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Intelligent facemask based on triboelectric nanogenerator for respiratory monitoring

Qixin Lu [a,b,1], Hong Chen [a,b,1], Yuanming Zeng [b,d,1], Jiehui Xue [a,b,1], Xia Cao [a,b,c,d,*,2], Ning Wang [f,**], Zhonglin Wang [a,b,d,e,*,2]

[a] *Center on Nanoenergy Research, School of Physical Science & Technology, Guangxi University, Nanning 530004, China*
[b] *Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing 100083, China*
[c] *Research Center for Bioengineering and Sensing Technology, Beijing Key Laboratory for Bioengineering and Sensing Technology, School of Chemistry and Biological engineering, and Beijing Municipal Key Laboratory of New Energy Materials and Technologies, University of Science and Technology Beijing, Beijing 100083, China*
[d] *School of Nanoscience and Technology, University of Chinese Academy of Sciences, Beijing 100049, China*
[e] *School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA*
[f] *Center for Green Innovation, School of Mathematics and Physics, University of Science and Technology Beijing, Beijing 100083, China*

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ABSTRACT

The fast-spreading of novel coronavirus disease (COVID-19) has been sweeping around the globe and brought heavy casualties and economic losses, which creates dire needs for technological solutions into medical preventive actions. In this work, triboelectric nanogenerator for respiratory sensing (RS-TENG) has been designed and integrated with facemask, which endows the latter with respiratory monitoring function. The output of RS-TENG for respiratory flow can reach up to about 8 V and 0.8 μA respectively although it varies with different respiratory status, which proves the high sensitivity of RS-TENG for respiratory monitoring. An apnea alarm system can be constructed by combining the smart facemask with circuit modules so that timely alarm can be transmitted after people stop breathing. Furthermore, RS-TENG can be used to control household appliances, which brings convenience to the life of the disabled people. Considering its incomparable advantages such as small volume, easy fabrication, simple installation and economical applicability, such design is helpful for developing multifunctional health monitoring gadgets during the COVID-19 pandemic.

1. Introduction

Coronaviruses are a family of viruses that can cause illnesses such as the common cold, severe acute respiratory syndrome (SARS) and Middle East respiratory syndrome (MERS). In 2019, a new coronavirus was identified as the cause of a disease outbreak and is now known as the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) [1]. Given the special importance of the harmful consequence, spotting a case of COVID early could very well be the key to stopping widespread transmission. And while most people know the most common symptoms of the virus, we may not know what to keep an eye out for in its earliest stages, taking measure in the earliest stages may plays a central role in lowering COVID19 incidents and mortality rates. Thus, finding a simple, accurate, cheap and quick detection approach for SARS-CoV-2 at early stage of the viral infection is urgent and at high demand all around the world.

Based on the typical symptoms such as shortness of breath, dyspnea and irregular breathing [2], many precaution diagnostic methods have been developed based on respiratory, heart rate and temperature measurement for COVID-19 health screening [3].

Although current technologies may detect illnesses symptoms such as temperature, heart rate, and even stress and other physiological

* Corresponding authors at: Center on Nanoenergy Research, School of Physical Science & Technology, Guangxi University, Nanning 530004, China
** Corresponding author.
E-mail addresses: caoxia@binn.cas.cn (X. Cao), wangning@ustb.edu.cn (N. Wang), zlwang@gatech.edu (Z. Wang).
[1] Authors contributed equally to this work.
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conditions, most of them suffer the declination of precision from a social distancing in performing the health screening on masked participants [4–6]. In addition, there are also other hidden issues. For example, traditional respiratory monitoring sensors usually have complex structure, huge volume and need external power supply [7–9], which has brought many inconveniences in using, analyzing and moving. And most of these technology monitor the breath state by measuring many other parameters, such as detecting sounds of breath, humidity of air flow, pressure differential, chest vibration and so on. These technology often need complex equipment and can not monitor respiratory state directly [10–15]. There is a tremendous need to develop a more simple and portable respiratory monitoring equipment which can identify a respiratory infection early—before a worker or student feels ill.

As a new energy harvesting technology, triboelectric nanogenerator (TENG) has invoked intense research interests since its invention in 2012. Based on the coupling effect of triboelectrification and electrostatic induction [16–19], TENG can effectively harvest all kinds of mechanical energy in the environment [20], including human motion [21–23], wind energy [24–26], water energy [27,28], tire rotating energy [29], vibration energy and so on. TENG is widely used in wearable [30], intelligent sensing [31–34], biomedical [35], environmental protection [36] and other fields. In the past several years, it has also demonstrated that TENG based sensors have excellent material compatibility, low cost, and flexibility. TENG based sensors technology must be a promising artificial intelligence technology for new generation of sensing systems that collect information by large amounts of self-powered sensors [37,38]. Thus it is ideal to combine TENG with facemask to seek a wearable device which can continuously track the key precautionary symptoms with very simple structure for COVID-19 and other respiration diseases at the very early station from hospital to home.

