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Integration of multiple bubble motion active transducers for improving energy-harvesting efficiency

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ABSTRACT

In energy-harvesting systems that collect energy from waste micromechanical energy, the integration of multiple systems is essential to improve the total harvesting energy. However, we found that a simple integration of multiple systems does not work in water–solid electrification systems working in water, such as bubble motion active transducers (BMATs), unlike their use for typical triboelectric nanogenerators. The difference comes from the presence of water, which acts as a conductor and increases the total capacitance in the electrode with the increase in the number of systems, reducing the electrification efficiency. We systematically investigate the underlying mechanism and suggest a method to integrate multiple BMAT systems without losing energy by introducing an individually rectified multi-electrode (IRME) circuit. The rectifiers in IRME provide two functions: the usual rectifier function and an isolation function that disconnects neighboring electrodes. We demonstrate that the IRME BMAT improves the energy harvesting efficiency by a factor of the number of integrated electrodes, and that the system connecting ten electrodes works well as a power source to light an LED brightly in-situ. This method provides a promising path to the development of actual BMAT applications.

1. Introduction

With the depletion of fossil fuels and the rapidly growing wireless electronics market in the Internet-of-Things era, investigating renewable and sustainable energy sources and harvesting energy from wasteful sources such as human motion [1,2], sound and vibration [3,4], and rain drops [5] have emerged as major issues in the scientific community. Triboelectric nanogenerators based on solid–solid contact electrification is one of leading technologies for harvesting wasted mechanical energy [6–10]. Lately, another type of contact electrification based on the liquid–solid interface has attracted interest owing to its simple fabrication process, excellent durability with little mechanical damage, and no need of initial bias voltage [11–14]. In addition, the scheme based on liquid–solid contact electrification broadens the applicability of the energy-harvesting technology to wet or underwater scenarios.

Recently, Chen et al. developed self-powered triboelectric microfluidic sensor utilizing the electrical signal produced from the droplet/air bubble, and Wijewardhana et al. developed bubble motion active transducer (BMAT) technology to harvest energy using drifting air bubble in water [15,16]. However, the energy harvesting devices based on liquid–solid interface have some major challenges to be overcome. The most important challenge will be the low energy conversion, which is about one order of magnitude lower than that in solid–solid-contact-type devices. To overcome this issue, several methods have been introduced, such as the use of highly hydrophobic solid surfaces, extra charge deposition, functionalization of the solid surface, and optimization of the ionic concentration in water [12,15,17,18]. One of the easiest ways to increase the harvesting energy may be to increase the number of electrodes. Such multi-electrode systems have been used in water-droplet-based triboelectric nanogenerators (TENGs) as well, to improve the energy conversion efficiency [17,19]. However, we find that the adoption of a multi-electrode system in BMAT is not simple; unlike the multi-electrode TENGs used in dry situations, a simple increase in the number of electrodes does not guarantee the improvement of the amount of harvested energy owing to the presence of water.

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In this study, we systematically investigate the optimal rectifier circuit system for multi-electrode BMAT to effectively harvest electrical energy in water. We have categorized two types of electrode configurations depending on the end connections of the multi-electrode system. One is the rectified interdigital electrodes (RIDE) method, which consists of two interlocking comb-shaped multi-electrodes, and all the end terminals are connected to a single rectifier. The other case is the individually rectified multi-electrode (IRME) system, consisting of multi-electrodes in which two adjacent electrodes are connected to a separate rectifier. We find that the output energy of both systems is remarkably different. Whereas the output energy dramatically decreases in the RIDE BMAT system with the increasing number of electrodes, that of the IRME BMAT system linearly increases with respect to the number of electrodes.

2. Experimental methods

2.1. Sample preparation and experiments

Glass substrates with multiple rectangularly shaped indium tin oxide (ITO) ($4 \times 0.8\,cm^2$) electrodes were prepared. The gap between the neighboring electrodes and the number of rectangular electrodes were varied depending on experiments. The patterned ITO substrates were cleaned ultrasonically in acetone for 5 min, dried in blown nitrogen, and then spin coated with polyimide as an insulator (AL62620, JSR, Japan), followed by soft backing at 70 °C and hard backing at 210 °C for 15 min. Next, the substrate was spin coated by Teflon (PTFE: Poly[4,5-difluoro-2,2-bis(trifluoromethyl)-1,3-dioxole-co-tetrafluoroethylene]) and baked in an oven at 160 °C for 2 h [15,20,21]. The polyimide dielectric layer has a thickness of about 500 nm, and the Teflon, as a hydrophobic layer, is also about 500 nm thick.

