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Energy harvesting using air bubbles on hydrophobic surfaces containing embedded charges

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HIGHLIGHTS

- A novel method for harvesting energy using air bubbles in water.
- Higher transducer efficiency than water droplets.
- Improvement of harvesting energy using artificially embedded surface charges.

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ABSTRACT

Technology to harvest electrical power from waste micro-mechanical energy is increasingly in demand. A promising approach lies in manipulating the electrical double layer on hydrophobic surfaces; however, the underlying mechanism is still unclear. Here, we demonstrate that ascending air bubbles in water can produce electrical power in a mode similar to other systems that use descending water droplets. Although the two systems, which are analogous to electrons and holes in semiconductors, are similar in fundamental principle, their detailed electrification mechanisms are significantly different. In the air bubble system, only the pre-existing charges on the surface are involved. However, electrification in the water droplet system is dominated by triboelectric charges accumulated on the surface over time. An air bubble can produce a maximum of nine times more energy than a water droplet due to its advantages in terms of its geometry, hydrodynamics, and electrocircuitry. We also suggest an innovative approach to improve energy-harvesting efficiency using artificially embedded charges.

1. Introduction

The era of the Internet of Things has facilitated rapid growth in the number of portable and wireless electronic devices commonly used while disconnected from an external power source [1,2]. As a result, self-powering schemes are increasingly in demand in various fields such as wearable electronics, sensor systems, and wireless networks [1–3]. During the last decade, significant achievement has been made to seek sustainable energy harvesting methods and to implement the methods in actual applications [2]. A few approaches for converting ambient mechanical, thermal, and chemical energy to electrical energy have been proposed, such as piezoelectric methods that use the mechanical rearrangement of dipole moments [4–7], triboelectric methods based on the charge transfer in solid-solid or liquid-solid interfaces [8,9], and capacitive transduction using electrical double layer (EDL) modulation [10–12]. The adoption of the self-powering scheme can overcome the limited life of batteries and reduce the pollution caused by the disposal of batteries.

Electrification on liquid-solid interfaces is one of the most promising approaches in energy harvesting [10–14]. A reverse electrowetting scheme has been proposed to generate electrical power using liquid-solid interfaces [12,15], but the system requires an initial bias voltage. EDL modulation at the interface between liquid and solid can generate electrical power without an initial bias voltage [8,10]. EDL-based methods can be implemented using a very simple fabrication process [13], and are extremely durable because there are no solid-solid contacts susceptible to mechanical damage. A notable example of EDL modulation system is the water-motion active transducer (WMAT) scheme that was recently reported in Kwon et al. [13]. In this system, a sliding water droplet on a hydrophobic surface carries ionic charges within the EDL near the surface and produces electric power. A WMAT device has the additional advantage in that the system can be used in natural circumstances using raindrops and ocean waves without using external kinetic stress, unlike other EDL-based systems. However,

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relevant studies into these methods have only just begun, and understanding the interaction between hydrophobic surfaces and water is still at the early stages. Lin et al. reported that surface charges on a hydrophobic layer were induced by triboelectricity on the first contact with a water droplet [8,16], and Park et al. investigated the ion dynamics depending on surface wettability and ion concentration in water [14]. In these reports, the charge density in the EDL was assumed to be constant with time after the initial contact with water; however, here we will verify this is not always valid. A better understanding of the mechanism for EDL formation on hydrophobic layers, which is still unclear [17–19], is critical for advancing the electrification scheme on liquid-solid interface.

Here we introduce an energy harvesting device that uses a rising air bubble in water without bias voltage or external mechanical stress. We term this device the bubble motion active transducer (BMAT). The air bubbles and water droplets are analogous to the holes and electrons in semiconductors because an air bubble is the absence of water with ions, similar to how the absence of an electron with charge creates a hole. It has been reported that an expanding air bubbler could be used for energy harvesting in a reverse electrowetting system [15]; however, this requires an initial bias voltage and does not use EDL modulation. Chen et al. demonstrated that an ascending bubble in water can be used as a liquid or gas flow sensor [20]; however the sensing signal strength was too low to harvest energy. Therefore, the use of bubbles for harvesting energy using EDL modulation has not been studied to date.

By comparing these two systems, we clarify the underlying mechanisms in the electrification process generated in the BMAT and WMAT devices, in which surface charges can be involved, pre-existing, triboelectric, and artificially embedded. We find that artificially embedded charges can dramatically contribute to energy harvesting efficiency, and a BMAT device with artificially embedded charges harvests about 18 times more energy than its counterpart without artificial charges. Moreover, the geometric, hydrodynamic, and circuitry differences create a crucial difference in the electrification efficiency, amounting to a maximum of 8.9 times the difference under the same surface charge conditions.

