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Electrothermal sterilization and self-powered real-time respiratory monitoring of reusable mask based on Ag micro-mesh films

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ABSTRACT

Since the COVID-19 pandemic outbreaks, the utilization of medical masks plays a critical role in reducing the infected risk. However, constructing multifunctional masks to achieve simultaneously self-sterilization, reusability, and respiratory monitoring capability remains still a huge challenge. Herein, a reusable Ag micro-mesh film-based mask is proposed, which enables the capabilities of electrothermal sterilization and self-powered real-time respiratory monitoring. Highly conductive Ag micro-mesh films prepared by continuous draw spinning method demonstrate excellent electrothermal performances for thermal sterilization and serve as working electrode to fabricate triboelectric nanogenerator (TENG) for real-time respiratory monitoring, respectively. Under a low driving voltage of 3.0 V, the surface temperature of Ag micro-mesh film enables a quick increase to over 60°C within 30 s, which endows thermal sterilization against S. aureus with antibacterial efficiency of 95.58% within 20 min to achieve the self-sterilization of medical masks. Furthermore, a self-powered alarm system based on the fabricated TENG as respiratory monitor is developed for real-time respiratory monitoring to render a timely treatment for patients in danger of tachypnea and apnea. Consequently, this work has paved a new and practical avenue to achieve reusable multifunctional masks with capabilities of electrothermal sterilization and real-time respiratory monitoring in clinical medicine.

1. Introduction

The global outbreak of COVID-19 has seriously affected human health and social economy by infecting more than 589 million and killing over 6.4 million people as of August 2022 [1]. Currently, wearing surgical face masks is still one of the most effective methods to inhibit the transferring of infecting agents, bacteria, and viruses from the environment to the human body [2,3]. However, the common face masks without antibacterial/antiviral activities and reusability will result in a huge amount of plastic waste and serious environmental pollution owing to the demand of replacing the mask with a new one after use for a short period [4,5]. Meanwhile, the discarded masks containing a high number of microorganisms and viruses would cause the risk of secondary transmission and raise high demand for their safe disposal [6]. Additionally, the COVID-19 pandemic has created an unprecedented need for remote patient respiratory monitoring including tachypnea, dyspnea and even respiratory failure [7,8]. According to suggestions of ProfessorGattinoni and co-workers, adequate respiratory monitoring plays a key role in the treatment of respiratory failure due to COVID-19 [9]. Therefore, it is an urgent demand to develop an innovative mask with advanced multifunction, such as self-sterilization, reusability, and respiratory monitoring capability.

To reuse the commercially available surgical face masks, various traditional disinfection methods including ethanol and steam sterilization have been attempted [10,11]. However, since the majority of face masks is based on nonwoven fabrics from non-biodegradable polypropylene (PP), both the solubility of PP in ethanol and high humidity of steam can damage the structure of masks resulting in lower filtering performances. Furthermore, tremendous efforts have been devoted to photothermal or photodynamic-mediated self-sterilized masks. Under sunlight illumination, the surface temperature of photothermal-mediated masks can quickly rise to over 70°C to realize...
the mask reusability [12,13]. The photodynamic-mediated masks can produce reactive oxygen species (ROS) by light irradiation to achieve biocidal function [14,15]. Unfortunately, these light-related photodynamic activity for the reusability and self-sterilization of masks will be incapacitated in some environmental conditions such as indoor room, rainy weather, and nighttime. Additionally, recent studies reported that SARS-CoV and MERS-CoV were rapidly inactivated by heating at over 56 °C within 20 min [16,17]. As an important alternative, the electrothermal materials through Joule-heating can achieve a controlled temperature up to 100 °C with thermal stability for the reusability and self-sterilization of masks [18]. Recently, the common electothermal materials such as graphene [19,20], carbon nanotubes [21,22] and some conductive polymers [23,24] have been investigated widely for flexible heaters. However, their electrothermal performances are not enough satisfactory due to high electrical resistance of carbon and conductive polymer-based materials that requires high driving voltages for heating. Silver-based fibers or micro-mesh as a universal material would be considered as an important candidate owing to its high conductivity and low heat capacity [25]. Therefore, to develop a novel Ag-based electrothermal material with rapid temperature response and low driving voltage is highly desired for the innovative masks with reusability and self-sterilization.

