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RAPID COMMUNICATION

3-Dimensional broadband energy harvester based on internal hydrodynamic oscillation with a package structure

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Abstract
Energy harvesting techniques which convert ambient waste energy into usable electrical power have emerged with the increased energy demand and rapid growth of self-powered systems. Among them, the triboelectric nanogenerator (TENG), which utilizes contact-electrification, has attracted a great deal of attention owing to its high output energy, good cost-effectiveness, and simple fabrication process. Here, the TENG harvesting ambient mechanical energy based on internal hydrodynamic oscillation (Hy-TENG), is demonstrated. The Hy-TENG shows an output voltage and current of 22 V and 1.45 μA, respectively, under vibration of 5 Hz. The maximum instantaneous power density is 26.5 mW/m^2. By utilizing water in the mechanical energy harvesting process, several powerful advantages are also guaranteed due to the shape adaptability of water. First, both a wide bandwidth and a low resonance frequency are verified, which are advantageous for applications based on human motion. These frequency response characteristics indicate the strong potential of the Hy-TENG in actual environments. Furthermore, the Hy-TENG is highly scalable, as water can easily be restored to its initial state without a mechanical conversion apparatus. Finally, Hy-TENG harvesting 3-dimensional random motion (3-D Hy-TENG) is developed with a simple design based on the easily shape-transformable characteristic of water. Additionally, enhanced endurance against environmental factors and mechanical damage can be expected based on the packaged structure and on the non-destructive water-solid contact.

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Introduction

Over the past few decades, energy harvesting techniques, which convert various forms of waste energy, such as solar, [1,2] thermal, [3,4] and mechanical energy 5-9 into usable electrical energy, have rapidly emerged given the high energy demand and the notable growth of wearable devices and wireless sensor networks. Among the many energy harvesting techniques currently being studied, interest in triboelectric nanogenerators (TENGs), [10,11] which typically convert ambient mechanical vibrations into electrical energy via contact-electrification [12-14] and electrostatic induction, has grown dramatically based on the cost-effectiveness, high performance capabilities, simple fabrication process, and numerous application areas of these generators.

Most TENGs introduced thus far have been based on contact electrification at a solid-solid interface. When two solid surfaces are brought into contact, these surfaces are charged with opposite polarities. The mechanical motions of these surfaces induced by applied mechanical excitations in the form of vertical contact-separation [10,11] or in-plane sliding [15,16] then induce an electrical potential difference through the electrodes. As a result, electron flows through the electrodes to attain a state of equilibrium by valancing this electrical potential difference. Based on this approach, various novel and efficient TENGs [17,18] have been used in conjunction with diverse energy sources, such as mechanical vibration, [19,20] human motion, [21,22] the impact of water [20,23] and air flows [24-26]. Apart from scavenging diverse energy sources, various power management techniques have been also well developed utilizing novel device configurations [27-29]. However, investigations of the capability of these devices to harvest ambient energy over a wide operational frequency range have remained insufficient despite the fact that broadband operation characteristics are often preferred in practical applications. Further, many TENGs are adaptable for the harvesting of ambient energy in specific directions; a well-designed structure is required to harvest three-dimensional (3-D) random motions by coupling both in-plane and out-of-plane vibrations [19]. Additionally, the continuous physical contact of solid surfaces has the potential to cause problems with long-term mechanical durability [30]. Environmental factors such as the relative humidity [31,32] and surface contamination by air-borne dust can also severely degrade the output performance of these applications.

Recently, several studies focusing on TENG, based on contact-electrification between water and a solid surface (water-based TENG), have been suggested, apart from some previous studies for harvesting energy from water with conventional electrostatic approaches [33-35]. Water-solid contact also induces triboelectric charges on surfaces, creating a charged electrical double layer (EDL) [36-40]. Although the exact charging species of the contact-electrification between water and solid surface is still elusive, this charging phenomenon is thought to be governed by selective absorption of ions in water to solid surface [36,37]. When the water comes into contact with solid surface, this ion absorption occurs immediately. Then conjugate ions in water, are attracted by Coulomb force, while forming electrical double layer. As the water begins to slide on the solid surface, absorbed ions are retained on the solid surface and water acquires excessive conjugate ions. Based on the contact-electrification between water and a solid surface, water-based TENGs have been developed for the harvesting of ambient water energy from various forms, such as flowing water, [41,42] water drops [43-45] and water waves [46]. However, to date, water-based TENGs have relied on naturally provided ambient energy in a water environment directly while not intentionally utilizing the water as the charge-driving source.

Herein, a packaged TENG which harvests ambient mechanical vibrations based on internal hydrodynamic oscillation (Hy-TENG) utilizing contact-electrification between water and a superhydrophobic solid surface, is suggested. The good shape adaptability of water provides practical advantages with regard to the design and operation of this water-based TENG. First, wideband operation (bandwidth of 22 Hz for output voltage and 250 Hz for output current) and a comparably low resonance frequency (5 Hz), often preferred for practical applications, are achieved. Secondly, the Hy-TENG can be highly scaled because it does not require any mechanical conversion devices such as an elastic spring apparatus for the restoration of water. Finally, the Hy-TENG harvesting of mechanical energy in three dimensions (3-D Hy-TENG) can be simply designed based on the multidirectional oscillation of water. The 3-D Hy-TENG can successfully harvest both in-plane and out-of-plane mechanical vibrations. In addition, it has robust immunity against environmental variations for outdoor use due to its inherent packaged structure. Enhanced durability can also be expected owing to the nondestructive water-solid contact.

Experimental section

Fabrication of the vertically aligned PTFE nanowires

A piece of 50-μm-thick PTFE film was prepared with desired dimension. On the PTFE film, 5 nm of Au thin film was deposited by thermal evaporation. Utilizing the inherent island-like Au film as a mask for the formation of the nanowire, the PTFE films were etched for 5 min under a flow of 15 sccm Ar, 10 sccm O_2, and 40 sccm SF_4 with an RF power of 400 W and a bias power of 100 W.

Preparation of the Hy-TENG and the 3-D Hy-TENG

To construct the Hy-TENG with the packaged cylindrical structure, a 1-mm-thick PTFE cylinder was prepared and both ends of the cylinder were blocked with 50-μm-thick PTFE films. In addition, aluminum electrodes were attached to the PTFE films with double-sided tape. Then, untreated tap water was filled into the cylinder and all side walls were sealed with silicone rubber to prevent water leakage. To fabricate the 3-D Hy-TENG, a 50-μm-thick PTFE cube was prepared and three electrodes pairs (Cu tape) were attached onto each surface of the PTFE cube. Then untreated tap water was filled inside the PTFE cube.