In this work, we designed a smart facemask for respiratory monitoring. The smart facemask conducts the respiratory monitoring work by a novel structured respiratory sensing triboelectric nanogenerator(RS-TENG) attached to it. When human body wear the smart facemask and breathe, the RS-TENG assembled on the facemask can generate a maximal output voltage of about 8 V and a maximal output current of 0.8 μA. The electrical signals can be used to monitor people's breathing status and served as a diagnostic index of some respiratory diseases such as COVID-19 pandemic. More importantly, the breath-driven human-machine interface (HMI) system integrated with the smart facemask can help disabled people to control small household appliances through

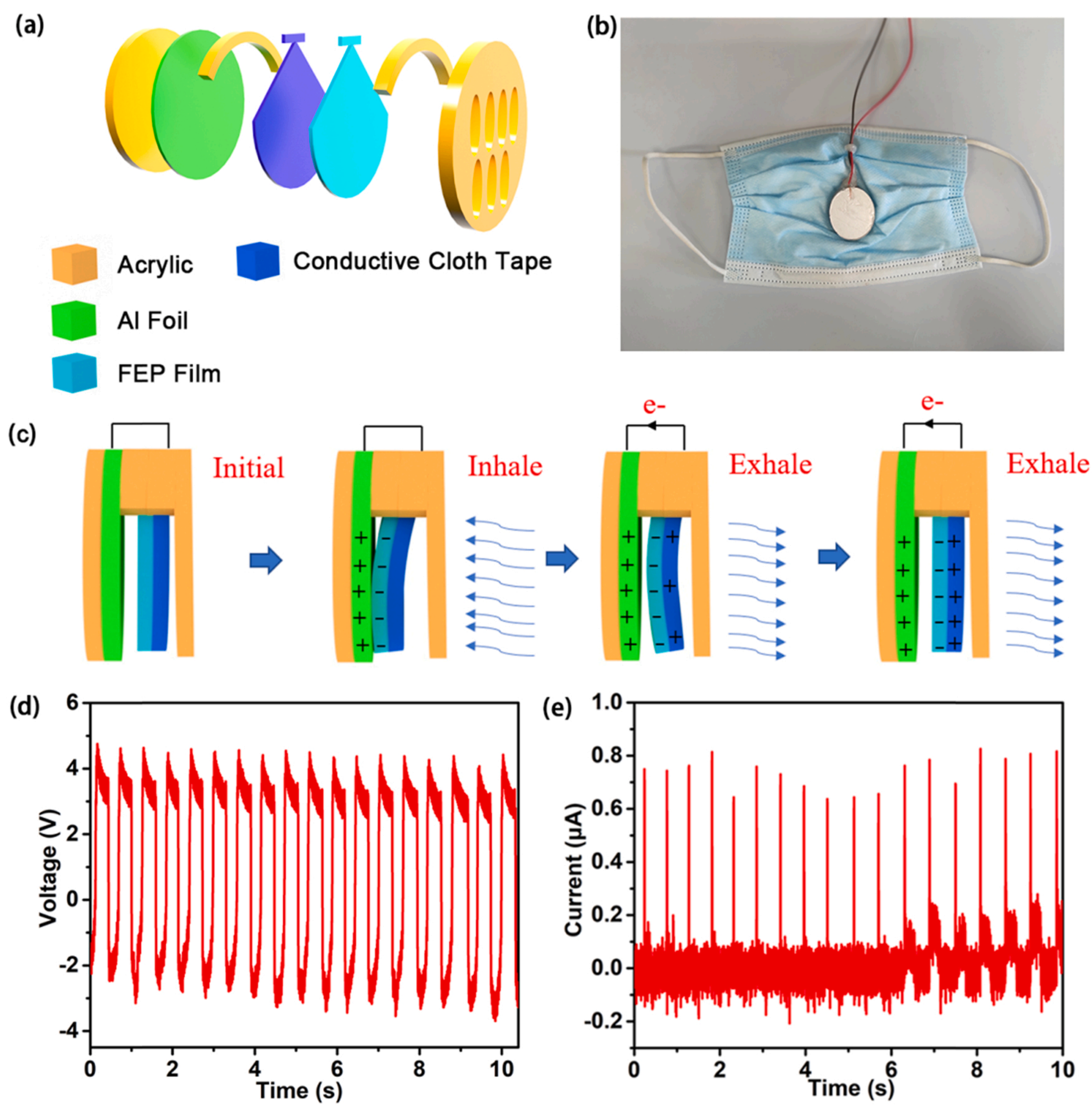

Fig. 1. Basic design and output of RS-TENG. (a) Detail structure of RS-TENG. (b) Photograph of facemask assembled with RS-TENG. (c) The working principle of RS-TENG when people inhale and exhale. The ideal (d) output voltage and (e) output current of RS-TENG.

breathing. An apnea alarm system was further constructed and demonstrated, so that timely alarm can be transmitted after people stop breathing.This work greatly prompts the development of respiratory monitoring, it is also expected to play a greater role in the treatment of respiratory diseases.