As is well known, continuous respiratory monitoring is an essential diagnostic routine for forecasting breath-related diseases such as obstructive sleep apnea syndrome and chronic obstructive pulmonary disease [26,27]. Severe breath-related diseases (including COVID-19) can cause respiratory failure and even threaten lives within minutes. Therefore, real-time respiratory monitoring is very critical to identify or predict high risk situations and even save lives. To timely monitor breath conditions, the respiratory monitoring sensors should be flexible and sensitive to breathing airflow. At present, although thermal-based flow sensors and humidity-based sensors with good stability have been developed for respiratory monitoring [28,29], their sensitivity, response speed and portability need to be further improved to enhance their practicability. Additionally, some piezoresistive and capacitive-based sensors have been employed for respiratory monitoring [30,31]. Owing to their requirement of an external power supply, these sensors still face a challenge of complexity and portability. To address this issue, a class of novel self-powered sensors based on triboelectric nanogenerator (TENG) have attracted tremendous attention in health monitoring [32-34], pressure sensing [35-38] and environmental sensing [39-42] due to its simple structure, low cost, easy fabrication, high power output, and diverse material option. As an emerging technology for energy harvesting, TENG can convert pervasive mechanical energy to electrical energy based on the coupling of contact electrification and electrostatic induction [43-45]. Especially, the electrical outputs based on TENG render abundant physiological signal monitoring [46-49], which would emerge as a promising self-powered real-time monitoring for respiratory activities.

Herein, we developed a reusable Ag micro-mesh film-based mask with capabilities of electrothermal sterilization and self-powered real-time respiratory monitoring, in which two Ag micro-mesh films act as electothermal layer and working electrode of a single-electrode mode TENG, respectively. The Ag micro-mesh films prepared by a continuous draw spinning approach exhibit excellent electrothermal performances including low driving voltage (1.5–4.5 V), rapid temperature elevation (38–100 °C within 30 s), and high thermal stability. Under a low driving voltage of 1.5 V, the surface temperature enables a quick increase to 67.5 °C, which endows thermal sterilization against S. aureus with antibacterial efficiency of 95.58 % within 20 min to realize the self-sterilization of mask based on Ag micro-mesh film. Moreover, the TENG as self-powered respiratory monitor was fabricated based on another Ag micro-mesh film as working electrode and electrospinning polyvinylidene difluoride nanofiber membrane (PVDF NM) and polyamide 6 nanofiber membrane (PA 6 NM) as two triboelectric layers, which is driven by breathing pressure during human breathing to retrieve respiratory information. Meanwhile, a series of different breathing states (shallow, normal, fast and deep breathing) can be accurately distinguished by the self-powered respiratory monitor based on the TENG. Furthermore, an excellent performance of a self-powered alarm system based on the TENG for real-time respiratory monitoring is demonstrated to enable the monitoring of weak, rapid, tachypnea and apnea states, which shows great potential in wearable medical electronics and clinical application.

