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RAPID COMMUNICATION

Vertically stacked thin triboelectric nanogenerator for wind energy harvesting

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Abstract
Wind has come to be considered as an attractive energy source due to its abundance, ubiquity, and sustainability in nature. When an energy harvester driven by wind is miniaturized with high-power and robustness, it can be useful for self-powered systems of mobile electronic devices. In this work, a vertically stacked triboelectric nanogenerator (VS-TENG) is investigated. When wind is introduced into the air gap of the VS-TENG, a thin and flexible polymer membrane repeatedly comes in contact with and separates from upper and lower electrodes. This thin device structure makes the VS-TENG suitable for vertical stacking without bulky volume. Vertical stacking not only provides multiplied output power via parallel stacking but also enables utilization of bi-directional wind by a cross stack.

Introduction

Energy harvesting is an efficient and eco-friendly technique to convert various environmental energies to useful electrical energy. As mobile electronic devices and wireless sensors have dramatically advanced recently, the importance of small-size energy harvesters is rapidly increasing [1-8]. Power requirements of such mobile devices are small enough that they can be operated with a battery, but the unavoidable recharging and replacement process is a critical limitation. A primary purpose of small-size energy harvesters is to extend the operation time of batteries and, ultimately, to allow for self-powered systems that do not require batteries [9].

Among various sources of energy, wind has attracted special interest because of its abundance, ubiquity, steady supply, and large energy capacity. The most widely used type of wind energy harvester introduced thus far is the electromagnetic wind turbine [10]. In order to implement a wind energy harvester on mobile devices, a miniaturized structure of the wind energy harvester has been introduced

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that is combined with several other mechanisms [11–15]. However, they inevitably demand the use of a blade, which has retarded the aggressive process of down-scaling.

A thin-film membrane based triboelectric nanogenerator (TENG) is a distinctive structure for wind energy harvesting that does not contain a blade part [16–18]. TENG is a mechanical energy harvester utilizing a combined mechanism of contact electrification and electrostatic induction [19–28]. The thin-film membrane-based TENG is a specific type of TENG that has structure suitable for aggressive down-scaling. For improved practicality of the TENG based wind energy harvester, a comprehensive design strategy to obtain both miniaturized device area and high performance should be formulated.

In this work, a vertically stacked thin-film triboelectric nanogenerator (VS-TENG) is proposed. A unit VS-TENG device is composed of a top outer electrode, a bottom outer electrode, and a vibrating membrane placed between the electrodes. The vibrating membrane consists of a polymer layer harnessed with an anti-stiction microstructure and a metal electrode encapsulated inside the membrane. The particular membrane design allows enhanced output power, rapid operation, and effective electrode configuration for multiple stacking. The primary purpose of the stacking is to enhance the output power while maintaining the device area. Moreover, if each of the VS-TENGs is rotated 90° in relation to the others, i.e., in the form of a cross stack, bi-directional wind can be fully utilized for the energy harvesting.

Experimental methods

To fabricate the electrode-encapsulated, microstructure-harnessed membrane, a new fabrication method is designed based on the double replica-molding process. The detailed fabrication process is explained in the Supporting information (Fig. S1). After the fabrication, each individual device is composed of two anodic rigid Al plates (outer electrodes) and a cathodic Al electrode (inner electrode) embedded in a flexible polymer membrane (Fig. 1a–c). The flexible membrane consists of three layers: one micro-pyramid-exposed PDMS with a thickness of 100 μm at the top, an intercalated Al (inner electrode) with a thickness of 20 μm in the middle, and another micro-pyramid-exposed PDMS with a thickness of 100 μm at the bottom. The micro-pyramid array at the top protrudes toward the top Al electrode, whereas the array at the bottom protrudes toward the bottom Al electrode. The overall structure of the membrane in the proposed TENG is a rib shape composed of three skeletons. At both ends of the cathodic membrane, spacers made of overlapped polyimide (Kapton) films with thickness of 300 μm are placed to form air gaps between the anodic outer electrodes and the vibrating membrane. The thickness of the spacer determines the size of the air gap. A narrow air gap is advantageous in terms of device volume, effective contact area, and mechanical robustness. However, if the separation distance becomes too small, loss of induced current can result due to the coupling of electrodes. The membrane thickness and air gap size are carefully determined considering the charge transfer efficiency. Detail explanation about the rationality of structural design is presented in Supporting information.

For the measurement of VS-TENG, wind is applied using a commercial air gun; then, the generated electric potential is detected using an oscilloscope (WaveRunner 625Zi, LeCroy). The velocity of the wind is measured via a commercial anemometer (AR816, SMART SENSOR). The load resistance of the oscilloscope is 10 MΩ, and the sampling frequency of the measurement is 50 kHz. Measurement of the load resistance dependency is done by an electrometer (Keithley 6514). Except the particular measurement, output signal is measured by the oscilloscope to ensure high sampling frequency.

Results and discussion

The interfacial microstructure in the PDMS membrane plays two crucial roles in the device operation. First, this interface microstructure is essential to prevent the stiction between the anodic outer electrodes and the PDMS membrane, which can be a critical problem impeding the rapid vibration, i.e., the contact and separation process. At the moment of contact, the protruded pyramids are instantaneously compressed, which generates a strong net restoring force. The direction of the restoring force is opposite to that of the adhesion force, and so the stiction problem caused by the adhesion force is resolved. Second, the embossed pyramid array enhances the effective contact area, which enlarges the triboelectric charge density. The relation between the interfacial micro- and nanostructures and the electrical performance enhancement is comprehensively understood [29,30]. Nanostructures are more beneficial for the effective contact area, but they are not suitable for the anti-adhesion property due to the smaller restoring force. On the other hand, a micro-rod or micro-striped line structure rather than the pyramid structure is favorable for the strong anti-adhesion property, but they are not efficient for the contact area enhancement. Considering both of these issues, the micro-pyramid array is employed, leading to optimal anti-adhesion property and the enhancement of the effective contact area.

When wind blows into the VS-TENG and hits the PDMS membrane layers, vortex wind is naturally generated inside the air gaps. The vortex wind drives the PDMS membranes, making them vibrate up and down to contact the anodic outer electrodes repeatedly (Fig. 1d). Triboelectric charging, i.e., contact electrification, happens in the first few cycles of contact. According to the triboelectric tendency, the Al electrodes are positively charged while the PDMS is negatively charged. The positive charges at the anodic outer electrodes are immediately redistributed after separation, while the negative charges at the PDMS membranes are fixed at the surface. The fixed negative charges drive an induced current to flow between the cathodic inner electrode and the anodic outer electrodes.

Because the VS-TENG contains two fixed anodic electrodes and one vibrating cathodic electrode, the total structure can be considered as two TENGs with one shared electrode. When the PDMS membrane is placed at the center of the air gap, negative triboelectric charges of the membrane are balanced by positive charges of the cathodic inner electrode. When the membrane contacts the anodic top electrode, equivalent negative charges at the PDMS surface induce positive charges at the top electrode, and so