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Full paper

A wearable pyroelectric nanogenerator and self-powered breathing sensor

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A R T I C L E I N F O

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A B S T R A C T

Wasted heat is one of the most abundant and widely available energy sources in our living environment and industrial activities. Pyroelectric nanogenerators (PyNGs) is emerging as a powerful tool to scavenge wasted heat. Here we designed and fabricated a wearable PyNG using PVDF thin film integrated in a N95 respirator for scavenging energy of human respiration. Due to the temperature fluctuation induced by human breathing at 5 °C ambient temperature, the PyNG can generate output signals with an open-circuit voltage of 42 V and a short-circuit current of 2.5 µA, respectively. The maximal power reached up to 8.31 µW with an external load of 50 MΩ, which can be utilized to directly drive electronics, such as a liquid crystal display and light emitting diodes. This PyNG has also been demonstrated as self-powered human breathing and temperature sensors. The excellent performances and unencumbered wearable mode of the PyNG demonstrate that the device can be developed as a promising wearable energy harvester and self-powered multifunctional sensors for practical applications.

1. Introduction

The renewable energy harvesting from the ambient environment has been attracted extensive attentions due to the concern about the increasing carbon emission from conventional fossil energy in the past decade [1–3]. Especially, the waste energy harvesting has been considered as an attractive alternative over traditional rechargeable batteries for providing electrical power to low-energy devices such as body worn sensors and wearable consumer electronics [4–8]. Piezoelectric nanogenerators (PENGs) [9–13] and triboelectric nanogenerators (TENGs) [2,14–19] have been successfully developed to scavenge varied forms of mechanical energy from our surroundings. They can be utilized to drive the LEDs, LCD, sensors, photodetectors and even consumer electronics [20–24]. The output level of energy harvesting devices has also been increased progressively with the optimization of materials and structure design. However, for PENGs and TENGs, there is still a great challenge that the repeating radical mechanical strain will bring a huge pressure to the reliability of the devices, which is always a hidden threat for practical applications, even though the researchers have taken great efforts to ensure the good cycle life of the PENGs and TENGs.

As well known, thermal energy is a kind of very common energy source, meanwhile wasted heat is widely existing in natural environment and our daily life, including solar photo-thermal energy, automobile exhaust, and so on [25–29]. The harvesting of wasted heat would provide a significant option for green and renewable energy. Thermoelectric materials have been successfully developed to convert thermal energy into electricity based on Seebeck effect [29–32], which can be suitable for the spatial thermal nonuniformity. However, for the situation where there is no spatial temperature gradient, it is difficult to employ thermoelectric materials for energy conversion. Recently, pyroelectric nanogenerators (PyNGs) have been developed to scavenge the thermal energy with time temperature gradient and a number of pyroelectric materials, such as ZnO [25], PZT [33], $KNbO_3$ [26] and PVDF [7,34,35], have been adopted to fabricate pyroelectric nanogenerators. In some cases, the output electrical signals research up to noticeable levels [27,34,36,37]. Compared to PENGs and TENGs, the PyNGs would not suffer the mechanical deformation, so there is no challenge for reliability of the devices.

In recent years, wearable electronic devices have received extensive attention. Correspondingly, wearable nanogenerators have also attracted strong interest, which present a significant potential for construct self-powered wearable electronic systems [5,16,38–42]. As well known, there is obvious temperature difference between the human body and the ambient environment, especially in the winter. The breathing process can create a region with a remarkable time-

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dependent temperature fluctuation around the mouth. If a pyroelectric nanogenerator (PyNG) is placed in this position, a temperature fluctuation induced change of polarization will generate potential between electrodes due to pyroelectric effect. In some places of the world, such as northern China, due to cold weather or air pollution, it has been popular for people to go outside wearing a respirator. The human body's temperature is constant at about 37 °C, while in the regions of middle and high latitudes, the outdoor temperature in winter is as low as about −30 °C. Therefore, if the PyNGs are integrated on the respirator to form a wearable energy harvesting device, the waste heat would be converted into electric energy in a natural way without extra burden for a person. Moreover, respiratory status is always an important indicator of human health. The urgent accident of human health can be effectively detected by monitoring respiratory state. Therefore, a wearable breathing sensor is meaningful for human heath monitoring, especially for special crowd, such as the elderly, people with serious hidden disease and asthma patients.

