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A triboelectric nanogenerator using silica-based powder for appropriate technology

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ABSTRACT

To harvest ambient mechanical energy, a triboelectric nanogenerator is actively researched as a sustainable energy source. One of the advantages of the triboelectric nanogenerator is the almost exclusive use of widely available materials that can be manufactured at a low cost. For example, silica, composed of silicon and oxygen, not only can play a role as a triboelectric material but is abundant everywhere in the earth's crust. Here, we report a triboelectric nanogenerator using three types of silica powder as a freestanding dielectric layer: sand, silicon, and silicon dioxide. Among them, the triboelectric nanogenerator with silicon dioxide powder and polytetrafluoroethylene film produces the highest electrical output power. The instantaneous peak power density is 0.3 mW/m^2, achieved by shaking the triboelectric nanogenerator by hand. Five serially connected commercial light emitting diodes are simultaneously turned on by persons with a hand. The proposed triboelectric nanogenerator can be utilized as a useful electric power generator in Third World due to its low-cost and widely available component materials.

1. Introduction

Appropriate technology, which helps people in Third World, has been intensively developed. For assuring the basic needs for people in Third World countries, the problems of poverty, unemployment, and inequality need to be urgently solved. Appropriate technology represents simple level technologies for assuring these problems and attaining an efficient result in selected area. It is reasonable for Third World societies to promote less complex and expensive sectors which are helpful to develop the countries. It can increase the level of technologies when the appropriate technology plays a role in a foundation technology in Third World. [1] For example, open source 3D printer designs, which enable low-cost distributed manufacturing system [2], are under development. Additionally, the technology of converting waste plastic into liquid fuel *via* thermal decomposition has been reported to solve waste disposal problems and circumvent the energy crisis [3]. Although those technologies help people in Third World, they cannot supply enough electric energy, which can turn on any electronic device. Therefore, low-cost energy harvesting technology can be favorably utilized for Third World.

Many types of energy are wasted in daily life. However, wasted energy can be transformed into useful electrical energy with the aid of energy harvesting technology. Thus, various types of energy harvesters have been studied using the piezoelectric, [4–6] electromagnetic [7,8], electrostatic [9–11], and thermoelectric effect [12,13]. However, each has their own limitations. A piezoelectric generator suffers from limited material availability, a relatively high-temperature process, and high energy demand in poling process. An electromagnetic generator has its high weight as a weakness, owing to the built-in, heavy magnet. An electrostatic electret generator demands a pre-charging process as an early step during operation. Additionally, a thermoelectric generator requires a large temperature difference to produce electric energy. Moreover, it is difficult to find a practical temperature difference for generating electricity in ambient conditions.

A triboelectric nanogenerator (TENG) was adopted to scavenge ambient energy in recent researches. The TENG device based on a combination of contact electrification and electrostatic induction resulting from the triboelectric effect, which has been known from electrical experiment in 600 BCE The phenomenon of contact electrification is occurred by the simple contact of dielectric-to-metal or dielectric-to-dielectric through friction. Charges move from one material to the other to equalize their electrochemical potential. The electrostatic induction occurs subsequently which is induced from the electric potential difference generated by contact electrification. The TENG showed several merits, such as wide

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material availability, simple fabrication with low-cost, light weight, autonomous manufacturing, and broad applicability in ambient environment. [14–21] Moreover, the efficiency of the TENG has been continuously grown [22–26], and eco-friendly technology has attracted considerable attention in recent years [27]. The TENG can be applied as a wearable electric energy generating device and self-powered active sensors [17].

Several operation modes have been developed for each customized applications. [28–30] The powder-based TENG, where the powder is free to move in any direction, was previously demonstrated [31]. The powder plays a role as a freestanding triboelectric dielectric layer, displaying back and forth movements on each other two electrodes [32]. This TENG has several advantages. First, similar to a single electrode mode, it can harvest energy regardless of the direction of vibration [30]. Next, the TENG can avoid the electrostatic shield effect; hence, the charge transfer efficiency can be improved compared to other single electrode-based TENGs comprised of a conventional dielectric film as a triboelectric layer [33].

In this paper, we utilized silica-based particles as a triboelectric material. Silica particles, which are easy to be found in ground, consist of silicon and oxygen. It is known that the elements of silicon and oxygen have weight percentages of 46.6% and 27.7%, respectively, in the configuration of the earth's crust. Particles of Si and SiO_2 with extremely low impurity concentrations were used in two experimental groups, whereas particles of natural sand with relatively high impurity concentration were used in a control group. The representative impurities in the natural sand are Al, Fe, etc. The control group using sand is prepared to evaluate the feasibility of practical use. Among the three different powders, the SiO_2 powder showed the highest output power under the same operation conditions. The electrical signals from the contact of surface between SiO_2 particles and polytetrafluoroethylene (PTFE) film in fabricated TENG show an open-circuit voltage (V_{OC}) of 15 V and a short-circuit current (I_{SC}) of 0.35 μA. By simply shaking by hand, the output power density was approximately 0.3 mW/m^2. Five commercial LEDs serially connected to each other are turned on using the proposed powder TENG, which can be applied for 'appropriate technology'. When a number of this powder TENG with sand particles are used together, sufficient electricity will be supplied to the people in Third World.