2. Experimental configuration and implementation

2.1. Sample preparation and experiments

Indium tin oxide (ITO) glass substrates were cut into rectangular shapes and electrode patterns were prepared by etching away unwanted ITO using ITO etchant (LCE 12, *Cyantek* Corporation, USA). The substrates were ultrasonically cleaned in acetone for 5 min and dried under a nitrogen gas stream. The substrates were coated with 100 nm thick silicon dioxide (SiO_2) using chemical vapor deposition (CVD). After spin coating with polytetrafluoroethylene (PTFE) (Teflon AF 1600) at 500 rpm for 30 s and 1000 rpm for 130 s, the SiO_2 coated substrate became hydrophobic [21,22]. The PTFE-covered substrate was heated in an oven at 160 °C for 2 h. The thickness of the hydrophobic layer was approximately 500 nm.

All experiments used deionized water exclusively. The rate of water flow in the WMAT and airflow in the BMAT remained constant throughout the experiments at 10 mL min^{-1}. The water droplets were released very close to the top electrode without requiring mechanical impact on the surface.

2.2. Plasma treatment

The PTFE surface was exposed to Ar plasma using a plasma chamber (MINI PLASMA station (ICP-RIE), Plasmart Company, Korea). The gas exposure time and plasma power were 4 s and 20 W. The gas flow rate and gas pressure were 30 cm^3/min and 30 mTorr, respectively.

2.3. Measurements

A programmable syringe pump (Pump 11 elite, Harvard Apparatus, UK) was used to control the volume of air bubbles and water droplets. Open circuit voltages were measured using a mixed domain oscilloscope (MDO 3024, Tektronix, USA). The output currents were measured with a 1.2 MΩ load resistor using a digital multimeter (DMM 7510, Keithley, USA). The electrical power and energy were calculated using the relationship I^2R and I^2RT, respectively, where I is the current through the load resistor with resistance R and T is time. The thickness of the PTFE film was measured using an Alpha-Step IQ surface profiler (KLA-Tencor, USA). The surface potentials of the pristine and plasma-treated PTFE surfaces were measured using electrostatic force microscopy (EFM) (Park systems XE-100, Park Systems, KOREA).

3. Results and discussion

3.1. Analogy between ascending air bubbles and descending water droplets

We fabricated two separate ITO electrodes on a substrate and coated them with a SiO_2 dielectric layer and hydrophobic PTFE layer, as shown in Fig. 1a and b. The substrate was placed at an angle of 45° in a water bath, and the bubble launcher released air bubbles along the surface at a regular rate, as shown in Fig. 1a and described in the Methods section. The equivalent electrical circuit can be represented as shown in Fig. 1c. There are two scenarios under which a bubble can interact with the surface depending on the surface wettability.

On a hydrophilic surface, a bubble moves on a thin liquid film layer sandwiched between the bubble and surface, while on a hydrophobic surface, a bubble moves along a circular three-phase contact (TPC) line and is directly attached to the surface [23]. The air bubble on the PTFE surface clearly behaves according to the second scenario. When a bubble is released from the bubble launcher located far enough from the bottom electrode, the bubble forms a circular TPC line on the solid surface (Fig.1d) and ascends upward due to its buoyancy [24]. The air bubbles on the TPC line sweep ions out onto the surface, in contrast to the alternative method in which the water droplets carry the ions. However, because the bubbles and water drops move in opposite directions, the effect caused by ascending air bubbles from the bottom (B)

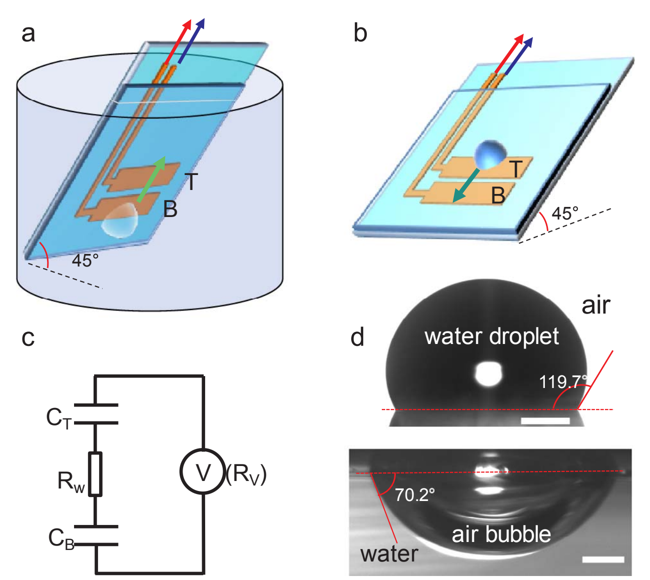

Fig. 1. Comparison between a bubble motion active transducer (BMAT) and a water motion active transducer (WMAT). (a and b) Schematics of the experimental configurations for a BMAT and WMAT. (c) The equivalent circuit for both the BMAT and WMAT. (d) A water droplet on the hydrophobic layer, an air bubble beneath it, and their contact angles. The scale bars are 0.5 mm.