2. Results and discussion

2.1. Fabrication of reusable mask based on Ag micro-mesh films

As schematically illustrated in Fig. 1a, the reusable mask is fabricated based on a designed device that consists of two main parts: One is an electrothermal layer based on former Ag micro-mesh film for thermal sterilization of viruses and bacteria; the other is the TENG (respiratory monitor) based on latter Ag micro-mesh film as working electrode and electrospinning PVDF NM and PA 6 NM as two triboelectric layers for self-powered real-time respiratory monitoring. The device was installed in the breather valve of N95 mask. Fig. 1b shows the internal and external photographs of the reusable mask, respectively. Both PVDF and PA 6 NMs were fabricated via electrospinning method. The AgNO3/polymer precursor fiber mesh was prepared firstly via continuous draw spinning method, as illustrated in Fig. S1 and Movie S1, then the Ag micro-mesh was prepared by sintering the AgNO3/polymer precursor fiber mesh, in which the AgNO3 was reduced to Ag nanoparticles that were stacked tightly to form the Ag submicron fibers. As shown in Fig. 1c, the scanning electron microscope (SEM) images exhibit the microstructure of the Ag micro-mesh and natural interconnected junctions of Ag fibers after sintering at 260 °C for 2 h, which provides the paths for electron transportation within different well-connected individual Ag fibers. Moreover, the X-ray diffraction (XRD) pattern of the Ag micro-mesh film is illustrated in Fig. 1d, which peaks correspond well to face-centered cubic phase metal silver (PDF#01–089–3722). The strong and narrow peaks are evidences of high-quality Ag micro-mesh films. Additionally, the morphologies of PA 6 and PVDF NMs with the nanofiber diameters of 132.6 nm and 144.2 nm can be observed by SEM, as displayed in Fig. 1e and f, respectively. Their wettability was also examined through placing a water droplet onto the Ag micro-mesh film, PA 6 NM and PVDF NM, respectively, and their corresponding water contact angles of 126.3°, 107.8°, and 136.1° are observed (Fig. S2), indicating their excellent hydrophobic surfaces. Moreover, owing to nanosized porous structure, both PA 6 NM and PVDF NM endow their good breathability. To provide the expiratory air flow, the Ag-PI-Ag membrane also requires to be perforated by laser as shown in Fig. 1b and Fig. S3, in which the hole size is about 223 µm and the density is 25 holes per square centimeter. Furthermore, the temperature variations under wearing have been evaluated by infrared thermal camera, as seen in Fig. S4. Significantly, the temperature variation (3.7 °C) of breather valve with imperforated membrane after wearing for 5 min is higher than that (1.0 °C) of the breather valve with perforated membrane owing to lack of air circulation, demonstrating the enhancement of expiratory air flow. As shown in Fig. 1g, the cross-sectional SEM image demonstrates that the PA 6 NM tightly covers on the surface of Ag micro-mesh film supported by a PI film and the overall thickness of Ag-PI-Ag membrane is about 17 µm.

Supplementary material related to this article can be found online at.

2.2. Electrothermal performances of Ag micro-mesh film

In virtue of the excellent electrical conductivity, the obtained Ag micro-mesh film exhibits excellent electrothermal performances based on Joule heating effect, in which the Joule heat power (P) is equal to $U^2/R$ when a bias voltage (U) is applied to conductive materials (R). As illustrated in Fig. S5 and S6, the electrical conductivity of the Ag micro-
mesh film significantly increases with decreasing substrate movement speed of continuous draw spinning process, which is ascribed to the little spacing of Ag fibers under a low movement speed. To demonstrate the mechanical stability of Ag micro-mesh film, the conductivity variation of the Ag micro-mesh film under the bending angle of 180° has been evaluated after 1500 bending cycles. As shown in Fig. S7, a negligible resistance change exhibits an excellent mechanical stability of Ag micro-mesh film. Moreover, when the Ag micro-mesh film as a cable connected in series with an orange LED in a closed circuit, the LED can be successfully lighted up all the time whether the Ag micro-mesh film is in the straight or bending states, as shown in Movie S2, demonstrating the excellent electrical conductivity, mechanical stability and flexibility of Ag micro-mesh film. The electrothermal performances of Ag micro-mesh film (1.2 × 10^4 S/m) were further valued by applying different stable driving voltages from a DC power and the corresponding temperature evolutions were recorded with an infrared (IR) camera, as shown in Fig. 2a. To demonstrate the controllability of electrothermal performance, the thermal response behavior of Ag micro-mesh film at various driving voltages of 1.5–4.5 V is shown in Fig. 2b, where the corresponding steady-state saturation temperature increases from 38.7 to 103 °C with increasing the driving voltage (1.5–4.5 V) as more Joule heat power is generated. Particularly, the electrothermal temperature exhibits a fast temperature response within 30 s, which can effectively reduce heating time under the Joule-heating operation. As presented in Fig. 2c, the IR thermal images of Ag micro-mesh film demonstrate highly qualified thermal distributions and reproducible temperature change with the increase of driving voltage from 1.5 to 4.5 V. To further confirm its electrothermal stability and repeatability, several repetitive on-off cycles at the driving voltage of 3 V were performed (Fig. 2d), showing that the steady-state saturation temperature of approximately 67.5 °C can be maintained and the temperature curves of every cycle are extremely similar. Moreover, the Ag micro-mesh film before/after the electrothermal process exhibits almost same microstructure, as shown in the SEM images of Fig. S8, which would guarantee its stable heating behavior for long-term usage. Therefore, the obtained Ag micro-mesh film demonstrates excellent electrothermal performances, including low driving voltage of 1.5–4.5 V, rapid temperature elevation (~100 °C within 30 s), and good electrothermal stability, which is superior to other reported conductive materials (Table S1).