2. Experimental

The diameter of the aluminum electrode is 40 mm and the acrylic container has an internal diameter of 32 mm. The height of the electrode and container are 5 mm and 52 mm, respectively. The thickness of the PTFE film is 100 μm. The container is capped by aluminum lids to prevent the powder from leaking. These lids also prevent the external humidity from affecting the performance of the TENG.

The surface characteristics of the Si powder, SiO_2 powder, and sand particles were observed and surface analysis was performed by field-emission scanning electron microscopy (FE-SEM) and energy-dispersive X-ray spectroscopy (EDAX), LEO SUPRA 55 (Carl Zeiss, Germany) with an operating voltage of 10 kV.

An electrodynamic shaker and human hand were used to generate vibration and convert mechanical energy to electrical energy, enabling contact and separation between the dielectric material and counter triboelectric layer with the intensity of 100 N. The output voltage and current generated by the fabricated S-TENG were measured by an electrometer (Keithley6514).

3. Results and discussion

Fig. 1a shows the conceptual illustration of the proposed silica-based powder-TENG (S-TENG). The S-TENG operates as the freestanding triboelectric-layer mode. [17] Three different types of powders, SiO_2, Si, and sand, can serve as a freestanding dielectric layer. Polytetrafluoroethylene (PTFE) surface, which tends to be negatively charged, is located between the powder and electrode. More electrons are transferred to the contact surface of two other materials between SiO_2 and PTFE than between Al electrode and SiO_2. According to triboelectric series, SiO_2 tends to be positively charged than Al. In contrast, PTFE tends to be negatively charged, and larger triboelectric effect at the surfaces between PTFE and SiO_2 occurs than between Al and SiO_2. A thickness of PTFE serving as a counter triboelectric contact surface affects the electrical output of the operating S-TENG device. The value of I_{SC} decreases as the PTFE film attached to the electrode becomes thicker. [34] A thick triboelectric contact surface can cause degradation in electrostatic induction due to the decreased electric field intensity of the contact surface. Therefore, PTFE film layer should be thin. Fig. 1b shows a photograph of the fabricated S-TENG. The diameter of the base side of the container is 40 mm, and its height is 62 mm.

Fig. 1c shows a field-emission scanning electron microscopy (FE-SEM) image of the Si powder and the inset is an image of the Si powder taken by a digital camera. Fig. 1e shows an image of the SiO_2 powder taken by FE-SEM and the digital camera. The particle diameter of the Si powder is approximately 30 μm and that of the SiO_2 powder is in the range of 2 μm–25 μm. The SiO_2 powder represents the non-uniform particle size compared to Si powder. The electrical output can be enhanced with the small particles, increasing contact surface by permeating into the closer position of the contact surface. The weight percent and atomic percent of the Si powder was characterized by energy-dispersive X-ray spectroscopy (EDAX), as shown in Fig. 1d. Fig. 1f represents the EDAX spectrum, weight percent and atomic percent of the SiO_2 powder. Through comparison of the EDAX spectrum of Si and SiO_2, it is confirmed that the elemental composition is obviously different. Moreover, this result illustrates that the SiO_2 powder consists of similar elements with sand particles than Si powder.

The operating principle of the S-TENG is shown in Fig. S1. When the S-TENG is in the initial state, the powder is located at the bottom part of a PTFE film. The powder will be positively charged and the PTFE film will be negatively charged when they come into contact. After shaking, the powder starts to move upward and is separated from the PTFE film. Due to the positively charged silica particles, the induced positive charges are collected at the upper part of the electrode. In this process, the current flows downward. When contact and separation occurs at the upper electrode, it shows the same charge transfer phenomenon which occurred at upper electrode. However, the direction of the current is reversed, because electrons move in the opposite direction.

Fig. 2 shows the open-circuit voltage (V_{OC}) and short-circuit current (I_{SC}) of the S-TENG. The experiment was performed with a vibration frequency at 3 Hz and a 50% volume ratio of the powder in the container. As shown in Fig. 2a, V_{OC} is 5 V and 15 V for the Si and SiO_2 powders, respectively. Fig. 2b shows that I_{SC} is 0.23 μA and 0.35 μA for the Si and SiO_2 powders, respectively. The S-TENG shows 3 times higher V_{OC} and 1.5 times higher I_{SC} using the SiO_2 powder than the output characteristics using the Si powder. Considering of the gap in triboelectric series, silica-to-PTFE shows better triboelectric characteristics than Si-to-PTFE according to the triboelectric series. [35] Moreover, the value of V_{OC} and I_{SC} were enhanced when using the SiO_2 powder, which size of particle is smaller than that of Si powder, as a triboelectric material due to the fact that effective contact area is increased as the size of parti-