Nano Energy 75 (2020) 104957

Contents lists available at ScienceDirect

Nano Energy

journal homepage: http://www.elsevier.com/locate/nanoen

Natural wood-based triboelectric nanogenerator as self-powered sensing for smart homes and floors

Saifei Hao [a,b], Jingyi Jiao [a,b,d], Yandong Chen [a,b], Zhong Lin Wang [a,b,e,**], Xia Cao [a,b,c,*]

[a] CAS Center for Excellence in Nanoscience, Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing, 100083, China
[b] School of Nanoscience and Technology, University of Chinese Academy of Sciences, Beijing, 100049, China
[c] Research Center for Bioengineering and Sensing Technology, Beijing Key Laboratory for Bioengineering and Sensing Technology, School of Chemistry and Biological Engineering, Beijing Municipal Key Laboratory of New Energy Materials and Technologies, University of Science and Technology Beijing, Beijing, 100083, China
[d] School of Advanced Materials and Nanotechnology, Xidian University, Xi'an, 710126, China
[e] School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, GA, 30332-0245, United States

ARTICLE INFO

Keywords:
Triboelectric nanogenerators
Nature wood
Natural biodegradable
Self-powered sensor

ABSTRACT

With the rapid development of Internet of things (IoTs), big data collection and analysis based on distributed sensing is particularly important. Here, we report a natural biodegradable wood-based triboelectric nanogenerator (W-TENG), which not only can produce high electric output to power microelectronic devices, but also can be used as a self-powered sensor. A pure natural biodegradable and pollution-free wood is used as the triboelectric material. The output voltage and current of the W-TENG (8 cm × 8 cm) is 220 ± 20 V and 5.8 ± 0.5 μA at a frequency of 2 Hz. The maximum output power density could be as high as 158.2 mW/m^2 at a resistance of 50 MΩ. On this basis, The W-TENG can be widely used as self-powered light switch, self-powered doorbell which can realize the intelligent control of the lights and contribute to the energy conservation to a great extent. In addition, it can be designed as a smart floor and installed on the stage wooden floor to track and record the dancers' movements. Moreover, dancers can control the lights themselves through the floor under their feet. This W-TENG based self-powered system breaks new ground for wood-based electronics, which will have potential applications in big data analysis, smart home and smart city environments.

1. Introduction

In recent decades, with the rapid development of Internet of things (IoTs) and big data, many application fields have undergone revolutionary changes [1–3], such as medical care, security monitoring [4,5], information communication [6], etc. In the digital era, smart home has also been impacted by technological advances and has received many people's great attention. A modern system of smart home is composed of various computing devices and sensors, which brings a brand-new challenge and requires a higher energy utilization efficiency. In the prevailing circumstances, there are two ways to power sensors, which is cable power supply and mobile power supply [7–9]. The characteristics of cable power supply are the high deployment costs and poor flexibility. Meanwhile, the mobile power supply is characterized by limited lifetime battery, and furthermore, the waste battery will cause pollution to the environment [10–12]. For this reason, a self-powered, highly flexible and pollution-free sensing technology is imminently required.

Recently, triboelectric nanogenerators (TENGs) [13–15] have many advantages, such as low cost, wide selection of materials and simple structure, have rapidly developed into a powerful technology [16] for converting mechanical energy into electrical energy, which is based on the coupling effect of triboelectrification and electrostatic induction. The integration of TENGs [17–19] and energy storage devices into a single unit provides a sustainable power source for microelectronic devices, which is the concept of self-powered supply [18,19]. In addition, TENGs based on Maxwell's displacement current can effectively convert mechanical energy into electricity, which can be self-powered with no power supply that greatly improves the space flexibility. Furthermore, it

* Corresponding author. CAS Center for Excellence in Nanoscience, Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing, 100083, China.
** Corresponding author. CAS Center for Excellence in Nanoscience, Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing, 100083, China.
E-mail addresses: zlwang@gatech.edu (Z.L. Wang), caoxia@ustb.edu.cn (X. Cao).

https://doi.org/10.1016/j.nanoen.2020.104957
Received 20 March 2020; Received in revised form 30 April 2020; Accepted 11 May 2020
Available online 25 May 2020