2. Result and discussions

The specific structure of the respiratory sensing triboelectric nanogenerator (RS-TENG) can be seen in Fig. 1a. The whole structure RS-TENG is simple and light. In order to realizing convenient respiratory monitoring, RS-TENG was assembled on a facemask to construct a special smart facemask. Fig. 1b directly displays the photograph of the smart facemask assembled with RS-TENG. The weight of RS-TENG is 4.7567 g while the mass ratio of RS-TENG and facemask is about 1.5: 1. Thus, RS-TENG is easily to be fabricated and fixed on many other respiratory monitor devices.

The working mechanism of RS-TENG is schematically shown in Fig. 1c. When people wear the smart facemask and inhale, FEP film and Al foil will make contact driven by the air flow. Due to triboelectrification effect, their surfaces will generate equal amount of different charges. Then when people begin to exhale, FEP film and Al foil will separate. Due to electrostatic induction effect, there will be a potential difference between Al foil and conductive cloth tape. If wires were used to connect Al foil and conductive cloth tape, the electrons will flow along the wires under the driving of the potential difference. Thus generates electric current. As people inhale again, the FEP film close to Al foil again, and there will be a reverse current generated. Thus, the periodical current will be generated when people breathe continually.

For measuring the electrical output of RS-TENG during human's respiration, RS-TENG was connected with an electrometer (Keithley Model 6514 system). When people wear the smart facemask assembled with RS-TENG and breathe, the electrical output signals can be measured and recorded by Keithley 6514 electrometer. The basic output voltage and output current are presented in Fig. 1d and e. It can be seen that RS-TENG can reach up to a high output about 8 V and 0.8 μA under an ideal condition. Thus the smart facemask can be used to monitor human's breath.

Before testing the output property of RS-TENG, it is necessary to investigate the potential distribution. Fig. 2a illustrates the calculated results of different working states for the RS-TENG. When FEP film and Al foil firstly contact under an inhale process, the potential differential is minimum (step i). Then the FEP film and Al foil separate under an exhale process, which result in the increase of potential differential (step ii). Finally, when the distance between FEP film and Al foil reach the maximum value, the potential differential also reach the maximum (step iii). After that, the distance and potential differential decrease when the wearer inhales. And the whole process come to next circle, so that the periodic change of potential different caused by breathe will finally form periodic current if the FEP film and Al foil was connected by wires.

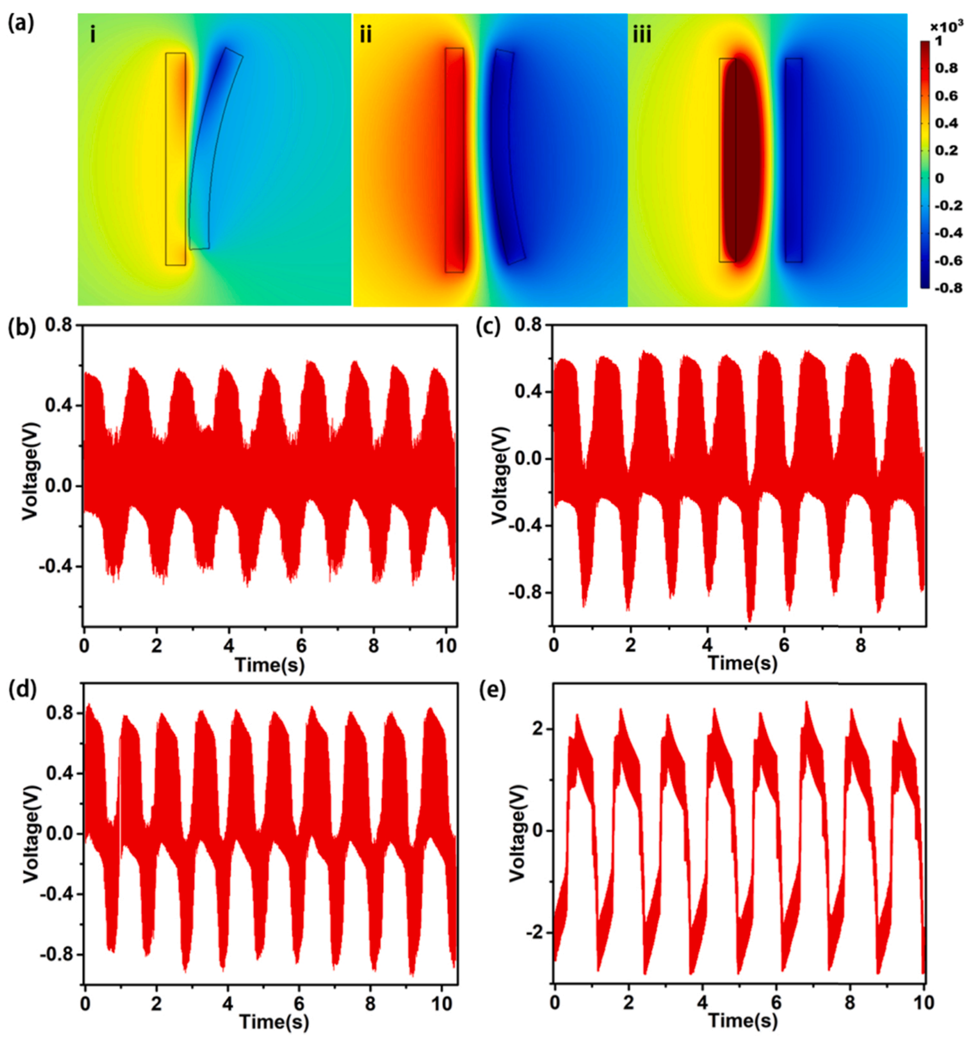

Fig. 2. Potential distribution and the output of RS-TENG driven by nose breath. (a) Potential distribution simulated by COMSOL. (b) The output voltage of RS-TENG when people breathe with nose in weakly intensity, (c) normal intensity, (d) moderate intensity and (e) high intensity.

