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RAPID COMMUNICATION

Hybrid energy cell for harvesting mechanical energy from one motion using two approaches

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Abstract
Harvesting mechanical energy from our living environment is an effective approach for self-powered electronics. One of the key issues is how to extract more electricity from one mechanical motion. Here, we report a hybrid energy cell that consists of a single-electrode based triboelectric nanogenerator (S-TENG) and an electromagnetic generator (EMG), which can be utilized to simultaneously scavenge mechanical energy from one mechanical motion. Due to the contact/separation between the polydimethylsiloxane (PDMS) film and the polyamide (PA) film, the S-TENG delivers an open-circuit voltage (peak to peak) of about 600 V, a short-circuit current of about 3.5 μA with a largest output power of about 0.25 mW (power per unit mass: 0.48 mW/g), which can directly light up tens of commercial light-emitting diodes (LEDs) in series. From the same mechanical motion, the EMG can produce an open-circuit voltage of about 3 V, a short-circuit current of about 1 mA with a largest output power of 0.58 mW (power per unit mass: 5.31 μW/g), which can directly light up tens of LEDs in parallel. Moreover, the hybrid energy cell exhibits a better charging performance than that of S-TENG or EMG for charging a capacitor. This work presents a hybrid energy cell technology to simultaneously scavenge mechanical energy from one mechanical motion for self-powered electronics.

Introduction

The emerging technologies for harvesting mechanical energy from our living environment to power some personal electronics have attracted increasing interest due to the extensive availability of mechanical energy [1-3]. Currently, the conventional approaches of mechanical energy harvesting have

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been actively developed by using the electromagnetic and piezoelectric effects [4-6]. In 2012, the coupling between triboelectrification and electrostatic induction has been utilized to fabricate the triboelectric nanogenerators (TENGs) for scavenging the mechanical energy from impacts, sliding, and rotations [7-11]. The recent invention of single-electrode based TENGs (S-TENGs) have expanded the potential applications further and decreased the fabrication cost of the devices [12-14]. Although different types of generators have been demonstrated to scavenge the mechanical energy, one of the key issues is how to obtain more electricity from one mechanical motion. A possible approach is to utilize the two kinds of generators to simultaneously scavenge the mechanical energy from one motion. The difficulty is how to design the two generators that can simultaneously and effectively work under the same mechanical motions.

Usually, the purpose of developing hybrid energy cells is to simultaneously/individually harvest several kinds of energies by using an integrated device, so that the sensors or personal devices can be powered by using whatever energy that is available at their working environments [15,16]. Although some hybrid energy cells have been designed to simultaneously/individually scavenge the mechanical, solar, and thermal energies [17,18], there are few reports about the hybrid energy cells that can simultaneously scavenge mechanical energy from one motion, which can not only increase the conversion efficiency of the device, but also greatly expand the potential applications of the hybrid energy cells. The TENG can scavenge the mechanical energy from the contact/separation between two triboelectric materials, and the electromagnetic generator (EMG) can also work from the relative movement between the magnet and the coil [19-21]. By integrating the triboelectric materials, the magnets, and the coil, it is possible to utilize the TENG and the EMG for simultaneously harvesting the mechanical energy from the same mechanical motions. Although the previous integration of two generators shows that a mass was used as the driving force by vibration in a cylindrical tube to deliver the output of the generators [20], the working mode of the TENG with double electrodes requires that the electrode on the mass needs to be connected with a conductive wire for the effective output, which may limit the movement distance of the mass and the working life of the device due to the broken wire induced by the mass vibration [22]. The S-TENG is an ideal solution for the long distance movement of the mass in the device and the long working life of the device due to no need of the electrode or conductive wire attached on the mass [23], which may be used to integrate with the EMG for the hybrid energy cells.

In this article, we report a hybrid energy cell that consists of an S-TENG and an EMG, which can simultaneously harvest mechanical energy from one motion. The fabricated S-TENG is based on periodic contact/separation between a polydimethylsiloxane (PDMS) film and a polyamide (PA) film. By utilizing the coupling between triboelectric effect and electrostatic effect, the periodic change in distance between the PDMS film and the PA film can result in the charge transfer between the Al electrode at the bottom of the PA film and the ground. The S-TENG delivers an open-circuit voltage (peak to peak) of 600 V, a short-circuit current of 3.5 μA with a largest output power of about 0.25 mW, which can directly light up tens of commercial light-emitting diodes (LEDs) in series. From the same mechanical motions, the EMG can produce an open-circuit voltage of 3 V, a short-circuit current of 1 mA with a largest output power of 0.58 mW, which can directly light up tens of LEDs in parallel. The produced energy by the hybrid energy cell can be also stored in a capacitor or a Li-ion battery. This work is an important progress toward the techniques of simultaneous harvesting mechanical energy and the practical applications of the hybrid energy cells as the energy power sources for powering some electronics.

Experimental section

Fabrication of the hybrid energy cell

The fabricated hybrid energy cell consists of an S-TENG and an EMG in an acrylic tube. The micro-structured PDMS films were fabricated by using a Si master with the surface of pyramid structures. The mixture of PDMS elastomer and cross-linker with a 10:1 ratio (w/w) was spin-coated onto the Si master. The PDMS film with the surface pyramid micro-structures were peeled off from the Si master after it was cured at 353 K for 1 h in an oven. Actually, the hybrid energy cell consists of a fixed part with a top-opening hollow tube surrounded with coils of 5000 turns at the bottom of the tube and a floating part with a magnet in acrylic cylinder that was connected with a spring at the both sides. When the floating part vibrates in the acrylic tube, the contact/separation between the PDMS and the PA film can induce the charge transfer between the Al electrode and the ground, resulting in the output of the S-TENG. Under the same mechanical motions, the relative change in distance between the magnet and the coils will result in the output of the EMG. The weights of the S-TENG and EMG are about 0.52 g and 109.23 g, respectively.

Measurement of the fabricated devices

The output current signals of the hybrid energy cells were measured by a low-noise current preamplifier (Stanford Research SR570). The output voltage signals of the hybrid energy cells were connected with an electrometer with very large input resistance. The output performance of the hybrid energy cell was measured on an electro-dynamic shaker under the different vibration frequencies.

Results and discussion

The fabricated hybrid energy cell consists of an S-TENG and an EMG in an acrylic tube, as schematically illustrated in Fig. 1a, where a cylindrical mass was connected with two circular acrylic sheets by using two springs and a magnet was put into the cylindrical mass. The coils of about 5000 turns were fabricated at the bottom of the acrylic tube. Since it is difficult to see the contact/separation between the PA and the PDMS at the bottom of the acrylic tube in the 3-D image, the inset in Fig. 1a illustrates the 2-D image at the bottom of the device, clearly showing the detailed layers. The PDMS film at the top of the mass can be used as the triboelectric material for fabricating another S-TENG on the top of the acrylic tube. Since the S-TENGs at the two ends of the acrylic tube have the