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2.3. Electrothermal sterilization properties of Ag micro-mesh film

Owing to face masks directly contacting with the human face, an excellent self-sterilized ability of medical masks would be a very significant advantage. The fabricated mask based on Ag micro-mesh film would achieve a self-sterilization through Joule heating effect of Ag micro-mesh film, in which under low driving voltage the generated heat can induce various antimicrobial effects, including ribonucleic acid (RNA) breakdown and protein denaturation [50]. When taking off the
mask, the electrothermal sterilization process can be realized through a wire connection between the Ag micro-mesh film and DC power supply without any additional circuit. In our study, the representative Staphylococcus aureus (S. aureus) were selected to evaluate the electrothermal sterilization properties of the Ag micro-mesh film. The viability of the bacterial cells was evaluated by using Live/Dead fluorescent staining (green-live, red-dead) under fluorescent microscopy. As shown in the Fig. 3a, the live/dead cell staining displays that dead cells (in red) are gradually dominant, whereas live cells (in green) are almost invisible with an increase of electrothermal time, indicating most S. aureus were inactivated by electrothermal treatment.

To further evaluate the electrothermal sterilization properties, the colony growth of S. aureus was assessed by counting the colony-forming units (CFUs) after being treated with the electrothermal Ag micro-mesh film for different time. As shown in Fig. 3b, under no electrothermal treatment the bacterial colonies are densely distributed on the agar plate, manifesting vigorous vitality. However, a considerably low bacterial survival was observed after electrothermal treatment of 20 min, indicating a great effect on bacterial inactivation. In addition, the surface morphologies of the pristine S. aureus and heat-treated S. aureus were also characterized by SEM. As shown in Fig. 3c, the pristine S. aureus were viable without membrane damage. Comparing with pristine S. aureus, the heat-treated S. aureus exhibited an evident cell wall deformation and damaged plasma membranes, as shown in Fig. 3d, meaning that the generated heat by Ag micro-mesh film can damage cell walls and plasma membranes to result in the bacterial inactivation due to the leakage of a lot of cytoplasmic components in bacteria. Fig. 3e reveals a lower value of CFUs with an increase of the electrothermal time. Furthermore, based on their statistics, the antibacterial efficiency of electrothermal Ag micro-mesh film can reach 95.58 % within 20 min, as shown in Fig. 3f. Therefore, the excellent sterilization properties of Ag micro-mesh film based on its excellent electrothermal performances enable the reusability of the fabricated masks.

2.4. Self-powered respiratory monitoring

As is well known, respiratory information including respiratory rate and intensity is the primary physiological signal to assess the physical condition and diagnose the possible diseases. A fast, non-invasive, and comfortable approach without external power supply would be highly desired for real-time signal analysis for respiratory monitoring. Fortunately, the emerge of TENG would provide an important alternative for self-powered respiratory monitoring, which can convert extensively existed low-frequent and irregular mechanical energy (including breathing pressure) into electrical output or signals. Owing to self-powered feature, the TENG based on Ag micro-mesh film installed in the inner of breather valve of the above-mentioned mask has been employed for real-time respiratory monitoring. As schematically illustrated in Fig. 4a, the single-electrode mode TENG is fabricated based on PVDF and PA 6 NMs as two triboelectric layers and latter Ag micro-mesh film as working electrode that is covered by PA 6 NM. The working principle of the TENG based on Ag micro-mesh film for respiratory