One of the most important characteristic for respiratory sensor is its sensibility in different breath state, which varies with intensity and speed of breathe. In the same way, RS-TENG should be able to produce considerable signals in different breathe states, even in very weak breath. To further investigate the sensibility of RS-TENG, the electrical output of RS-TENG in different breath speed and different breath strength was measured, which can prove its sensibility and stability in complicated working state. When human body wears the smart face-mask and breathes with nose, the corresponding output results of RS-TENG in different breath strength and speed have been measured. As shown in Fig. 2b, under weakly breath, it can be seen that the output voltage of RS-TENG can reach nearly 1 V. And for normal breath strength, as shown in Fig. 2c, the output voltage of RS-TENG is around 1.4 V. For moderate intensity breath, as shown in Fig. 2d, RS-TENG can reach a maximum output voltage of nearly 1.6 V. For high intensity breath, as shown in Fig. 2e, RS-TENG can reach a maxium output voltage nearly 4 V. The output voltages of RS-TENG with different breath strength illustrate its output signal is sensitive with different breath strength and increase with the breath strength.

Normally, human body sometimes also breathe with mouth, the electrical output when human body wears the smart facemask and breathes with mouth was also tested. The corresponding electrical output results of RS-TENG in different breath speed and different breath strength are shown in Fig. 3a. When people wear the smart facemask and breathe weakly, it can be seen that the output voltage of RS-TENG can reach up to nearly 1.5 V. And for normal breath strength, as shown in Fig. 3b, the output voltage of RS-TENG is around 4.5 V. For moderate intensity breath, as shown in Fig. 3c, RS-TENG can reach a maxium output voltage nearly 6 V. For high intensity breath, as shown in Fig. 3d, RS-TENG can reach a maxium output voltage about 8 V. All the electrical output results shows that RS-TENG is sensitive in different breath conditions. In addition, people also can breath with mouth and nose simultaneously in some special situations and the RS-TENG output in such situation is also investigated. The related experiment can be found in the Supporting Information. Also, the output RS-TENG is sensity to the position of RS-TENG on the face so the RS-TENG is always opposite to the mouth in above experiment. And the impact of position is also tested, related experiment detail can be found in the Supporting Information. Modern medicine has confirmed that long-term oral breathing will cause certain harm to human health. If the air passes directly into the respiratory tract without nasal filtration, the bacteria, viruses, dust and even PM 2.5 dust in the air can easily block the airway, and even

