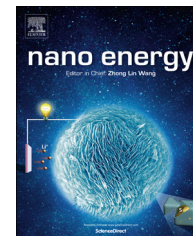


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COMMUNICATION

Generating induced current through the diving-surfacing motion of a stimulus-responsive smart device

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Abstract

Energy conversion from chemical to mechanical forms and then to electricity has experienced an explosive development in recent years. However, most of the current studies are challenged by producing a high output of induced current through cutting the strong magnetic line with a conductive line. Herein, we designed and fabricated a mini-generator to perform a diving-surfacing motion with an intelligent initiation based on pH-responsive materials, and the obtained mechanical energy can be converted into electricity through cutting the strong magnetic line with a conductive line. Under acidic conditions, the device floated on the surface of water, and its locomotion was switched on through the addition of a basic solution. The re-float process was initiated by adding an acid solution and hydrogen peroxide. By investigating the influencing factors of the smart motion, we found that the device that consisted of one pH-responsive part, one hydrophobic part and a quartz cell performed the best under a 0.9% concentration of hydrogen peroxide during the diving-surfacing motion with a high frequency, leading to the highest output of induced current. Moreover, the device with bilateral-pyramidal structure provided the highest diving-surfacing frequency and maximized vertical motion velocity because of its drag-reducing property, achieving the highest output of induced electromotive force.

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Introduction

Inspired by biomotors, researchers have attempted to design a self-propulsion strategy to understand the mechanism of motions, control the motion, and develop potential applications in directed transportation [1,2], drug delivery [3-7], biomimicking [8,9], separation of special cargo [10], manipulation of cells [11,12], and macroscopic supramolecular assembly [13,14]. In addition to the above applications, the production of electrical energy through Faraday's law from mechanical forms originating from chemical power has been a focus of recent research; this process realizes the reutilization of energy resources. Previously, two strategies have been developed to realize the conversion from chemical power to electric energy. One strategy is to generate electricity in coils through the locomotion of a magnet. For example, Osada developed a gel-generator which consisted of a gel rotor equipped with a pair of permanent magnets and a solenoid coil and realized the generation of electricity through the rotation of the gel rotor under the propulsion of a surface tension gradient [15]; similarly, Matsui and coworkers incorporated diphenylalanine peptides into metal-organic frameworks to power the rotation of a device with a permanent magnet via the Marangoni effect and induced the generation of electric power [16]. Chattopadhyay et al. observed the induction of electromotive forces into a Faraday coil by the motions of a composite magnetic particle and Pd nanoparticles, which performed diving/surfacing cycled motion by decomposing hydrogen peroxide [17]. However, because the chemical power is not sufficiently strong to drive the locomotion of a large device, the magnet loaded in the small device displays weak magnetic field intensity. The other strategy is to cut the magnetic line with a conductive line in the vertical direction. We designed a functionally cooperating device that could convert chemical energy into electricity through diving-surfacing cycles propelled by the hydrogen bubbles released from the reaction between magnesium and acid [18]. In our system, we utilized one conductive line to cut the magnetic line produced from the large magnet; the generated power is potentially comparable with that in the above work. However, the propulsion system in our previous work was not sustainable because the motions and electricity generation would stop once the loaded fuel of magnesium ran out [19]; a similar problem occurs in the system driven by the Marangoni effect [20-22]. Therefore, challenges remain in developing a generator with a sustainable property when using a conductive line to cut the strong magnetic line.

In this paper, we fabricated a mini-generator that can convert the chemical energy of hydrogen peroxide into electricity in a diving-surfacing cycle. This cycle is driven by the generation of oxygen bubbles resulting from the decomposition of hydrogen peroxide in response to the pH value. Moreover, we investigated the influencing factors of the controllable motion: the surface wettability, the concentration of hydrogen peroxide and the shape of the device. The results showed that the device with a hydrophobic upper part and a transformable bottom part (from superhydrophobicity to superhydrophilicity) best realizes a controlled locomotion with a switch-on effect; that the frequency of the diving-surfacing cycled motions increases with the increased concentration of hydrogen peroxide; and that the device with a bilateral-pyramidal shape (compared to rectangular and arch shapes) develops the highest

frequency of the induced current. The current study improves the understanding of the existing system of the mini-generator [23,24] induced by the conversion from chemical energy to mechanical energy and then electrical energy.

Experimental section

Materials and methods

HF (40%), AgNO₃ and 1-dodecanethiol (SH(CH₂)₁₁CH₃) (Sino-pharm Chemical Reagent Beijing Co., Ltd.); 1-decanethiol (SH(CH₂)₉CH₃) (Aldrich), 11-mercaptoundecanoic acid (SH(CH₂)₁₀COOH) (Sigma); silicon wafer (GRINM semiconductor Materials Co., Ltd.) were used as purchased. The copper foam was acquired from Anping Xinlong Wire Mesh Manufacture Co., Ltd, China; this foam was a porous film formed by continuous meshes that contained staggered holes with a diameter of approximately 500 μm.

The contact angle was characterized on an OCA20 instrument (Data Physics Instruments GmbH, Filderstadt, Germany). SEM measurements were performed on a Zeiss EVO MA25 at 20.0 kV. Photographs were taken with a Nikon camera (D5000). The current was monitored by an electrochemical workstation (CHI660E).

Fabrication of the pH-responsive smart device

The fabrication processes of the functional parts including the pH-responsive one, the superhydrophobic one, the superhydrophilic and the hydrophobic ones are outlined in Scheme 1a, respectively. The assembly and integration process of the pH-responsive smart device is illustrated in Scheme 1b.

Fabrication of the pH-responsive part

First, a piece of copper foam was folded into an uncovered rectangular box with the dimensions of 15 mm × 15 mm × 7 mm; second, the box was tightly nipped with a silicon wafer by a clamp and immersed into a mixed aqueous solution of AgNO₃/HF (0.02 M/5 M) for 15 min through an electroless metal deposition [25,27], washed with deionized water and then dried in an oven at 65 °C; third, the above box was modified with a mixed monolayer of thiol molecules through the immersion in an ethanol solution containing SH(CH₂)₉CH₃ and SH(CH₂)₁₀COOH (mole ratio=6:4) overnight.

Fabrication of the superhydrophobic part

A similar rectangular box of copper foam without top cover (15 mm × 15 mm × 7 mm) was alternately washed with ethanol and deionized water for three times in an ultrasonic field. Then it was immersed into a mixed solution of AgNO₃ (0.02 M)/HF (5 M) for 15 min and dried in an oven at 65 °C. Afterwards the box was then modified with SH(CH₂)₁₁CH₃ through chemical vapor deposition (CVD) in an oven at 65 °C overnight.

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