![Fig. 2. Electrothermal performances of Ag micro-mesh film. (a) Schematic illustration of the electrothermal measurements. (b) Temperature profiles and (c) IR images of Ag micro-mesh film under driving voltages of 1.5, 3.0, and 4.5 V, respectively. (d) Repeated and rapid on/off thermal response under driving voltage of 3.0 V.](image-url)
monitoring is the coupling of contact electrification and electrostatic induction (Fig. 4b), which can convert subtle breathing mechanical energy to electricity when two nanofiber membranes (including PVDF and PA 6 NMs) contacting and separating each other under the pressure driving of periodical respiration. Initially, when the two nanofiber membranes completely contact each other, the equal amount of positive and negative triboelectric charges will be generated on the PA 6 NM and PVDF NM, respectively, due to the ability of PVDF attracting more electrons comparing with PA 6 (Fig. 4b-i). During inhalation, once the two nanofiber membranes are separated, a potential difference will be established, followed by the flowing of free electrons from the ground to the Ag micro-mesh film electrode through external circuit to balance the potential due to electrostatic induction effect (Fig. 4b-ii). When the two membranes are completely separated, no free electrons flow through external circuit due to the complete screening of positively charges on the PA 6 NM by the electrostatic induced negative charges in the Ag micro-mesh film (Fig. 4b-iii). During exhalation, the breathing pressure leads to the approaching of PVDF NM back to PA 6 NM again. Meanwhile, the accumulated negative charges in the Ag micro-mesh film will flow back to the ground through the external circuit (Fig. 4b-iv). Therefore, the breathing changes between inhalation and exhalation will generate an alternating current following the induced charges flowing periodically between the ground and the Ag micro-mesh film through external circuit.

A convenient, comfortable, and nonintrusive respiratory monitoring is a highly important assessment of respiratory condition, diagnosis of disease, and medical treatment. When installed into the inner of mask breather valve, the fabricated TENG based on latter Ag micro-mesh film as a self-powered respiratory monitor is capable of capturing the detailed physiological signals of breathing. Fig. 4c shows continuous electrical signals from the regular inhalation and exhalation process, respectively. Due to regular and periodic feature of human breathing, the respiratory monitor can steadily produce a responding electrical signal output, which helps assess the medical condition of a person and give clues to possible diseases. In addition, other masks (including N95 mask without respiratory valve and medical surgical mask) installed by the Ag micro-mesh film-based TENG can also demonstrate the same ability as the mentioned-above mask (seeing Movie S3), in which the respiratory signal can be recorded in real time to exhibit excellent matching capability of our proposed Ag micro-mesh film-based TENG with various
Moreover, the electric signals of different respiratory states that involve shallow, normal, fast and deep breathing were recorded. As shown in Fig. 4d, different respiratory states demonstrate obvious differences in respiratory rate and respiratory intensity, indicating that the respiratory monitor based on the TENG is capable of distinguishing different breathing states. For instance, the output voltage corresponding to deep breathing is about triple comparing with shallow breathing. Moreover, the respiratory rate of shallow breathing is calculated as about 13 bpm, while for fast breathing, the respiratory rate can reach approximately 24 bpm. Subsequently, to further evaluate the stability and durability of output performance of the respiratory monitor, the voltage output of the TENG in realistic scenarios has been examined, as shown in Fig. S9. Obviously, the stable output voltage of the TENG based on PVDF and PA 6 NMs can be maintained for over 4 h, which demonstrates the excellent durability of TENG in long-time respiratory monitoring.

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To further optimize the output performance, the effects of structure parameters for Ag micro-mesh-based TENG on the output voltage have been investigated detailledly. The output voltages of the TENG are closely related with the electrospinning time of PVDF and PA 6 NMs. As shown in Fig. 4e and f, the gradual increases in the voltage output are presented with an increase of electrospinning time of PVDF NM (15–45 min) and PA 6 NM (1–2 h), respectively, followed by an obvious decrease with further increasing the electrospinning time. It is because more and more nanofibers are collected on the flat surface with an increase of electrospinning time. Moreover, owing to low liquid flow rate of electrospinning process, the PA 6 NM required more electrospinning time in comparison with PVDF NM. Nevertheless, due to a decrease of electrical forces between the needle tip and the more nanofibers-covered collector, a further increase of electrospinning time leads to higher roughness, which would deteriorate the voltage output. Additionally, the optimal thickness (500 µm) of spacer for the voltage output was also assessed, as shown in Fig. 4g. According to Gauss’ theorem, the relationship of the voltage (V) and the gap (d) between two frictionally charged layers can be given as below:

