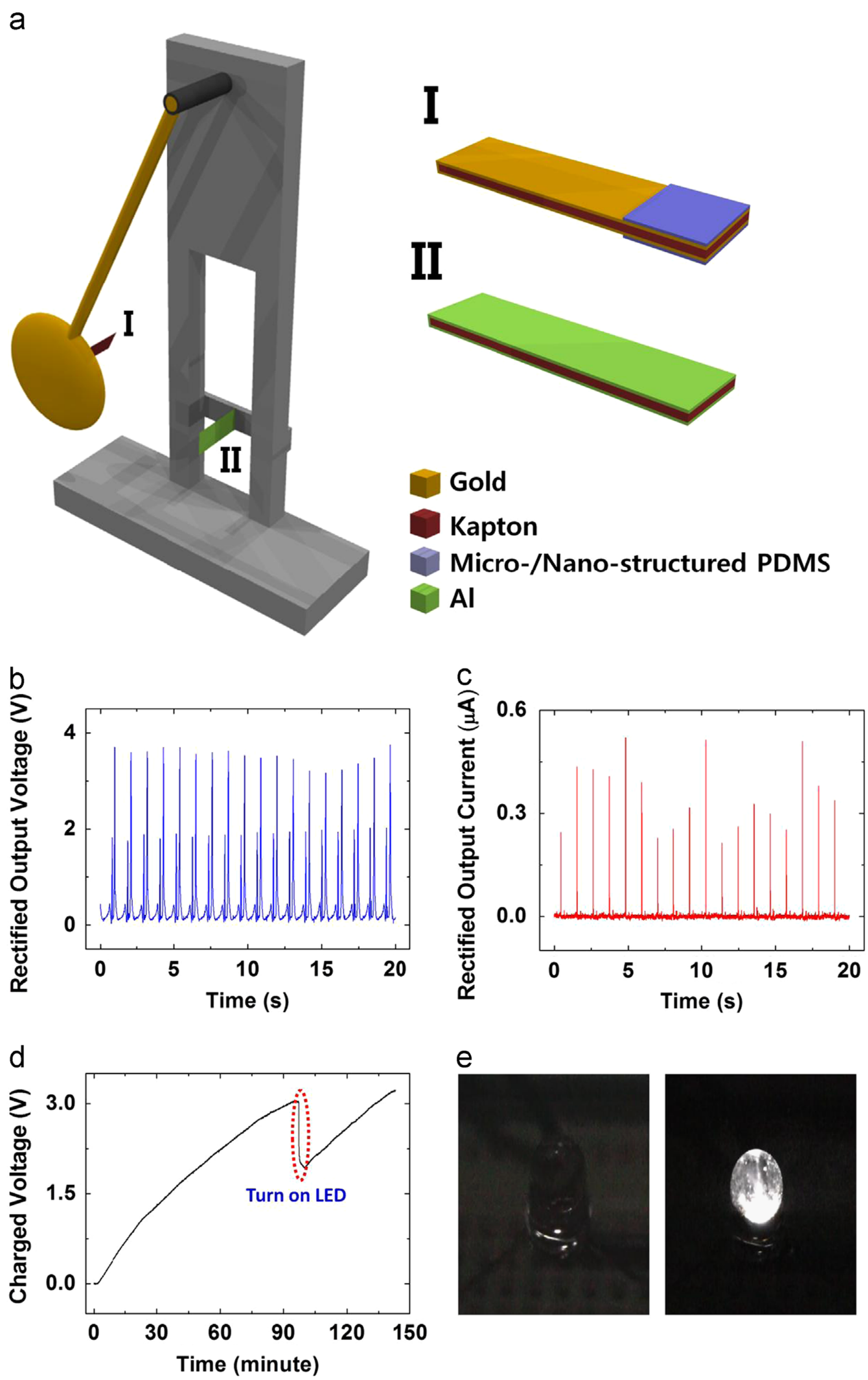

Figure 6 The performance of pendulum motion based TENG using a battery run wall clock. (a) Schematics of TENG and the pendulum of the clock. The TENG has two components (I and II) with the first one composed of Au-coated Kapton film with micro-nano structured PDMS attached on top and Al-coated Kapton film. Measurement of (b) rectified output voltage and (c) rectified output current. (d) Graph of charged voltage of the capacitor vs. time. (e) Demonstration of lighting up commercial LED light bulb by charging the capacitor with TENG.

3.6 V whereas the rectified output current was around 0.5 μA (See Figure 6b and c). Then, in order to demonstrate the feasibility of converting energy from the mechanical pendulum motion to useful electricity, a 1 μF capacitor was connected to the TENG through the bridge rectifier for a practical direct current (DC) power source, and the increasing voltage curve is shown in Figure 6d. The pendulum motion based TENG charged the capacitor for about 100 min which was enough to light up the LED bulb for a moment, and the charged voltage decreased the instant the LED turned on (See Figure 6d and e). Then, the output voltage was recharged from the sustainable pendulum motion. Further, under the same condition, the clock's pendulum based TENG maintained its motion after 24 h of operation (See Figure S2 in Supporting Information). This indicates that the clock's pendulum operated by a battery can sustainably generate the electricity from the motion otherwise lost without difficulty because the opposing force from the TENG is smaller than the operating force from the battery run wall clock. Our strategy can provide a promising platform as energy harvester for self-powered devices for practical use with low-maintenance energy.

