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Flexible pyroelectric device for scavenging thermal energy from chemical process and as self-powered temperature monitor

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HIGHLIGHTS

- A flexible pyroelectric device composed of CNT/PVDF/CNT was prepared.
- This pyroelectric device could convert waste heat from chemical process into electricity.
- This pyroelectric device was also proved to be a self-powered temperature monitor.
- Application of the pyroelectric device to power a small electronic was demonstrated.

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ABSTRACT

As one of the most important renewable and green sources, the development and utilization of waste heat have been received more and more attentions. A big part of waste heat comes from chemical process, which is ubiquitous in industry and laboratory. However, this form of waste heat is difficult to be utilized due to its low grade and easy dissipation. In this paper, we present a flexible pyroelectric device as a potential approach for effectively harvesting waste heat from chemical exothermic process. To achieve practical application, the pyroelectric device simply attaches to the outside of a beaker, in which various chemical exothermic processes happen. The output voltage (under input impedance of 100 M Ohm) and short-circuit current can be 9.1 V and 95 nA when the neutral reaction of sodium hydroxide and hydrochloric acid per amount-of-substance concentration proceeds in the beaker. The generated electricity can directly drive a liquid crystal display. Moreover, this pyroelectric device is also proved to be a self-powered temperature monitor reflecting chemical process in real time, as the calculated temperature variation of solution based on pyroelectric current well agrees with the measured one by thermometry reference. This work expands the development of pyroelectric device for harvesting chemical waste heat and opens up the potential applications on self-powered chemical process monitor.

1. Introduction

Due to the global environmental challenges and energy crises, the development and utilization of unused ambient energy that would otherwise be lost as heat, light, sound, vibration, stress or movement, have attracted considerable attention [1–5]. Many chemical processes, which are ubiquitous in industry and laboratory, produce a large amount of waste heat every day. For example, the traditional method of wastewater treatment in industry adopts neutral reaction between acid and alkaline, which can generate the heat of 57.3 kJ mol^{-1} [6]; Many combustion reactions, such as natural gas and coal combustion, can produce the heat of dozens of kilojoule per gram [7]. These rich waste heat resources can be potentially converted into usable energy such as electricity for powering small electronics and wireless devices. However, the waste heat from chemical process has the features of low grade (temperature below 130 °C) [8] and easy dissipation, which both increase the difficulty of utilization. Besides, the lifespan of the devices working in the chemical environment would be shortened since they are exposed to corrosive solutions or gases [9]. Therefore, material with chemical stability for utilizing waste heat from chemical processes remains challenge.

Many approaches exist for recycling waste heat, such as stirling engines can convert thermal energy into mechanical energy [10]; Organic Rankine cycles use refrigerants and hydrocarbons to

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harvest heat up to 200–300 °C [11]. However, they cannot function well for low-grade heat due to the associated small Carnot efficiencies [12]. Energy harvesting technologies provide a route for the conversion of low-grade waste energy into electricity [13–15]. Thermoelectric and pyroelectric harvesters both can scavenge heat energy via Seebeck effect and pyroelectric effect respectively [16,17]. The Seebeck effect utilizes a temperature difference between the two ends of the device for driving the diffusion of charge carriers to generate a sustainable electric power [18]. For example, Zhisong Lu et al. developed a silk fabric-based thermoelectric generator converting thermal energy into electricity based on thermal gradient between the hot junction that is in contact with the skin and the environment-exposed cold junction [19]. Alternatively, pyroelectric effects do not need a temperature gradient, but time-dependent temperature changes [20]. Leng et al. reported a pyroelectric generator, which was alternately driven to contact the hot flow and cold flow by an electric oscillator, for harvesting heat energy from hot/cold water [21]. Considering the fact that a chemical process generally causes a time-dependent temperature fluctuation based on chemical reaction progress, the pyroelectric harvester could offer an opportunity for utilizing the waste heat from chemical process, while the thermoelectric one could fail. However, to the best of our knowledge, studies on waste heat harvesting from chemical process based on pyroelectric effect have not been reported.

The pyroelectric device generally consists of pyroelectric material between two electrode layers [22]. Many pyroelectric materials are commercially available and easy to be scale up, such as polyvinylidene difluoride (PVDF) that was lightweight, flexible [23], polymeric material. In particular, the chemical stability of PVDF is well known [24], which is important for working in the chemical environment. Moreover, the flexibility can determine if conformal contact with some irregular vessel surfaces and increase the area of device leading to an increase in power efficiency. However, the electrode materials for pyroelectric devices are generally metals [23], metal oxides [25] and graphene [26]. Most metal materials are easy to corrode, and metal oxides, graphene are generally prepared through a high-cost and complex procedure. Currently, the multi-walled carbon nanotube (MWCNT) was successfully used as a stretchable and durable electrode material [27,8] due to its high electrical conductivity [28], corrosion resistance [29] and low cost. Therefore, MWCNT could be a viable candidate as an electrode material to realize the applications in the chemical environment.