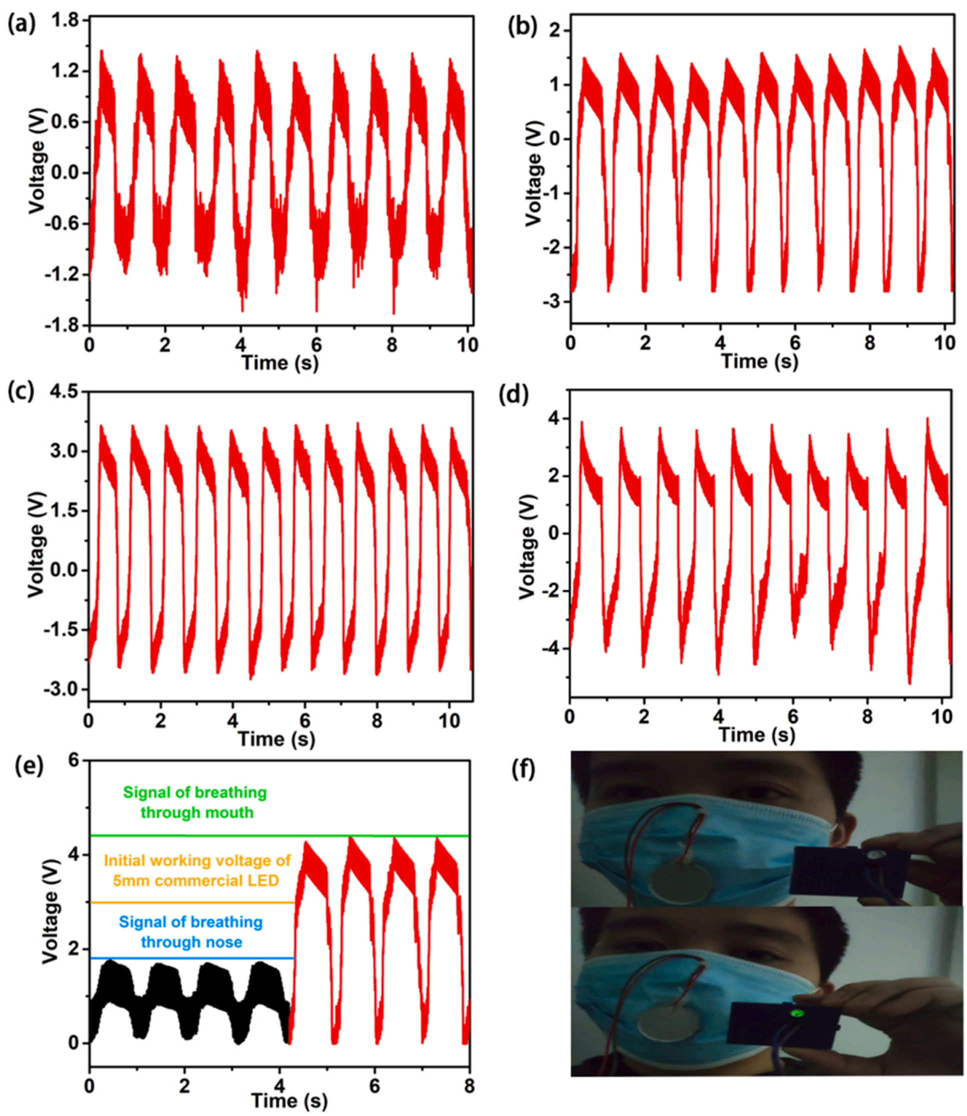

Fig. 3. (a) The output voltage of RS-TENG when people breathe with mouth in weakly intensity, (b) normal intensity, (c) moderate intensity and (d) high intensity. (e) The comparison of output voltage of RS-TENG when breathes with mouth and nose respectively. (f) Schematic diagram of mouth and nose respiratory monitoring alarm light.

lead to pneumonia, bronchitis and various lung related diseases. Moreover, oral breathing not only affects people's health, but also affects their appearance, body shape, intelligence and other aspects. By comparing the voltage of human body breathing with nose and mouth, a very simple but practical application can be achieved. As illustrated in Fig. 3e, The highest voltage of human body breathing with nose is much lower than 3 V, while the lowest voltage of human body breathing with mouth is much higher than 3 V under normal breath strength. Usually, when the voltage across the LED exceeds 3 V, the LED will be lighted on. Therefore, an LED can be used to indicate the breathing mode of the human body. As shown in Fig. 3f, one LED was connected to the smart facemask. When people started breathing with mouth, the LED will be lighted up immediately, the warning signal from the LED can help people correct the breathing mode in time. Furthermore, the ability of RS-TENG to distinguish mouth breath and nose breath in high humidity also investigated, the RS-TENG can still light LED by mouth breath, detail experiment can be found in the Vedio S1 in the Supporting Information.

Supplementary material related to this article can be found online at doi:10.1016/j.nanoen.2021.106612.

In order to make RS-TENG better used in daily life, many external factors that affect the output performance of RS-TENG need to be investigated. For standardlizing driving signal and getting more accurate data, a small air-blower and a signal generator were used to simulate human breathing. The air-blower is controlled by the pulse signal generated by signal generator to generate periodic air supply and air stop, which simulates the breathing patterns of human body. For convenience, all the following experiments were completed in the form of simulated human breathing. Fig. 4a shows the driving signals of the signal generator. The Vm presents the working voltage of air-blower which provided by signal generator and it was setted to 12 V. And the T_1, T_2 present the action time of high level signal and low level signal respectively. T_1, T_2 were always kept equal and setted to 1s in this experiment unless otherwides stated. The real tested driving signal was shown in the inset of Fig. 4a.

Previous studies have shown that ambient humidity has a great impact on the output performance of TENG. Generally, humidity will greatly reduce the electrical output of TENG. As a lot of water vapor will be produced during the process of human breathing, it is necessary to investigated the humidity's impact on the output of RS-TENG. Fig. 4b