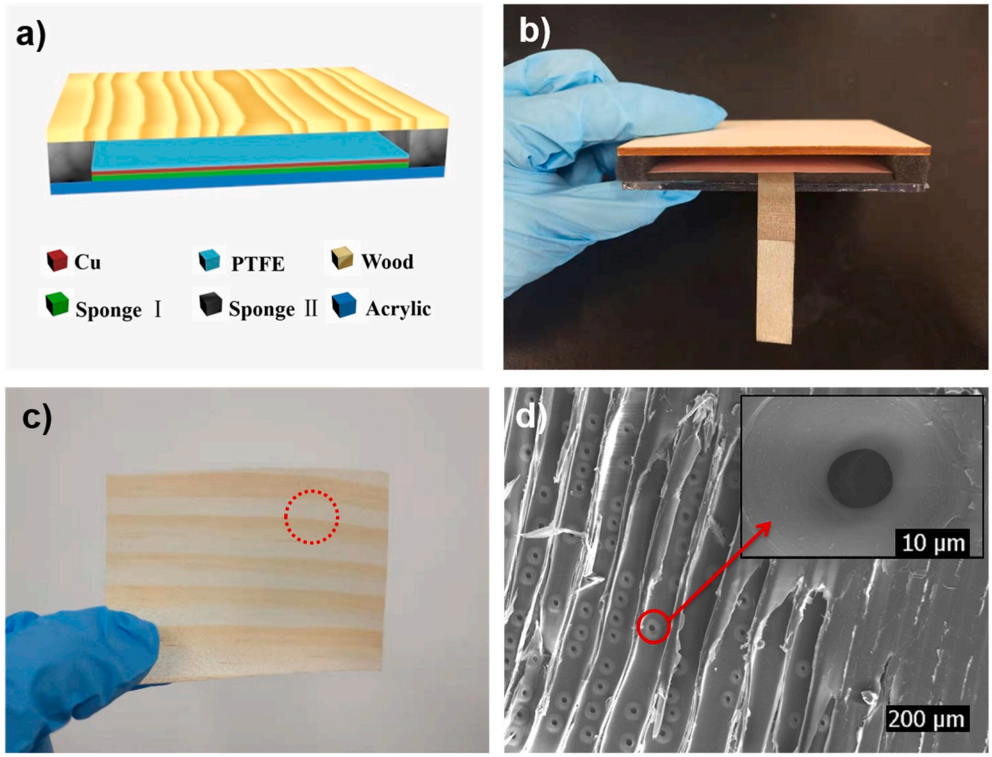

Fig. 1. The structure of natural wood assembled TENG. a) Schematic diagrams of W-TENG. b) Photograph of W-TENG. c) The surface topography of New Zealand pine. d) SEM images of morphology of New Zealand pine.

has been fully demonstrated that TENGs can work as a self-powered sensor for pressure [20], tactile and motion sensing without additional power supply. Therefore, this technology has become an effective power supply solution for sensor networks [21,22], artificial intelligence and IoTs [23]. However, the former TENGs are usually composed of metals and polymers which are difficult to reclaim and degrade. It might cause potential harm to the environment after a long-term accumulation [24,25]. In this paper, we adopted a kind of pure natural biodegradable and pollution-free material as a triboelectric layer which is wood. Wood is one of the most common and widely used decoration materials, which plays an important role in interior design.

The wood-based triboelectric nanogenerator (W-TENG) is environmental-friendly, renewable, sustainable and easy fabrication. It can be used as the switch sensor of the lighting lamps in smart home. At present, the light switch in smart home can be divided into voice operated switch and light control switch. However, the lamps controlled by these two kinds of switches in smart home [26] need a period of time to turn off automatically when the lamps are on, which makes electric energy consumed and wasted. In this research, the W-TENG is fabricated into wooden floors as switch sensors [27,28]. The mechanical energy of people walking can be harvested and transferred into electric energy, it requires no external power. As a light switch. It can effectively avoid the problem that the lighting time is longer than actual time needed and effectively saves energy.

Herein, a single-electrode mode triboelectric nanogenerator (TENG) is fabricated by natural New Zealand Pine and polytetrafluoroethylene (PTFE) purchased from the manufacturers as the triboelectric layers. The output performance of the W-TENG is 220 ± 20 V, 5 ± 1 μA. In this work, six sorts of wood are compared, and the New Zealand Pine was chosen for the subsequent experiments because of its highest open-circuit voltage and short-circuit current. In subsequent experiments, the influence of the contact area of the triboelectric layers and the frequency of the linear motor were investigated and proved that the output performance has positive correlation to the two factors. Meanwhile, the power density is 158.2 mW/m^2 and it can drive at least 42 commercial LEDs. Owing to its excellent performance, this paper explores the potential applications of the W-TENG in invisible alarm, stage pointing device, switch control and position tracking, etc. This W-TENG based self-powered system breaks new ground for wood-based electronics, which will have potential applications in big data analysis, smart home and smart city environments.

2. Results and discussion

Natural wood, with the characteristics of environmental-friendly, pollution-free, light in weight but high in intensity, is always the choice of people for materials for building homes and furniture. Nowadays, with the evolution of the IoTs and big data, wood develops a brand-new application aspect which is smart sensors and smart homes. Here, the following investigations are based on the wood which advantageously purchased from the manufacturer. Fig. 1a illustrates the schematic diagram of the W-TENG which composed of natural wood, copper (Cu), PTFE, sponge and acrylic (PMMA). Among that, the two triboelectric layers are natural wood and the PTFE. The reason for choosing PTFE as one of the two triboelectric layers is the greatest tendency of gathering electrons. Besides, copper is chosen as the electrode.

The physical graphic of W-TENG is depicted in Fig. 1b. The two sponges are placed between the natural wood and PTFE which creates a certain gap between them with the purpose of increasing the effective contact area during the triboelectrification. Fig. 1c and d reveal the surface topography and micromorphology of New Zealand pine respectively. And the inset gives further insight into the microstructure of the external surface, where a typical morphology of stomata can be found. The presence of a large number of stomata illustrates that the surface of the material has conditions for generating and storing electrons, which convincingly demonstrates the capacity of natural wood being assembled as a triboelectric layer.

The working state of W-TENG is shown in Fig. 2a and b, it was placed on the linear motor. As the reciprocating motion of the linear motor, the