In this paper, we present a pyroelectric device design composed of CNT/PVDF/CNT sandwich as a potential approach for scavenging heat from chemical process (Fig. 1). The pyroelectric device is stuck outside the surface of a beaker for the performance test, which can convert random and large amount of heat from various chemical processes into electricity directly. The generated electricity can power a liquid crystal display (LCD). Also, the device is proved to be a self-powered temperature monitor, as the calculated temperature variation of chemical solution based on pyroelectric current has a good agreement with the measured one by thermometry references. The temperature monitoring can provide direct information about the progress and intensity of chemical process, which is important for measuring reactor conditions and improving the performance of chemical processes [30]. Pyroelectric sensors have the advantages of both converting temperature variation into electric signals directly and needing no external bias [31]. Therefore, this pyroelectric device can not only scavenge heat from chemical exothermic process as a harvester, but also monitor chemical process in real time as a self-powered temperature monitor. Given the extremely low cost and unique applicability, the MWCNT-based pyroelectric device renders a simple alternative to traditional methods potentially for thermal energy harvesting, self-powered monitoring, and others.

2. Experimental

2.1. Fabrication of a flexible pyroelectric device

The PVDF film with the thickness of 30 μm was purchased from Jinzhou KeXin electronic materials Co. Ltd. The MWCNT dispersion we used was purchased from XF NANO, INC. The pyroelectric device was fabricated by depositing MWCNT on both sides of PVDF film by the spin-coating method. The thickness of MWCNT electrode layer was dependent on spin-coating speed. Two copper wires were fixed on the top and bottom electrode layers of device with copper conductive tape.

2.2. Characterization and performance analysis of the pyroelectric device

The pyroelectric device was stacked outside surface of a beaker (100 mL). Five kinds of chemical exothermic processes were selected to react in the beaker: calcium oxide and water; calcium hydroxide and sulfuric acid; sodium hydroxide and water; sodium hydroxide and hydrochloric acid; concentrated sulfuric acid dilution. All chemical reagents are analytically grade. The stirring rate of solutions was controlled by a magnetic stirrer. The thermal infrared imager (SC7300M, FLIR Systems AB) was used to record the temperature variation of the chemical process. The generated

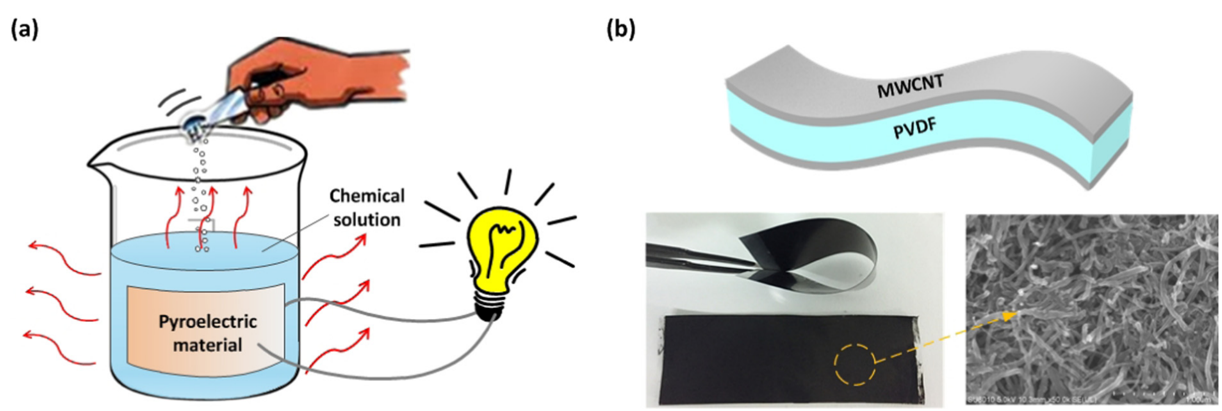

Fig. 1. (a) Schematic illustration of a pyroelectric device harvesting heat from chemical process. (b) Schematic diagram (top) and photograph of the flexible pyroelectric device composed of CNT/PVDF/CNT sandwich (bottom left), and SEM images of MWCNTs (bottom right). Scale bars: 1 μm.