2.2. Measurements

A programmable syringe pump (Pump 11 Elite, Harvard Apparatus, UK) was used to control the volume of the air bubbles. The rate of the air flow in the BMAT was maintained constant throughout the experiments at $10\,ml\,min^{-1}$. The mean volume of an air bubble is approximately 0.25 ml, and about 40 air bubbles per minute are launched from the air launcher in water. The open-circuit voltages without connection a resistor and the output currents through a load resistor of 1.2 MΩ were measured using a digital multimeter (DMM 7510, Keithley, USA). The energy was calculated using the relationship I^2R, where I is the current through the load resistor with resistance R. To collect the electrical energy, an aluminum electrolyte capacitor (4.7 μF, 50 V, Panasonic) was used. The stored energy (E) can be calculated by measuring the voltage (V) across the capacitor (C) and using the relationship, $E = CV^2/2$.

3. Results and discussion

BMAT is composed a parallel array of strip-shaped ITO electrodes on a glass substrate, as illustrated in Fig. 1a. The hydrophobicity of the Teflon layer was evaluated by measuring the contact angle of water on it, which was found to be 119°, exhibiting excellent hydrophobicity. The BMAT device was submerged in a water bath at an angle of 45°, and air bubbles launched from the bottom of the substrate rose along the hydrophobic surface at a regular rate. The moving air bubbles caused desorption and adsorption of ions on the hydrophobic surface (Supporting information Fig. S1a) [15]. The equivalent electrical circuit and the voltage gained via the circuit are described in supporting information Fig. S1b. The bubble overlaps with the electrodes, changing the equivalent capacitance, which results in an electrical signal in the circuit.

First, we investigated the output performance of three types of BMATs with different electrodes: BMATs with (i) a single electrode, (ii) dual electrodes having a large interelectrode gap (8 cm), and (iii) dual electrodes having a small gap (0.2 cm). Because the diameter of the contact area of a bubble on the surface is approximately 1 cm, the interelectrode gaps in BMATs (ii) and (iii) are larger and smaller than a bubble, respectively, as illustrated in Fig. 1b. The BMAT with a single electrode produces a single alternating current (AC) signal; a negative peak appears when a bubble enters the electrode, and a positive peak appears when the bubble leaves the electrode, as shown in Fig. 1c.

The positive and negative peaks have almost the same absolute values of current. The dual-electrode BMAT with a large gap produces two separate AC signals with opposite polarities, as shown in Fig. 1c, where the opposite polarities are caused by the circuit connections to the external electrodes with opposite signs, and the time interval between the two AC signals is determined by the interelectrode distance (8 cm) and the bubble speed. The peak currents in the dual-electrode BMAT are similar to those in the single-electrode BMAT. When the gap between two electrodes is smaller than the diameter of the bubbles, the two AC signals are overlapped, that is, the bubble leaves the first electrode and enters the second electrode simultaneously. Hence, the signal is composed of a positive peak that is twice as large as that in the BMAT with a wider gap, as well as two small negative peaks (Fig. 1c). The energy gained from the three devices is shown in Fig. 1d, which shows that the dual-electrode BMAT with a small gap produces the highest energy among the three. Note that the energy is proportional to the square of the electric current; thus, the larger peak in the third device produces more energy than the two smaller peaks.

From the comparison between the single- and dual-electrode BMAT devices, one may intuitively conclude that an increase in the number of electrodes in BMAT can effectively improve the total energy harvested from a rising bubble. To verify the concept, we investigated the output signals from BMAT devices with varying number of electrodes from two to ten, as described in Fig. 2a, where the interelectrode distance was fixed to be 0.2 cm and the electrical circuit had interdigitated electrodes (IDEs) connected to the external digital multimeter, as described in Fig. 2a. The short-circuit current was measured while increasing the number of electrodes. The output current produced by a single air bubble is shown in Fig. 2b. The number of peaks increased as the number of electrodes increased, and the first and last peaks had the smallest heights compared to the other peaks in the same signals owing to the overlap effect. The number of positive and negative peaks are the number of interelectrode gaps plus two, where the added two peaks correspond to the first and last peaks. However, contrasting with the expectation, the output current continued decreasing as the number of electrodes increased. Fig. 2c shows the total energy harvested from each device using a single air bubble. The effect from the current decrease with the increasing number of electrodes surpassed the increase in the number of peaks. As a result, the total energy slightly increased when the number of electrodes increased from two to four, but it decreased with further increases in the number of electrodes, which remarkably contrasts with the TENG system with multi-electrodes [17,19].

To find the mechanism associated with the decreasing current with respect to the increasing number of electrodes, we designed a dual-electrode BMAT with wing patterns in each electrode, as illustrated in the inset image in Fig. 3a, in which the total area of the electrodes varies while the contact area of bubble and electrode remains unchanged. Hence, the capacitance between the two