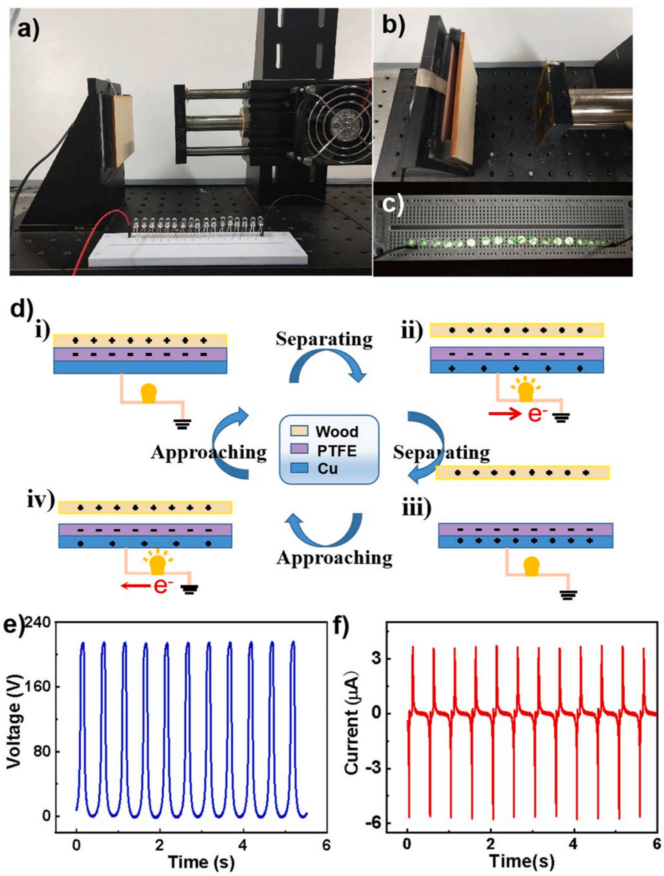

Fig. 2. The experimental setup and mechanism of W-TENG. a) Photograph of the setup with a linear motor system, b) An enlarged view of installation of the W-TENG and c) LEDs were lit. d) Schematic illustration of working principles of W-TENG in the single electrode mode; i–iv) Charge distribution of the W-TENG during a complete recycle i) contact state ii) separate state iii) released state and iv) approaching state. e) The open circuit voltage and f) short circuit current of the W-TENG (8*8 cm^2) with the frequency is 2Hz and the peak velocity of 0.352 m/s.

wood and the PTFE layers are going to conduct a contact-separation movement. The LEDs were lit when the linear motor worked as shown in Fig. 2c. The working mechanism of the W-TENG is based on the coupling of the triboelectric effect and the electrostatic induction effect which is illustrated in Fig. 2d. When the wood is contacted with PTFE layer under an external mechanical force, owing to the different electron sequences, the contact electrification will be produced at the interface which generates equivalent negative and positive charges (Fig. 2d–i). When the two triboelectric layers are separated, the Cu electrode would produce positive charges owing to the electrostatic induction effect. There is a potential difference between the Cu electrode and the ground which causes the electrons flowing and generating a current (Fig. 2d–ii). When they leave a certain distance, the PTFE layer and the Cu electrode can reach the electrical equilibrium and the electrons will stop flowing (Fig. 2d–iii). And next the wood layer is approaching to the PTFE layer. The electrons will flow backward from the ground toward the Cu electrode to achieve the balance of charges (Fig. 2d–iv). Another working cycle would restart as the two triboelectric layers contact each other, there would be an alternating current with the periodical contact separation.

Fig. 2e and f shows the open-circuit voltage and short-circuit current of W-TENG which assembled with New Zealand Pine. For this W-TENG, it was assembled and tested in the single-electrode mode. As shown in Fig. 2e, a positive voltage with a maximum value of 220 V is generated owing to the oppositely induced charge on the PTFE and wood surfaces with the contact area is 8 cm × 8 cm, the linear motor frequency of 2 Hz and the peak velocity of 0.352 m/s. Fig. 2f reveals the asymmetric current value during the single current cycle. The maximum peak value is 5.8 μA when the wood layer is separated from the PTFE layer.

Former researches have confirmed that the contact electrification effect is closely related to the material of two triboelectric layers. For this reason, W-TENGs which assembled with different kinds of natural wood were selected for this experiment. Therefore, the investigation based on distinguished triboelectric layers is conducted as follows. Fig. 3a shows the open circuit voltage of the W-TENGs which assembled with various woods when other experimental conditions remain the same, and the experiment proves that the New Zealand Pine could be the optimal option compared to the other kinds of wood. It can be concluded that the voltage output is related to the species of natural wood on account of the divergent surface electron affinity. Several factors like contact area, mechanical frequency, and external resistance were compared to investigate the output performance of the W-TENG. Fig. 3b demonstrates the relationship between the area of W-TENG and the electrical output with the linear motor frequency of 2Hz. Next, the relationship between working frequency of linear motor and the output performance of the W-TENG (5 cm × 5 cm) were analyzed in Fig. 3c. Through the above experiments, it can be concluded that the W-TENG's output performance is positively correlated with the contact area and the linear motor frequency.

Fig. 3d shows that commercial capacitors with different capacities (1 μF; 4.7 μF; 10 μF) were charged by the W-TENG, and the inset is the equivalent circuit of charging capacitors. In this experiment, an experimental parameter was chosen with a contact area of 8 cm × 8 cm, the movement frequency of 2 Hz. Within 120 s, the voltage of 1 μF capacitor can reach up to 7.4 V, the 4.7 μF capacitor can reach up to 4.7 V and the voltage of 10 μF capacitor can be charged to 3.2 V. This experiment explains that lager capacitors have better storage capacity, yet they take longer time to reach the desired voltage.

To further evaluate the performance of the W-TENG (8 cm × 8 cm), different external resistance was connected to examine the resistance dependence. As shown in Fig. 3e, when the resistance is raised from 0 to 1000 MΩ, the current drops incrementally with load resistance due to the Ohmic loss. With the increase of resistance, the instantaneous power value increases sharply at first and then tends to flatness. The instantaneous power reached a maximum value corresponding to a power density of 158.2 mW/m^2 with the optimized loading resistance of 50 MΩ. Therefore, this experiment illustrates the potential of W-TENG for being widely used in sensors or smart devices. As exhibited in Fig. 3f, repeating the experiment 500 times with the frequency of 2 Hz and the contact area is 8 cm × 8 cm. It can be seen that the open-circuit voltage and the short circuit current are basically stable after 500 cycles, which fully demonstrates the superior stability and high-cyclical characteristics of W-TENG.