\[ V = \frac{\sigma d}{\varepsilon_0} \]

where \( \sigma \) is the surface charge density of the triboelectric layers and \( \varepsilon_0 \) is the vacuum dielectric constant [51]. An increase in thicknesses of the spacer renders an improvement of the voltage output. However, an excessive thickness would cause the poor contact of triboelectric layers to deteriorate the voltage output.

2.5. Demonstration of self-powered alarm system

Prompt treatment for the patients in danger of tachypnea and apnea is of the utmost importance to avoid biological death. A self-powered alarm system based on the TENG is further developed for real-time respiratory monitoring, in which the digital signal processing is applied owing to its great capacity of resisting disturbance especially in
the low frequency range. As displayed in Fig. 5a and S10, the detailed procedures of signal processing system are presented. The electrical signals are firstly amplified by the electrostatic amplifier ADA44530–1, then are collected using an analogue-to-digital conversion (ADC) followed by conditioning and signal processing with a microprocessor (Arduino Uno R3). Tachypnea is a common early clinical symptom caused by respiratory disease, which can progress to respiratory distress or dyspnea without timely treatment. According to the literature [52], the respiratory rate over 24 breaths min\(^{-1}\) was considered as tachypnea, thus the critical value of warning was set at 0.4 Hz. As shown in Fig. 5b, the top is the original signal produced by the TENG, the middle is the square wave signal transmitted by the voltage comparator, and the bottom is the photograph of warning. Once the respiratory rate of a volunteer becomes suddenly faster than 0.4 Hz, the system will automatically sound the alarm (Movie S4). Moreover, the apnea is also another dangerous behavior which may result in death, so it is necessary to alert the doctors timely when the apnea occurs. The respiratory signals in Fig. 5c, d and corresponding Movie S5 and S6 clearly present that the apnea over 5 s under different respiratory states (rapid and weak breathing, respectively) can cause the device to warn immediately. The above results indicate that the self-powered alarm system is capable to accurately process the real-time respiratory signals from the TENG based on Ag micro-mesh film to timely sound the alarm when the patients in danger of tachypnea and apnea, which is significantly advantageous in medical diseases monitoring.

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3. Conclusion

In summary, we successfully fabricated a reusable Ag micro-mesh film-based mask with capabilities of electrothermal sterilization and self-powered real-time respiratory monitoring. The conductive Ag micro-mesh film via continuous draw spinning method exhibits satisfyingly high heating temperatures with a fast response (30 s) at low driving voltage (1.5–4.5 V), which can realize over 67 °C under only 3.0 V. As a result, with the assistance of Joule-heating, the antibacterial efficiency against S. aureus can reach 95.58 % within 20 min to realize the self-sterilization of the fabricated mask. Moreover, the Ag micro-mesh film-based TENG as self-powered respiratory monitor is capable to continuously monitor and distinguish breath states including shallow, normal, fast and deep breathing. Meanwhile, a self-powered alarm system based on the TENG for real-time respiratory monitoring is further developed to render a timely treatment for patients in danger of tachypnea and apnea. Consequently, the reusable Ag micro-mesh film-based mask demonstrates a tremendous potential in environmental protection, human healthcare monitoring, smart wearable medical electronics and many other fields.