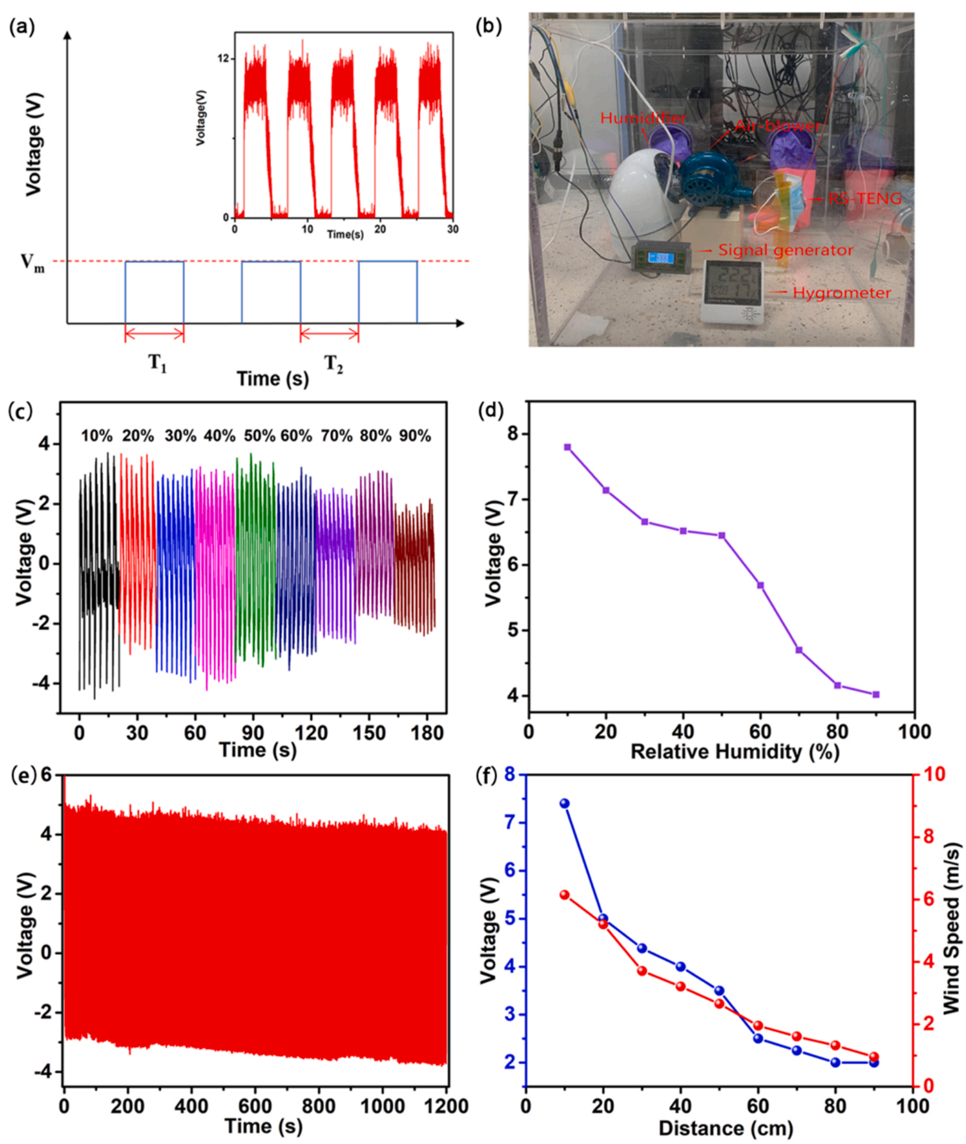

Fig. 4. (a) The driving signals of the signal generator. (b) The experimental arrangement for the humidity test. (c) The output signals of RS-TENG under different ambient humidity. (d) The trend chart of output voltage changing with ambient humidity. (e) The output voltage of RS-TENG in 20 min. (f) The output voltage of RS-TENG under different wind speed.

presents the experimental arrangement for the humidity test. A humidifier is used to generate water mist to simulate different ambient humidity, and a hygrometer is used to monitor the degree of ambient humidity. The output voltage of RS-TENG under 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90% nine groups of relative humidity were tested. Fig. 4c shows the corresponding results. With the increase of the ambient humidity, the output voltage of RS-TENG shows a downward trend. The line chart in Fig. 4d intuitively shows the decreasing trend of humidity. It can be seen that when the humidity increases from 10% to 50%, the output voltage of RS-TENG drops slowly.When the humidity increases from 50% to 80%, the output voltage of RS-TENG decreases significantly. When the humidity drops to 90%, the output voltage of RS-TENG is still about 4.2 V. The result indicated that the water vapor produced by human breathing will not affect the respiration monitoring effect of RS-TENG. Also, to investigate the output of RS-TENG in real environment, the contrast experiment is done in a rainy day, the output of RS-TENG drops by 3 V as the humidity increase in a rainy day so the impact of environment on RS-TENG should be considered in practical application. The detail of contrast experiment is shown in the Vedio S2 in the Supporting Information.

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Respiratory monitoring requires good stability of the monitoring device，so that the real-time respiratory monitoring of the human body can be achieved. As a device applied in respiratory monitoring field, it is a necessary property for RS-TENG to be able to produce continuous and stable electrical output. Therefore, the output stability of RS-TENG under constant wind speed was tested. The output voltage of RS-TENG after 20 min cycle are shown in Fig. 4e. It can be seen that the RS-TENG can maintain a very stable output, which is very beneficial for the real-time respiratory monitoring.