Here, the utilizations of W-TENG are illustrated. W-TENGs provide a way to supply sustainable power by harvesting environmental mechanical energy. It can not only convert biomechanical energy into electrical energy, but also can be used as a self-powered sensor for switche. In this experiment, W-TENG can be installed on a house or room door in order to be a self-powered and simple-fabricated doorbell which has made a step forward to the TENGs which can be applied into the smart home. The assembled W-TENG (5 cm × 5 cm, New Zealand Pine) is placed on a house door and triggered by hand. The output electrical performance is revealed in Fig. 4a and b. The open circuit voltage is about 110 V, and the short circuit current is about 5.5 μA. Fig. 4c shows the actual scene photo of the W-TENG lighting commercial LEDs which installed on the door. Fig. 4d shows a schematic diagram of the W-TENG which installed on the door as a sensor for completely self-triggered light switch. The self-triggered light system consists of a freestanding W-TENG (5 cm × 5 cm), a signal transmitter, a signal receiver and star-shape lamps. The actual photo of the W-TENG utilized as the light switch on the house door in smart homes is shown in Fig. 4e. And the

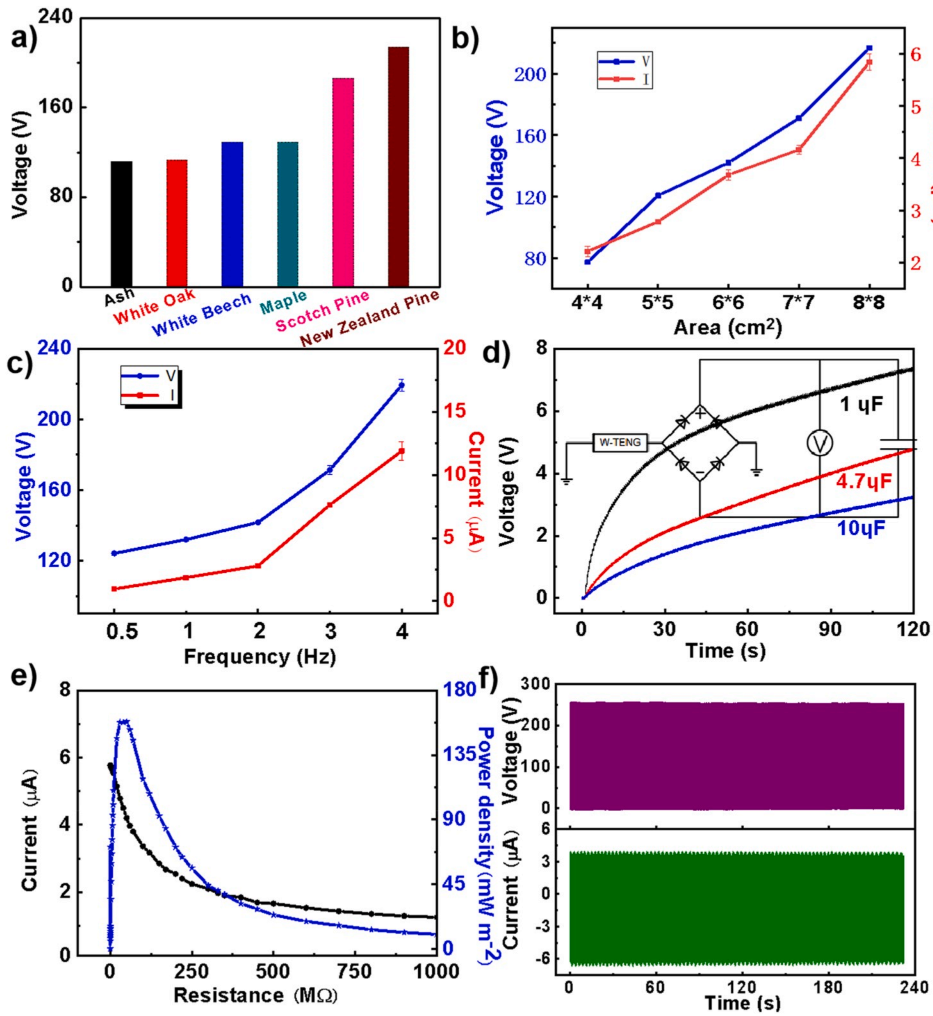

Fig. 3. The output performance and the influence factors of W-TENG. a) The open-circuit voltage of W-TENG assembled with various woods. b) The relation between the area of W-TENG and the electrical output. c) The relation between the working frequency of linear motor and the electrical output of W-TENG (5 cm × 5 cm). d) Voltage profile of capacitors (1 μF; 4.7 μF; 10 μF) charged by the W-TENG, the inset shows equivalent circuit. e) The power density and short circuit current with the external loading resistance. f) Stability and robustness test f) The open circuit voltage and short circuit current were recorded for 500 cycles in 10 min with the working frequency of 2 Hz and the peak velocity of 0.352 m/s.

inset is a photo of the house with the star lamps on, which controlled by the W-TENG.

In addition to be a light switch, it can also be assembled as a doorbell sensor, which is shown in Fig. 4f. It works the same as a self-triggered light system. There are four sections involved, W-TENG, signal transmitter, signal receiver and buzzer bell. When the W-TENG is triggered, it produces a large voltage signal which can drive the buzzer bell to ring. Meanwhile, the W-TENG can also be embedded in wood products to achieve the effect of invisible sensors, for example, when a W-TENG is hidden in a wooden table, it can trigger an alarm in case of emergency. Besides, The W-TENG can be easily fabricated at a large scale and in arrays because of the simple, reliable and low-cost advantages. Compared with the traditional switching device, this self-triggered light and switch system provide a simple and reliable technology which eliminate the reliance on the external power supply and can be a truly green energy for energy harvesting and saving.