In this study, we report a wearable PyNG integrated on a respirator, which was driven by human breathing activity and also presented the function of a self-powered breathing sensor. Here, the flexible PVDF films were used for the assembly of PyNG as key materials based on their good pyroelectric properties. The PVDF film with electrodes on both sides was installed on a common respirator to form a wearable PyNG which presented the capabilities of both sustainable energy harvesting and self-powered breathing monitoring. The output electric signals of the PyNG with a linear dependence on ambient temperature also demonstrate an outstanding performance as a temperature sensor.

2. Experimental

2.1. Fabrication of the PyNG and the self-powered breathing Sensor

A metal coated PVDF film which was purchased from Measurement Specialties Inc (USA) were adopted as a core pyroelectric component for fabrication of the PyNGs. A piece of PVDF film with size of 3.5 cm × 3.5 cm was cut from above film. Two copper wires were attached to two sides of the obtained film, fixed by using a silver paste, and further sealed by Kapton tapes. This film was installed on a common N95 respirator to form a pyroelectric nanogenerator (PyNG) for human breathing energy harvesting with functions of self-powered breathing sensor and temperature sensor.

2.2. Characterization and application

For testing the performance of the PyNGs, the experiments were conducted in low temperature laboratory with the temperature of 5 °C to simulate the winter outdoor environment. The respirator equipped with a PyNG were worn on the human face and the temperature change induced by human respiration lead to the electric outputs of the device. In addition, by adjusting the intensity and frequency of breathing, the output signals were tested to evaluate the performance of the device as self-powered breathing sensor. A NTC temperature sensor, which was fixed on the PyNG, was used to measure the real-time temperature fluctuations of the PyNG during human respiration. The output voltage and current of the device were measured by Keithley 2400 digital source meter. The PyNG were connected with LCD and LEDs to demonstrate the application of powering electronic devices. A varistor as external load was connected to the PyNG to evaluate the power output of the device.

3. Result and discussion

The wearable breathing driven PyNG is shown in Fig. 1a. The pyroelectric polymer film, covered with electrodes, is mounted on the respirator at the location where the airflow of the breath is most concentrated. As shown in Fig. 1b, the pyroelectric film is composed of three layers, including PVDF thin film with thickness of 30 μm as active layer and Al films with thickness of 60 nm as top and bottom electrode layers. According to the structure of the respirator and the effective area of human respiration, the pyroelectric film was fabricated with the size of 3.5 cm × 3.5 cm.

As well known, human body temperature is constant at 37 °C and

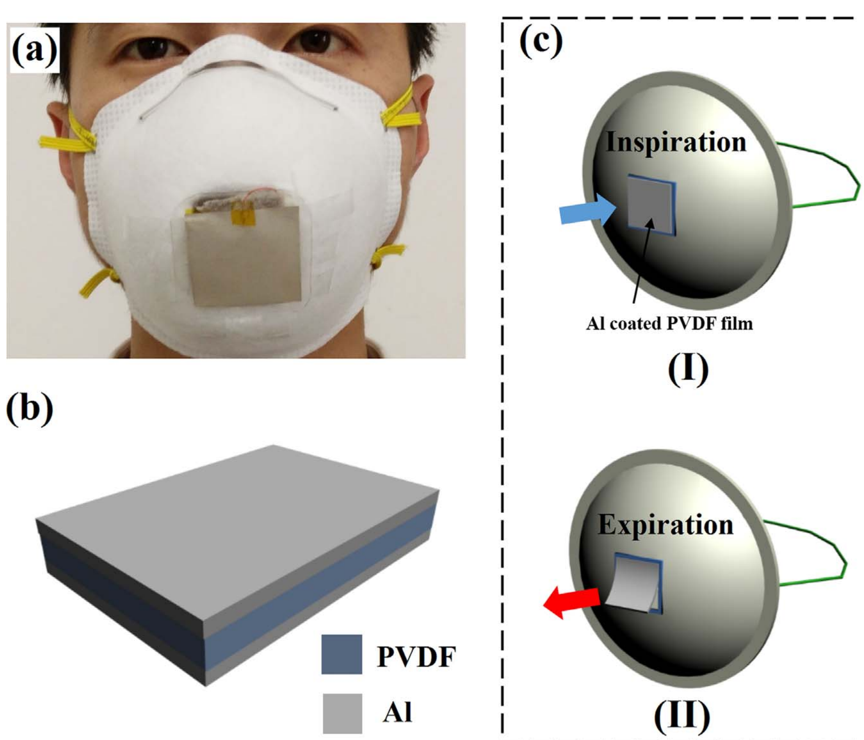

Fig. 1. (a) The physical photo of the wearable PyNG. (b)The schematic of the pyroelectric PVDF film. (c) Schematic of a wearable PyNG driven by human respiration (I) Inspiration; (II) Expiration.

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