At the same time, the influence of wind speed on the output of RS-

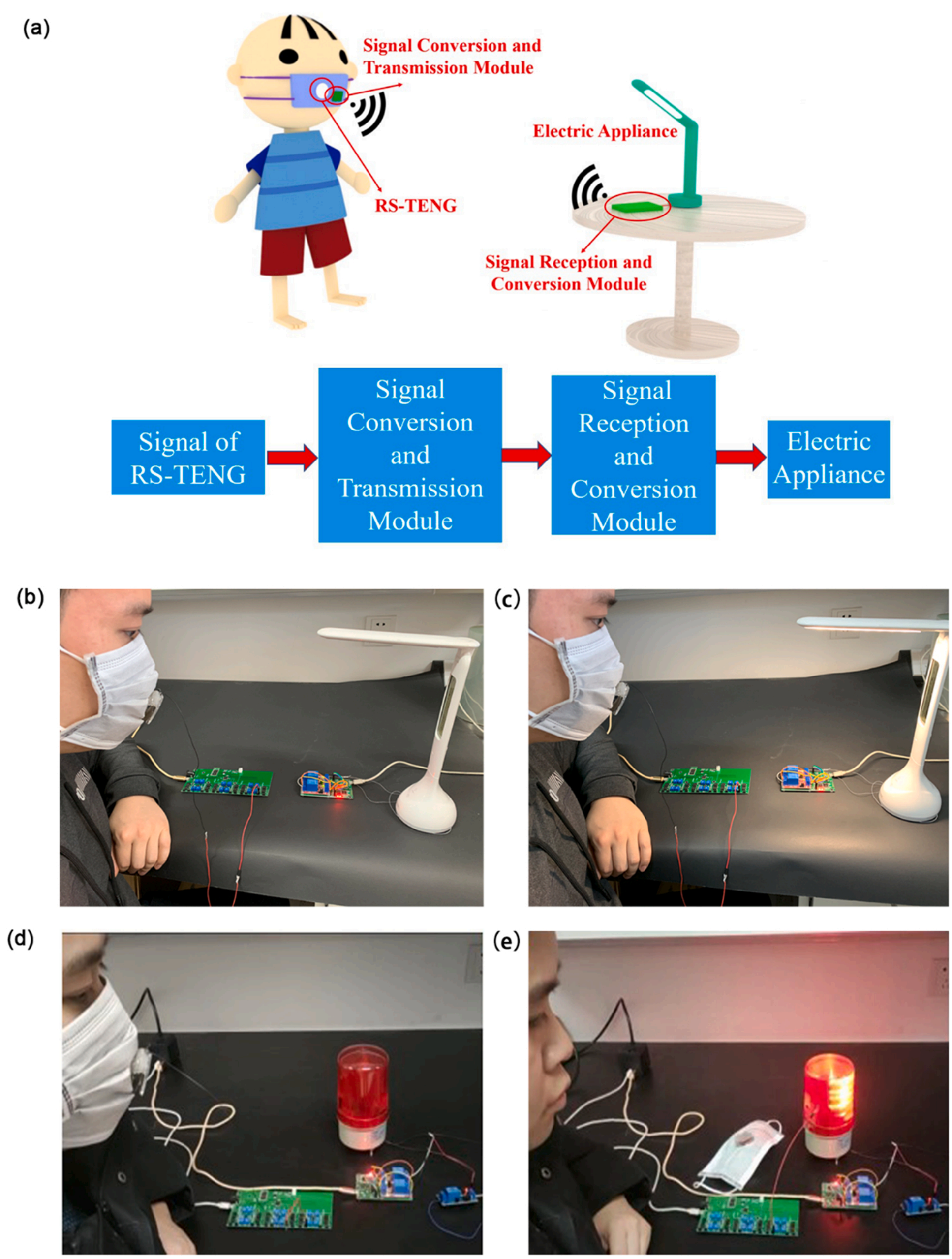

Fig. 5. (a) The control circuit diagram of the smart facemask. (b) The table lamp is off. (c) The table lamp is lighted on driving by the smart facemask. (d) The alarm is off. (e) The alarm sounds after the smart facemask is removed.

TENG was also investigated. Fig. 4f is the corresponding output voltage of RS-TENG. The wind speed around RS-TENG was controlled by controlling the distance between the air-blower and RS-TENG. The distance was selected as 10 cm, 20 cm, 30 cm, 40 cm, 50 cm, 60 cm, 70 cm, 80 cm, 90 cm. Each group of distance corresponds to a voltage value and a wind speed value. As the distance between the air-blower and RS-TENG increases from 10 cm to 90 cm, The wind speed around RS-TENG decreases from 6.147 m/s to 0.954 m/s, and the output voltage of RS-TENG decreases from 7.4 V to 2 V. When the distance reaches 100 cm, the RS-TENG has no signal output. It can be known that the minimum wind speed for RS-TENG to produce electrical output is about 0.954 m/s.

Thus the sensor will have a considerable prospect in the fields of smart home and intelligent wearable devices. To prove the prospect of RS-TENG in the fields of smart home, intelligent wearable device and intelligent medicals. The RS-TENG on the smart facemask was combined with two circuit modules with two kinds of relay to construct a human-machine interface system and a respiratory arrest alarm system respectively. The schematic control circuit diagram is shown in Fig. 5a. When the RS-TENG produces an electrical signal by harvest the respiratory energy, the electrical signal is firstly inputted the signal conversion and transmission module, then it is amplified, converted, and finally transmitted in a wireless form. And the wireless signal is received by the signal reception and conversion module subsequently. Then it is converted into a proper form to control the relay to turn on or turn off the electric appliance. The only difference of two systems is different relay was adopt at the output end to realize different functions. The practical operation of Human-machine interface system base on RS-TENG is shown in Fig. 5b and c, the lamp is off at the beginning when wearer's breath is in a normal state. Because the respiratory signal hasn't reached the trigger threshold of signal conversion and transmission module. The value of trigger threshold can be adjusted by adjusting the variable resistance on module so spurious triggering can be avoided. But when the wearer breathes heavily or blows to the mask directly, the respiratory signal will over the trigger threshold. Then the electric signal can be amplified, converted, and transmitted by signal conversion and transmission module, and received by signal reception and conversion module, then the table lamp will be turned on. More detail was shown in the Video S3 in the Supporting Information.