Based on the peculiarities of W-TENG, it can be manufactured to the smart floor. Here, a single-electrode mode W-TENG is depicted in Fig. 5a. This W-TENG consists of three layers, which is EVA (slipper sole material), nature wood (New Zealand pine, 30 cm × 20 cm × 0.3 cm) and the copper foil. As is shown in Fig. 5b, the experimenter who wearing an EVA-made slipper stepping on the W-TENG and connecting it to 42 LEDs. When the experimenter stepped on the W-TENG with his feet up and down, the LEDs were lit consist of the words "Wood", which is shown in Fig. 5c. Furthermore, in order to test its electrical output performance of this device, the experimenter wore slippers (about 265 mm in length) to step up and down lift and fall to simulate human walking. The open-circuit voltage and short-circuit current are shown in Fig. 5d and e, and the peak values are 200 V and 3 μA which sufficiently confirmed that the energy of people walking can be transformed into electricity and the output values are relatively impressive.

Fig. 5f shows the voltage profile of capacitors (1 μF) charged by W-TENG and slippers, the voltage can be charged to 5.8 V when walking for about 90 s. By collecting the mechanical energy of people walking on the W-TENG and converting it into electrical energy, the electrical energy is stored in commercial capacitors (47 μF). When the stored voltage value reaches 1.5 V, it can power the electronic watch, as shown in Fig. 5g. In consequence, if these walking mechanical energy can be effectively collected and transformed, it will provide more possibilities for the evolution of smart floor and Home Automation.

Many families have installed somatosensory lights in their homes, when people pass by, the lights will be turned on. There might also be another circumstance, when people pass by and with no need for the light, the light will still on and sustain a long time, which could cause a waste of electricity and trouble people. W-TENGs provide a solution to this situation. As shown in Fig. 5h, there are five wooden boards (15 cm × 20 cm × 0.3 cm) which are W-TENGs. The middle W-TENG is connected with a Bluetooth signal device and a wireless receiver. When the slipper stepped on other W-TENG, the light would not be lit. Only when the slipper stepped on the W-TENG in the middle, the lights would be turned on and another step will suspend the light. This design of W-TENG can realize the intelligent control of the lights and contribute to the energy conservation to a great extent.

This experiment will demonstrate that W-TENGs can be combined

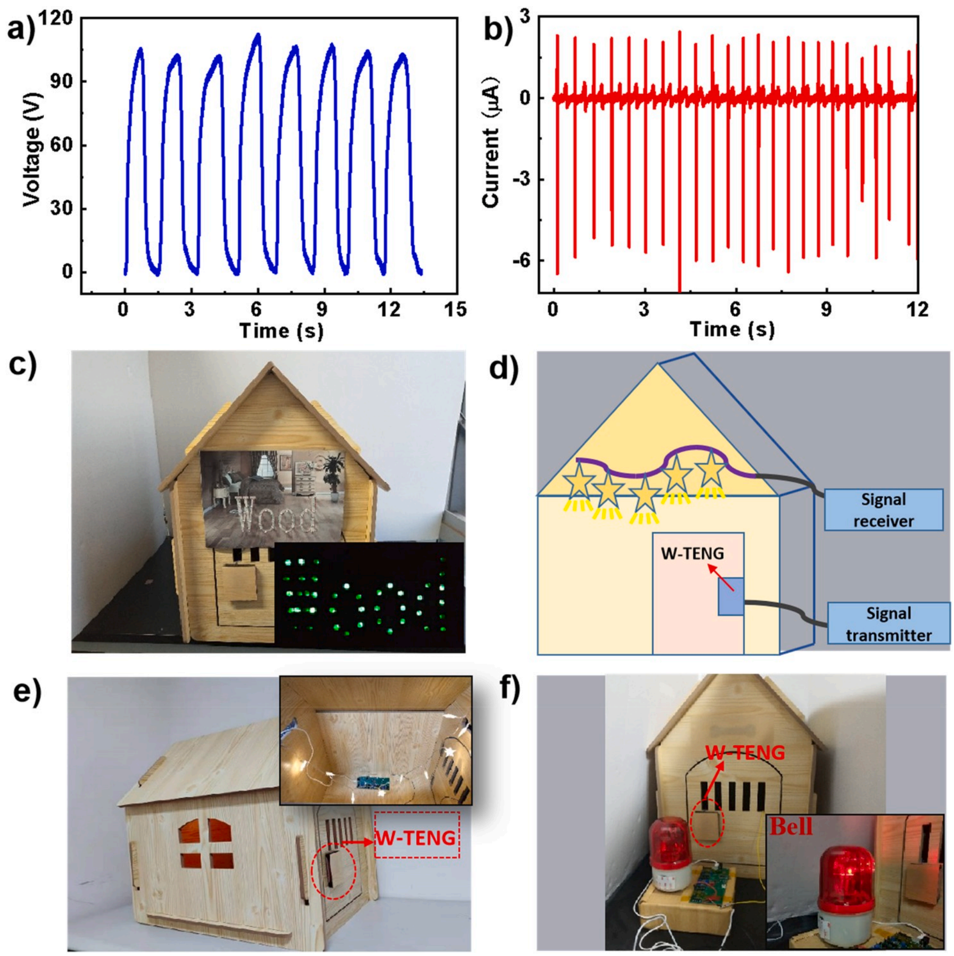

Fig. 4. Applications of the W-TENG in the smart home. a) The open circuit voltage and b) the short circuit current of the W-TENG on the home door when pressed by hand. c) The W-TENG on the door driven by hand to light LEDs. d) Working principles of the W-TENG working as a sensor. e) Photo of the W-TENG applied for light switch in smart homes. Inset: Photo of the house with the star lights on, which controlled by W-TENG. f) Photo of the W-TENG applied for doorbell switch in smart homes. Inset: Photo of the bell is on, which controlled by W-TENG.

