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RAPID COMMUNICATION

Multifunctional triboelectric nanogenerator based on porous micro-nickel foam to harvest mechanical energy

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Abstract
To strengthen the effective contact area of two materials with the opposite triboelectric polarities was proved to be an effective solution to enhance the electronic output of triboelectric nanogenerator (TENG). Presently, that mainly focused on the surface modification of negative materials by micro/nano structure, however, rarely for the positive materials. Here, we presented a simple, low-cost and multifunctional TENG based on the porous micro-nickel foam (PMNF) for harvesting the natural vibration energy. With the surface modification of PMNF with the positive polarity, the newly designed TENG produced an open-circuit voltage up to 187.8 V and a short-circuit current of 71.9 μA with the peak power density of 3.7 W/m^2 at the resonance frequency of 13.9 Hz by harvesting vibration energy. This TENG could simultaneously and continuously light up 100 commercial light-emitting diode bulbs. Additionally, by the footfalls force of about 500 N, the corresponding open-circuit voltage and short-circuit current were as high as 403 V and 336 μA, respectively. The newly designed TENG can be used for the self-powdered floor by footfalls and also for powering some wireless electronics by harvesting the vibration energy from highways, railways, and tunnels in remote mountain areas.

Introduction

In the past few years, many research efforts have been devoted to harvest ambient mechanical energy as the supplementation of traditional power source owing to the increasingly less fossil fuels and the rapid-growing energy consumptions. Usually, several mechanisms on harvesting mechanical energy are as follows: electrostatic effect [1-5], piezoelectric effect [6-10], electromagnetic effect [11-13] and magnetostrictive effect [14]. Based on them, these methods mainly focused on the small-scale energy harvesting, intending to power micro/nanosystems and portable electronics [15-24] because of their small size, lower power

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consumption and special working environment. However, these widespread techniques toward large-scale energy harvesting are potentially shadowed by some possible restrictions, such as the energy harvesting method, the material cost [25], structural complexity [15], environmental influence and feasibility in practice.

The triboelectric effect, which has been known for thousands of years, was an undesirable phenomenon in past years owing to the potential threats to public safety and electric product. However, triboelectric nanogenerators [26-36] (TENGs), on this basis, has been hatched up to harvest mechanical energy as an efficient means. In virtue of coupling effect of contact electrification and electrostatic induction, the periodic contact and separation between two materials with triboelectric polarities could drive the charges between electrodes to produce an alternating current. The dramatically increasing effective contact area of contact materials by the micro/nano structure surface modification technique was proved to be one of the most important factors to strengthen the electronic output of TENG. Currently, only a few surface modification of positive materials by micro/nano structure [34] has been reported to date. The overwhelming majority of TENGs focused on the surface modification of positive materials [37-40].

Here in this paper, for the first time, a king of low-cost, stable and porous micro-nickel foam (PMNF) with the positive property was applied to fabricate a TENG that can harness ambient vibration and footfalls, which are the most common and available mechanical motion for powering electronics, especially portable devices. With the hybridization [41-46] of both the contact-separation mode and sliding electrification mode of PMNF top inserting into flexible PDMS, the reasonably designed TENG can generate a uniform signal output at a short-circuit of 71.9 μA and an open-circuit voltage up to 187.8 V, which corresponded to the power output of 9.3 mW and power density of 3.7 W/m^2. Additionally, by the footfalls force of about 500 N, the corresponding open-circuit voltage and short-circuit current are up to respectively 403 V and 336 μA, which unambiguously presented some potential applications of PMNF for the, self-powered floor and anti-theft devices as well as vibration sensor system by harvesting the vibration energy from highways, railways, and tunnels in remote mountain areas.

Results and discussion

Figure 1a illustrates the schematic diagram of TENG that consists of two substrates, electrodes, triboelectric materials and springs. Acrylic was selected as supporting substrate in virtue of its felicitous strength with good processing, light weight, graceful appearance and low cost. As the as-fabricated TENG schematically shown in Figure 1b, a sheet of porous PMNF that has dual roles as a contact surface and an electrode was attached on the lower side. This porous electrode was prepared via an electrolytic-deposition method, which will be discussed in details in the *Experimental section*. A scanning electron microscopy (SEM) image of PMNF sketched in Figure 1c. In addition, the corresponding energy dispersive spectrometer (EDS) is presented in Figure S1. On the other side, a thin layer of aluminum foil, called back electrode, was fixed on the substrate and the polydimethylsiloxane (PDMS) as contact surface directly spin-coated on it. Then, four springs support the two substrates remaining a narrow gap at the corners. Figure 1d distinctly schemes the fabrication flow and the concrete fabrication process is describe in detail later.

The working principle of this nanogenerator can be expounded as schematically depicted in Figure S2 by means of the triboelectric effect and electrostatic effect. The electricity generation process in this TENG is based on the sequence of contact-separation motion induced by a standard vibration shaker system (from Dongling Technologies Inc.). When an external force from the vibration shaker system gives rise to the contact, an electrical signal distinct is obtained by the contact and sliding mode of the TENG. Subsequently, with the separation achieved up until the maximal point, the inductive charges gradually transfer from PMNF to PDMS's back electrode [46]. In addition, when the two contact surfaces narrow the interval of two contact surfaces until contact, an electric potential difference is produced once again and free electrons flow back to PMNF. In this process, the TENG is similar to an electric pump that drives electrons back and forth between electrodes, producing an alternating current. Furthermore, in order to reinforce the working principle, we took a further step to simulate the periodic potential change between the two electrodes upon vertical contact and separation by virtue of COMSOL, as demonstrated in Figure 2. And the continuous variation of the potential distribution is visualized in Supporting information Movie 1.

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.nanoen.2015.06.012.

In order to investigate the performance of TENG for harvesting vibration energy [20], the standard vibration shaker system as a vibration source supplied an adjustable frequency and amplitude in form of a sine-wave oscillation. The bottom substrate of TENG was fixed on the shaker, making sure that this TENG should be on the safe side and its upper part can run free. The peak value of open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}) as functions of input vibration frequencies at an invariable amplitude were measured in Figure 3a and b to characterize the TENG electric performance. A far-ranging common vibration frequency in daily was surveyed from 1 to 300 Hz in a super-low-frequency (SLF) scale (Table 1, Supporting information). And a considerably wider working bandwidth of 11.2 Hz was obtained (see Figure S3, Supporting information).

Experimentally, the open-circuit voltage and the short-circuit current of TENG reached the maximum values of respectively 187.8 V and 71.9 μA at the vibration frequency of 13.9 Hz, revealing that 13.9 Hz should be the resonance frequency of TENG. In theory, for a degree-of-freedom vibration system, the natural is given by the following equation [47]:

$$f_0 = \frac{1}{2\tau}\sqrt{\frac{4k}{m_0}} \tag{1}$$

where f_0 is the natural frequency, k is the stiffness coefficient is 132 $N\,m^{-1}$ and m_0 is 69 g for the TENG. We can acquire the nature frequency of 13.9 Hz by inputting