

論文の内容の要旨

論文題目 Development of wearable energy harvester based on triboelectric
nanogenerator
(摩擦帯電に基づいたウェアラブルエネルギーハーベスター
の開発)

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In the past few decades, the rapid development of electronic devices have gradually become an indispensable part of people's daily life. Especially now that the Internet of Things has become the mainstream of informatization development, various sensors have begun to provide more comprehensive information and services. With the progress of “top-down” manufacturing technologies, the dimensions of autonomous electronics have decreased significantly, while offering more vital functions. However, batteries, which are the most common power supply components, are becoming increasingly difficult to meet the demands of rapidly miniaturized and diversified electrical devices and systems, especially in terms of environmental safety and ease of integration. Wearable devices have great development prospects in terms of providing more convenience and safety for society and daily life, and will undoubtedly place stringent requirements on the wearability of power supply components. The triboelectric nanogenerator (TENG), based on the combination of contact charging and electrostatic induction, is able to effectively convert the mechanical energy from body motion into usable electricity. The advantages such as environmental friendliness, economic efficiency and structural diversity have

made TENGs one of the most promising candidates for replacing batteries in wearable power generation systems.

Because the working mechanism of TENGs mainly relies on external vibration and friction, they are often integrated on clothes or worn somewhere on the body to collect local mechanical energy. The main production methods are mainly divided into two types, coating and weaving. The coating is to integrate the necessary friction materials and electrode materials in a layered manner; weaving is to weave the fabricated polymer wire with an electrode metal core into a textile form. Currently, the limitations in the wearable TENG's field are as the following: First, for the goal to be widely used and accepted by the public, the adaptability of current processing methods is weak. The coating's requirements toward the substrate, the coated material, and the processing conditions are generally high. In application, many wearable materials that people are familiar with in daily life have to be eliminated for reasons that are not suitable for processing. Furthermore, the device with a simple structure that is "one layer of friction material, one layer of electrode", can only harvest mechanical energy from one side; if it is a multi-layer structure, excessive accumulation of materials may cause the lack of flexibility, and complication of processing as well. The other method of weaving also inevitably makes the TENGs become bulky, putting a burden on wearing and integrating. Subsequent weaving process also leads to complicated process and high cost. The second problem is that the choices of raw materials gradually tend to be singular and non-daily. Most of the friction materials are industrial synthetic materials, not soft nor breathable enough. For electrode, metals have always been the first choices, not only imposing the risk of allergy, but also not safe or comfortable for wearing. Another problem is that the structures of the TENGs are neither simple nor customizable, being restricted to the specified power generation mode. Friction can occur at any time in various forms, but the design of the TENGs cannot adapt to multiple situations at the same time. Finally, the high power generation output that determines applicability is difficult to coexist with other characteristics that are also actually required. In other words, the inability to meet low cost, simple structure, simple production process, common wearable materials and high output at the same time, has always been one of the reasons that limit the widespread application of TENG technology.

In this study, simply structured wearable TENGs with a hybrid mix of carbon nanotube (CNT) and silk are developed. Two natural biodegradable materials, silk and CNT, are employed as the triboelectric material and electrode material, respectively. For the first time, a highly effective wearable TENG based on a mix of friction material and electrode material is realized. The combination of the two materials, proposed structure and processing methods are newly developed here, so this study is worthy of reference for the future development of wearable TENGs. Two sets of processing methods are proposed, and two types of TENGs with different internal structures and characteristics are fabricated. One is to make a mixing membrane TENG

by molding casting, and the other is to make a fiber-substrated TENG by combining electrospinning and electrospray.

In response to the existing challenges, firstly, the processing of raw materials and the manufacturing methods of the developed TENGs equip high adaptability. Simple and low-cost productions have made the same simple and low-cost devices, being carried out under normal temperature and humidity environment, without specific requirements for processed material properties. Secondly, the selection of raw materials adheres to the concept of practicability, safety and economy. The natural fibroin of silk is skin-friendly and commonly used by people; the CNT used as electrode material has a simple composition and excellent performance. By combining them together, a high-output wearable power supply is realized. In addition, the TENGs of the two structures have reached the requirements of lightweight, thinness, and free use. They can be worn as a separate power-generating device, or integrated into clothing or other equipment, with almost no additional wearing burden. The membrane-based structure can be easily customized and integrated into gloves to charge capacitors, also into microneedle capsule to release microcurrent for healthcare effect. The fiber-substrated structure has stronger elasticity and tensile ability, so it can be worn on finger to drive the humidity thermometer by randomly touching the skin, tapping the keyboard, holding a pen to write; also be worn alone on the wrist or sewed into the clothing with a larger area. According to the charging curve of the capacitor, it can be roughly estimated that the mean power obtained every time the keyboard was tapped is 10.78 nW, and the average power obtained each time the pen was held to write is 11.979 nW, which are already able to power up micro sensor nodes. The customization of the scale is very important for evaluating the applicability of the TENG. Being able to be processed into 1~20 cm² while providing usable electrical energy was set as the basic goal of achieving wearability. Finally, the output of the TENGs meets the pre-set requirements of having a output over 100 μ W regardless the area, and is representative in this field. Here, the electrical features were investigated by contacting with polyethylene terephthalate (PET) film under periodic shaker patting and random hand patting. The output power of membrane-based structure reached 190.73 μ W/cm² with shaker patting and 285.91 μ W/cm² with hand patting, with a matched load of 30 M Ω . And fiber-substrated structure reached 140.99 μ W/cm² with shaker patting and 317.4 μ W/cm² with hand patting. In addition, in this study, the initially established durability goal is that there are no destructive defects for more than 50,000 cycles of work. The mixing membrane showed impressive stability under a 75,600-cycle continuous operation condition, with merely a 16.7% reduction in voltage.

The performance of the developed TENGs as well as corresponding processing methods have been able to lay a reliable foundation for the wearable TENGs to break through the development bottlenecks. Furthermore, customization can be easily achieved according to different

requirements referring to this study, and a wider range of materials, applications and developments can be considered in the future.