with the stage art in order to achieve the application of TENGs in the aspect of stage dancing. As shown in Fig. 6a, the dancer presents a formation on the stage. After the dancer stands still, that is to say when the dancer stands on the W-TENG, the lamp overhead will light the dancer and present a highlight moment of the stage. For this reason, and on account of the former investigation, W-TENGs can also be primely combined with the stage art, in case of the most theater stages are made of wooden floor. The feasibility of this conceive has been testified as followings. The experiment was proceeded on the acrylic board (40 cm × 60 cm), five W-TENGs (15 cm × 20 cm) were placed, the distribution of ABCDE is shown in Fig. 6b. By connecting 5 W-TENGs to 5 electrometers at the same time, on the purpose of recording the output electrical signals of five W-TENGs in real time. When the dance shoes step on the W-TENG according to the path of A-B-C-D-E, the corresponding output current signals with time as shown in Fig. 6c, indicating the feasibility of tracking the movement track. It can also be combined with a lighting system, when a current signal appears, the light will automatically turn on and track in real time to achieve the effect of follow spot. At the same time, W-TENGs can also be used by dancers for daily practice. When the dancer walks or jumps along this path which is instructed by AD-AB-AB-C-E, the real-time output current signal of each channel is depicted in Fig. 6d.

To summarize, the W-TENGs can be applied in area of stage art, which can not only record the movement trajectory of dancers, but also be combined with lights to realize the function of automatic follow spot. It is no doubt that this brand-new assumption opens up a broader application of the TENGs.

3. Conclusion

In conclusion, the triboelectrification on a nature wood, which is a pure natural biodegradable and pollution-free material, has been demonstrated. This W-TENG can play a very important role in energy harvesting and self-powered sensing. The output voltage and current of the W-TENG (8 cm × 8 cm) is 220 ± 20 V and 5.8 ± 0.5 μA at a frequency of 2 Hz respectively. The maximum output power density reaches the value 158.2 mW/m^2 at a resistance of 50 MΩ on this W-TENG which can be stored in capacitor. This research also explored the influence of the contact area of the triboelectric layer and the working frequency of the linear motor, proved that the output performance is positively related to these two factors. It is generally known that wood is the most familiar and widely used building decoration material, which plays an important role in the interior design. Combining the W-TENG with these can realize home automation, including self-triggered light switch, self-triggered doorbell, self-triggered floor, etc. At the same time, wood is also often used as the material for the stage floor. W-TENGs are installed on the stage wooden floor to track and record the dancers' movements, even dancers can control the lights themselves through the floor under their feet. This W-TENG based self-powered system provide a new assumption for the application of TENGs in smart homes and electronics.

4. Material and methods

4.1. Methods

Fabrication of the first W-TENG mode: The natural wood purchased from the manufacturer is cut into 8 cm × 8 cm, then cut the sponge,