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An apnea alarm system was then constructed by combining the smart facemask with the circuit modules, so that timely alarm can be transmitted after people stop breathing. The practical operation of the apnea alarm system base on RS-TENG is shown in Fig. 5d and e. The relay in this systems is normally closed and continually output electric signal to electric appliance. When wearer is in a normal breath state, the electric signal generated by breathe was continually proceed by two module and finally inputted the relay. Then the relay will open and stop the alarm, as shown in Fig. 5d. But if the wearer in a respiratory arrest state, the relay state will delayed for about 5 s and turn to a close state and trigger the alarm, as shown in Fig. 5e, the wear take off the mask to simulate respiratory arrest, and the alarm begin to sound. More detail was shown in the Video S4 in the Supporting Information.

Supplementary material related to this article can be found online at doi:10.1016/j.nanoen.2021.106612.

3. Conclusion

In summary, we successfully fabricated a simple respiratory sensing triboelectric nanogenerator (RS-TENG) and assembled it on a facemask. By wearing the as-designed facemask, different breathing status of human body can be monitored. The RS-TENG shows high sensitivity and feasibility in respiratory monitoring, it can be used to diagnose many respiratory diseases of human bodies, especially in latest COVID-19 pandemic. Moreover, the smart facemask was integrated into a smart breath-driven human-machine interface (HMI) system, so that people can control small household appliances through breathing. This will largely benefit the lives of the disabled people. The apnea alarm system which was further constructed based on the HMI system can be used to monitor human respiration, and give timely alarm after breathing stops. This work explores a simplified and portable device for respiratory monitoring, which can achieve self-powered respiratory sensing anytime and anywhere. It could greatly reduce the financial and human cost of respiratory monitoring, and prompt the development of medical field.

4. Experimental section

4.1. Fabrication of the RS-TENG

An ultrathin FEP film and Al foil was choosed as the tribolelectric layers, and the conductive cloth tape was choosed as electrode. the acrylic boards were used as substrate and several hole was dilled in one of the acrylic board to allow the air flow pass through. One arched acrylic tablet was used to make a gap between two tribolelectric layers, another arched acrylic tablet was served as a buffer layer. Assemble the acrylic boards, Al foil, arched acrylic tablet, FEP film pasted with conductive cloth tape, arched acrylic tablet, acrylic boards with holes in turn, then connect two wires with conductive cloth tape and Al foil respectively to make RS-TENG work in a dual-electrode mode.

4.2. Characterization

RS-TENG was assembled on the facemask to test the output electrical performance. The electrical measurement of RS-TENG was measured by electrometer (Keithley Model 6514 system). A small air-blower and a controller are used to simulate human breathing, and the air-blower is controlled by the controller to generate the periodic working mode of air supply and air stop, so as to achieve the rhythm similar to human exhalation and inspiration. During the measurement of humidity's impact, a humidifier is used to generate water mist to simulate the ambient humidity, and a hygrometer is used to test the ambient humidity.

CRediT authorship contribution statement

Qixin Lu: Data curation, formal analysis, Writing – original draft, Investigation. **Hong Chen**: Data curation, Formal analysis, Visualization, Investigation. **Yuanming Zeng**: Visualization, Investigation. **Jiehui Xue**: Visualization, Investigation. **ZhongLin Wang**: Supervision, Resources, Writing – review & editing. **Xia Cao**: Conceptualization, Supervision, Resources, Writing – review & editing. **Ning Wang**: Supervision, Writing – review & editing.

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.nanoen.2021.106612.

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Qixin Lu is a master degree candidate of school of Physical Science and Technology at Guangxi University, and joint training at the Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences. His current research mainly focuses on energy harvesting and fabrication of devices.

Hong Chen is a master degree candidate of school of Physical Science and Technology at Guangxi University, and joint training at the Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences. Her current research mainly focuses on energy harvesting and and self-powered systems.

Yuanming Zeng is doctoral candidate at Beijing institute of Nanoenergy and Nanosystem, Chinese Academic Science. His research interests include the study of self-powered devices for sensors, and nanogenerators for energy harvesting.

Jiehui Xue is a master degree candidate of school of Resources, Environment and Materials at Guangxi University, and joint training at the Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences. Her current research mainly focuses on energy harvesting and and self-powered systems.

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.

Ning Wang obtained his Ph.D. from Beijing University of Aeronautics and Astronautics in 2008. He is currently an associate professor of chemistry at Beijing University of Aeronautics and Astronautics. His research interest is application of bimetallic nanomaterials to electrocatalysis and to understand fundamental mechanisms underlying experimentally observed phenomena with specific focus on electrochemical interface.

Zhonglin 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 mechani cal 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 piezoelec tric potential gated charge transport process in fabricating new electronic and optoelectronic devices. Details can be found at: www.nanoscience.gatech.edu.