4. Experimental section

Preparation of Ag-PI-Ag membrane: The Ag micro-mesh/PI/Ag micro mesh (Ag-PI-Ag) membrane was manufactured using a continuous draw spinning method. Firstly, 1.5 g AgNO\(_3\) was added in 2.5 mL acetonitrile containing 0.45 g PVP, and then added 0.5 mL SDS aqueous solution (10 % m/v). The resulting solution was stirred until the solution was homogeneous and no bubbles. Then the solution was inhaled in a syringe of 1.0 mL with the needle diameter of 60 µm and jetted toward a continuous rotating PI substrate fixed on a rotating motor with a stable movement speed. The spacing of fibers was controlled by the movement speed. The AgNO\(_3\)/polymer precursor submicron fibers arrays were presented.
firstly enwound on the PI substrate, then the AgNO₃/polymer precursor fiber mesh can be obtained through rotating substrate in vertical direction to the direction of syringe. After the end, repeated the above steps on the back of the PI substrate to gain the double-sided AgNO₃/polymer precursor fiber mesh. Then the Ag-Pt-Ag membrane was obtained by sintering precursor fiber mesh at 260 °C for 2 h in the air environment via a constant temperature oven. Finally, the Ag-Pt-Ag membrane was perforated by a 10.6 μm CO₂ infrared laser engraving machine (Mingchuang C-M4060) to ensure breathability of the membrane.

Fabrication of reusable mask: The preparation of the nanofiber membranes was conducted using an electrospinning machine. The 20 wt % PVDF was dissolved in DMF and acetone (weight ratio of 7:3). The electrospinning was performed at a high voltage of 20 kV and a flow rate of 3 mL/h with a 20 cm distance between the needle and drum collector. The temperature was maintained at 25 °C and the relative humidity was controlled around 30 %. Nanofibers were spun on the Al foil. The nanofiber membrane collected to Al foil was cut to the circle with a diameter of 40 mm. Similarly, the 15 wt% PA 6 was dissolved in formic acid, which was conducted with a high voltage of 18 kV and a flow rate of 0.5 mL/h. The distance between the needle and Ag-Pt-Ag membrane collector was fixed to 15 cm. The aggregation of PA 6 NM on the Ag-PI-Ag membrane was also cut to the circle with a diameter of 40 mm. The annular double-sided tape with an inner diameter of 3 cm and an outer diameter of 4 cm was used as spacer. Finally, the PVDF NM, spacer, PA 6 NM and Ag-Pt-Ag membrane were successively assembled and then was installed in the breather valve of a medical N95 mask.

Electrothermal sterilization: The Ag micro-mesh film was cut into a square shape of 2 × 2 cm and sterilized under UV light irradiation for 12 h. Subsequently, the Ag micro-mesh film samples in the Petri dish were dipped with 5 mL of S. aureus suspension and cultured in an incubator at a temperature of 37 °C for 24 h. Then the samples were washed with ringer solution for three times to remove the unattached bacteria and then dried at room temperature. Next, each sample was performed the Joule heating under a 3 V DC power supply for 0, 5, 10, 15 and 20 min, respectively, and then immersed in 20 mL ringer solution. The bacteria were separated from the ringer solution by a 10 % ultrasonic power wave for 5 min and then were diluted 100 times. Finally, 100 μL bacterial solution was evenly distributed in the nutrient agar solid plates. All plates were further incubated at 37 °C for 24 h, and the value of colony-forming units (CFU) in each plate was calculated to evaluate the sterilization properties.

Characterizations and measurements: The morphologies of Ag micro-mesh film, nanofiber membranes and the cross-sectional image of the PA 6/Ag-Pt-Ag membrane were measured by field emission scanning electron microscopy (SEM JSM-7001F, Japan). The sample for the cross-sectional SEM image was obtained by carefully cutting the membrane with a scissor. The crystal structure of Ag micro-mesh film was identified through X-ray diffraction (XRD, Bruker D8 Advance, Germany). The output signals of the TENG were recorded by Keithley 6514 electrometer. All thermal properties and images were obtained by an infrared (IR) camera (FLIR T450sc).

CRediT authorship contribution statement

Wenquan Liu: Methodology, Software, Data curation. Yu Sun: Methodology, Software, Data curation, Writing – original draft. Anni Cui: Methodology, Software, Data curation. Yifan Xia: Methodology, Software, Data curation. Qizhu Yan: Methodology, Software, Data curation. Yongxin Song: Methodology, Software. Liangliang Wang: Methodology, Software, Data curation. Guiyue Shan: Conceptualization, Methodology, Data curation, Supervision, Writing – review & editing. Xin Wang: Conceptualization, Methodology, Data curation, 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.

Data Availability

Data will be made available on request.

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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.2022.107987.

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