Despite the advantages of pendulum motion driven TENG such as requiring low maintenance energy as well as multiple output per single triggering, it may be largely limited by small output performance. In order to minimize the opposing force from the TENG during the pendulum motion, the TENG was composed of flexible and thin Kapton film. Hence, the flexibility of the TENG combined with lack of friction and low pressing force greatly reduces the output performance. To overcome such limitation, one may apply the pendulum motion driven TENG to different configurations to enhance the performance without sacrificing the previously mentioned advantages. To do so, it is crucial to increase the contact force between two triboelectric materials. With higher output, the TENG will have wide applicability in harvesting lost energy such as a moving pendulum of a clock.

Conclusions

In summary, we have successfully developed a pendulum driven TENG that maintains its motion with low maintenance energy. A comparison of the output performances of different PDMS surface shows the increase in the output for micro-nano structured surface that gives four times larger than the unaltered, flat surface. Hence by utilizing the enhanced triboelectric effect of the micro-nano structured PDMS surface and the sustainability of the pendulum motion, we successfully demonstrated lighting up commercial LED using a capacitor and thereby proving its applicability. Our strategy of using oscillatory motion can be a promising means of developing a sustainable, low maintenance system to harvest lost mechanical energy.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.nanoen.2013.08.007.

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Sangmin Lee received his Ph.D. in Mechanical Engineering from Pohang University of Science and Technology (POSTECH) in 2011. Now he is a post doctor in the School of Materials Science and Engineering at Georgia Tech working with Prof. Zhong Lin Wang. His main research interests focus on the fields of super-flexible piezoelectric nanogenerator for self-powered/active sensor, high-output triboelectric nanogenerator for effective energy harvesting and hybrid cell for harvesting multiple type of energies.

Yean Lee is a an undergraduate student at Georgia Institute of Technology in BSME (Mechanical Engineering) program. He is currently working as an undergraduate research assistant at Prof. Zhong Lin Wang's group. His main research focuses on expanding nanotechnology in energy harvesting which include energy harvesting through triboelectric and piezoelectric nanogenerators and super-flexible self-powerd/active sensors.

Dongseob Kim received his Ph.D. in Mechanical Engineering from Pohang University of Science and Technology (POSTECH) in 2010. Now he is a senior researcher in the Mechanical Engineering at POSTECH working with Prof. Woonbong Hwang. His main research interests focus on the fields of analysis and fabrication of nanostructures for mechanical characterization and nanofabrications for metamaterials and nanomechanics.

Ya Yang received his Ph.D. in 2011 in Materials Science and Engineering from University of Science and Technology Beijing, China. He is currently a research scientist in the group of Professor Zhong Lin Wang at Georgia Institute of Technology. His main research interests focus on the field of pyroelectric, piezoelectric, triboelectric, and thermoelectric nanogenerators for energy storage, driving some personal electronic devices, and some novel applications.

Long Lin received his B.S. in Materials Science and Engineering from Tsinghua University, China in 2010. He is currently a Ph. D. student in School of Materials Science and Engineering at Georgia Institute of Technology. He is working as a graduate research assistant at Prof. Zhong Lin Wang's group. His research mainly focuses on nanomaterial synthesis and characterization, fabrication of high-output nanogenerators, self-powered nanosystems, piezo-tronic and piezo-phototronic effect of semiconductor nanostructures and various applications.

Zong-Hong Lin received his Ph.D degree from Department of chemistry, National Taiwan University in 2009. Now he is a postdoctoral researcher working with Professor Zhong Lin Wang in the school of Material Science and Engineering, Georgia Institute of Technology. His research interests include the development of high-output generators with novel design for efficient energy harvesting, self-powered systems for biomolecules detection and environmental sensors, highly efficient and stable catalysts for fuel cell applications, and fabrication of metal/semiconductor nanowires.

Woonbong Hwang received his Ph.D. from State University of New York in Mechanical Engineering. In 1988, he joined the Department of Mechanical Engineering in Pohang University of Science and Technology (POSTECH), Korea, where he is currently full professor and heads Nano Structures and Composites System research group. He now is the Guest Professor of State Key Laboratory of Advanced Forming Technology & Equipment, invited as talent in 'Dragon City Talents Plan' at Changzhou city from Jiangsu Province Government and invited as foreign expert in '1000 Plan' from Chinese Government in China. His research interests include fabrication and applications of nanostructures, mechanics and mechanical characterization of nanostructures, adaptive structures and smart skins, optimum design of composite structures, fracture and fatigue of composite materials and engineering of creativity. Details can be found at: http://nscs.postech.ac.kr/

Zhong Lin (ZL) Wang received his Ph.D. from Arizona State University in physics. He now is the Hightower Chair in Materials Science and Engineering, Regents' Professor, Engineering Distinguished Professor and Director, Center for Nanostructure Characterization, at Georgia Tech. Dr. Wang has made original and innovative contributions to the synthesis, discovery, characterization and understanding of fundamental physical properties of oxide nanobelts and nanowires, as well as applications of nanowires in energy sciences, electronics, optoelectronics and biological science. His discovery and breakthroughs in developing nanogenerators established the principle and technological road map for harvesting mechanical energy from environment and biological systems for powering a personal electronics. His research on self-powered nanosystems has inspired the worldwide effort in academia and industry for studying energy for micro-nano-systems, which is now a distinct disciplinary in energy research and future sensor networks. He coined and pioneered the field of piezotronics and piezo-phototronics by introducing piezoelectric potential gated charge transport process in fabricating new electronic and optoelectronic devices. Details can be found at: http://www.nanoscience.gatech.edu.