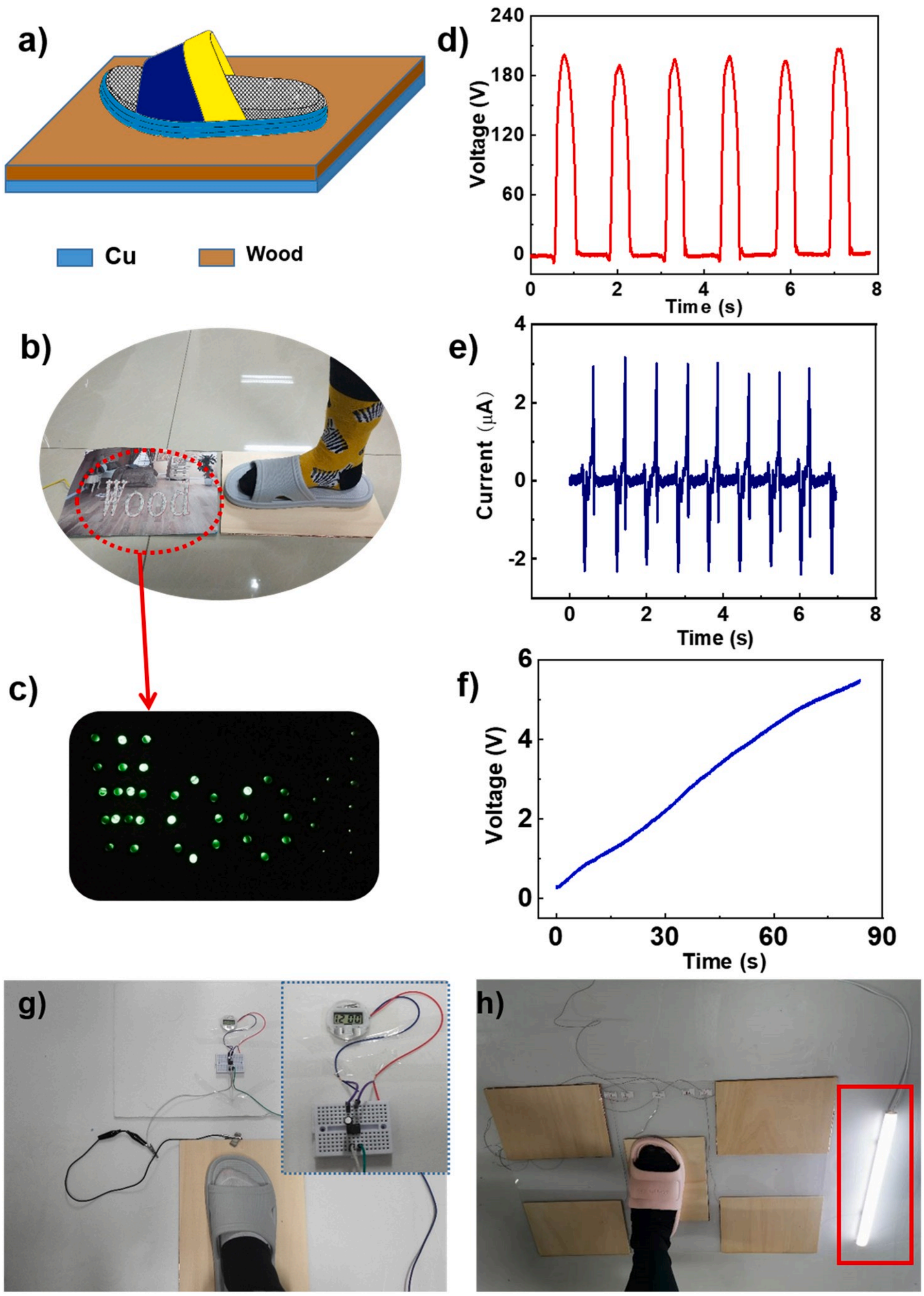

Fig. 5. Application of the W-TENG in the smart floor. a) Schematic diagram of a TENG composed of a wooden floor and a slipper. b) Photo of slipper in contact with the wooden floor, connected with LEDs. c) An enlarged view of the "Wood" LEDs. d) The open-circuit voltage and e) short-circuit current of experimenter stepping on wooden floor in slippers. f) Voltage profile of capacitors (1μF) charged by TENG with wooden floor and slippers. g) Photo of an electronic watch driven by electricity stored by the W-TENG. h) Photo of a lamp controlled by the W-TENG.

PTFE membrane and copper foil as the same size. The acrylic (PMMA) is cut into 11 cm × 8 cm as the support layer, prepare two 8 cm × 1.5 cm sponge strips.

W-TENG manufacturing process in smart floor: Attach a piece of copper foil of the same size to the wood, and then attach it to the acrylic. The slippers and dance shoes in this experiment are purchased from the manufacturer.

4.2. Characterization

The W-TENG was driven by a linear motor (Linmot E1100) for electrical measurements. A programmable electrometer (Keithley 6514) was used to test the open-circuit voltage, short-circuit current. The software platform was constructed on the basis of LabVIEW, which is capable of realizing real-time multi-channel data acquisition and analysis. The surface morphology of natural wood was characterized by Nikon Eclipse Ti Inverted Microscope, Quanta FEG 450 SEM and Nova Nano SEM 450.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Saifei Hao: Methodology, Formal analysis, Investigation, Data curation, Writing - original draft. **Jingyi Jiao:** Investigation, Resources. **Yandong Chen:** Methodology, Data curation. **Zhong Lin Wang:** Writing - review & editing. **Xia Cao:** Conceptualization, Methodology, Writing - review & editing.

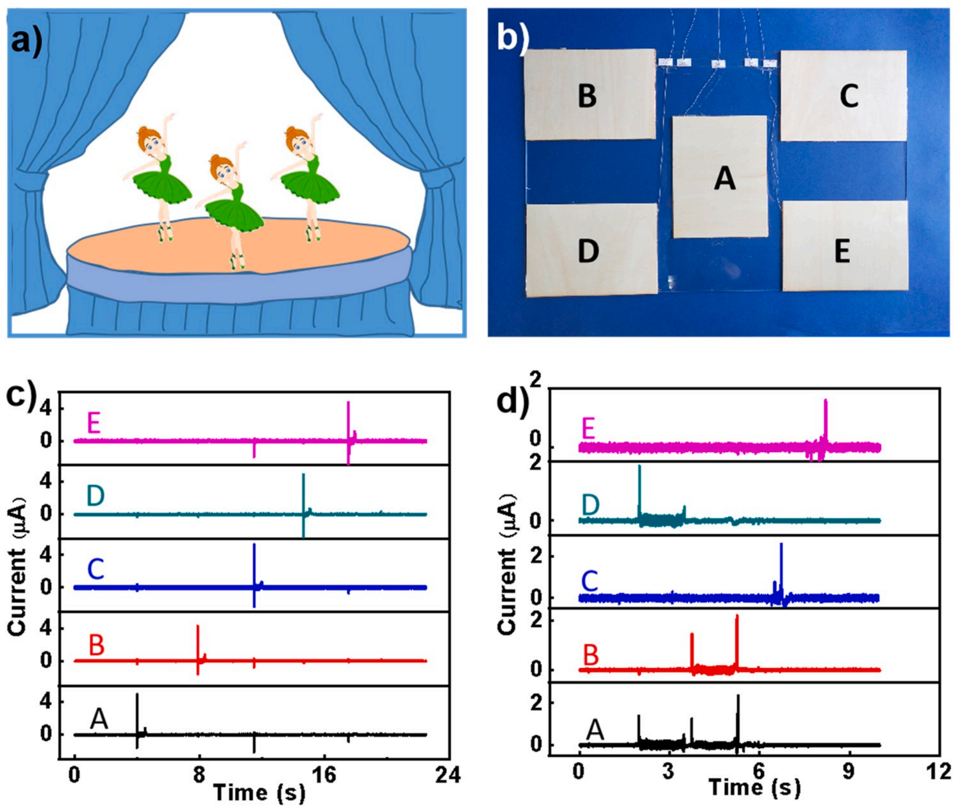

Fig. 6. Application of the W-TENG in the stage art. a) Schematic diagram of dancers dancing in line on the stage. b) Photo of W-TENG's arrangement. c) When the dance shoes follow the path of A-B-C-D-E, the real-time current signal output by the W-TENG. d) When the dance shoes follow the path of AD-AB-AB-C-E, the real-time current signal output by the W-TENG.

Acknowledgements

We thank the financial support from the National key R and D project from Minister of Science and Technology, China (2016YFA0202702, 2016YFA0202701) Patents have been filed to protect the reported inventions.

References

[1] M. Chan, D. Esteve, C. Escriba, E. Campo, Comput. Methods Progr. Biomed. 91 (2008) 55–81.
[2] J. Gubbi, R. Buyya, S. Marusic, M. Palaniswami, Future Gene. Compute. Sys. Int. J. Esci 29 (2013) 1645–1660.
[3] M.A.A. Pedrasa, T.D. Spooner, I.F. MacGill, IEEE TransSmart Grid 1 (2010) 134–143.
[4] C. Debes, A. Merentitis, S. Sukhanov, M. Niessen, N. Frangiadakis, A. Bauer, IEEE Signal Process. Mag. 33 (2016) 81–94.
[5] C. He, W. Zhu, B. Chen, L. Xu, T. Jiang, C.B. Han, G.Q. Gu, D. Li, Z.L. Wang, ACS Appl. Mater. Interfaces 9 (2017) 26126–26133.
[6] A.C. Jose, R. Malekian, N. Ye, IEEE Access 4 (2016) 5776–5787.
[7] V.J. Ovejas, A. Cuadras, Sci. Rep. 9 (2019).
[8] K. Parida, J. Xiong, X. Zhou, P.S. Lee, Nano Energy 59 (2019) 237–257.
[9] Q. Song, A. Li, L. Shi, C. Qian, T.G. Feric, Y. Fu, H. Zhang, Z. Li, P. Wang, Z. Li, H. Zhai, X. Wang, M. Dontigny, K. Zaghib, A.-H. Park, K. Myers, X. Chuan, Y. Yang, Energy Storage Mater 22 (2019) 48–56.
[10] Y. Song, H. Wang, X. Cheng, G. Li, X. Chen, H. Chen, L. Miao, X. Zhang, H. Zhang, Nano Energy 55 (2019) 29–36.
[11] W. Wu, X. Cao, J. Zou, Y. Ma, X. Wu, C. Sun, M. Li, N. Wang, Z. Wang, L. Zhang, Adv. Funct. Mater. 29 (2019).
[12] Q. Zhang, Z. Zhang, Q. Liang, F. Gao, F. Yi, M. Ma, Q. Liao, Z. Kang, Y. Zhang, Nano Energy 55 (2019) 151–163.
[13] Z.L. Wang, ACS Nano 7 (2013) 9533–9557.
[14] Z.L. Wang, Faraday Discuss 176 (2014) 447–458.
[15] Z.L. Wang, J. Chen, L. Lin, Energy Environ. Sci. 8 (2015) 2250–2282.
[16] Y. Xi, J. Wang, Y. Zi, X. Li, C. Han, X. Cao, C. Hu, Z. Wang, Nano Energy 38 (2017) 101–108.
[17] X. Cao, Y. Jie, N. Wang, Z.L. Wang, Adv. Energy Mater 6 (2016).
[18] C. Wu, X. Wang, L. Lin, H. Guo, Z.L. Wang, ACS Nano 10 (2016) 4652–4659.
[19] X.-S. Zhang, M.-D. Han, B. Meng, H.-X. Zhang, Nano Energy 11 (2015) 304–322.
[20] G.G. Szarvas, H.G. Suyderhoud, COMSAT Tech. Rev. 10 (1980) 151–178.
[21] S.J. van der Molen, J. Liao, T. Kudernac, J.S. Agustsson, L. Bernard, M. Calame, B. J. van Wees, B.L. Feringa, C. Schoenenberger, Nano Lett. 9 (2009) 76–80.
[22] J. Wei, Z. Zang, Y. Zhang, M. Wang, J. Du, X. Tang, Optic Lett. 42 (2017) 911–914.
[23] M.O. Farooq, I. Wheelock, D. Pesch, IEEE Consumer Electronics Magaz 9 (2020) 22–29.
[24] J. Luo, Z. Wang, L. Xu, A.C. Wang, K. Han, T. Jiang, Q. Lai, Y. Bai, W. Tang, F. R. Fan, Z.L. Wang, Nat. Commun. 10 (2019) 5147.
[25] Y. Zhong, H. Zhao, Y. Guo, P. Rui, S. Shi, W. Zhang, Y. Liao, P. Wang, Z.L. Wang, Adv Mater Technol 4 (2019).
[26] N. Zhang, C. Tao, X. Fan, J. Chen, J. Mater. Res. 32 (2017) 1628–1646.
[27] Q. Liang, Q. Zhang, X. Yan, X. Liao, L. Han, F. Yi, M. Ma, Y. Zhang, Adv. Mater. 29 (2017).
[28] S. Gao, Y. Chen, J. Su, M. Wang, X. Wei, T. Jiang, Z.L. Wang, ACS Nano 11 (2017) 3965–3972.

Saifei Hao received her B.S. degree from Nanjing Agricultural University in 2017. She is currently a master degree candidate at the Beijing Institute of Nanoenergy and Nanosystems, Chinese Academic of Sciences. Her research interests include energy harvesting and self-powered systems.

Jingyi Jiao is currently a Ph.D. candidate of Xidian University and joint training at the Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences. Her research interests include electrochemical sensors and self-powered systems.

Yandong Chen is currently a Ph.D. at the Beijing Institute of Nanoenergy and Nanosystem, Chinese Academic Science. His research interests include zinc oxide nanowire based sensors, energy harvesting and self-powered systems.

Zhong Lin (Z.L) 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 understand-ing 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 roadmap for harvesting mechanical energy from the 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 piezophototronics by introducing piezoelectric potential gated charge transport process in fabricating new electronic and optoelectronic devices. Details can be found at: www.nanoscience.gatech.edu.

Xia Cao is currently a distinguished professor at University of Science and Technology Beijing, and a professor at Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences. Her main research interests focus on the energy materials, nanoelectroanalytical chemistry, self-powered nanobiosensors and piezoelectric sensors.