ELECTROSTATIC/TRIBOELECTRIC HYBRID POWER GENERATOR USING FOLDED ELECTRETS

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ABSTRACT

Recently, electret-based electrostatic and triboelectric energy harvesting devices have demonstrated their great potential in converting ambient mechanical energy to electrical energy due to their merits of low cost, easy formation and long-term stability. For electret-based generators, the performance of the state-of-the-art MEMS energy harvesters mostly falls into the range of nW or µW level, limiting their potential applications. For triboelectric generators, the output power is severely constrained by the effective surface charge density that only relies on the contact triboelectrification. Herein, we demonstrate a hybrid power generator with folded electrets, which takes the merits of non-contact electrostatic induction by high residue charge within electrets as well as contact triboelectrification by increased surface area. High output power can be readily achieved. Triggered by gentle finger tapping, the instantaneous peak-to-peak output voltage and short-circuit current of up to 1000 V and 0.11 mA have been achieved, which are capable of directly lighting up hundreds of off-the-shelf LEDs. The outcome of this work demonstrates the possibility of using such hybrid generators for wearable and portable electronics.

INTRODUCTION

Recent advances in internet of things (IoT) and low-power electronic devices have given rise to tremendous interests in developing self-sustained microsystems. Conventional methods by using electrochemical batteries may not be the choice due to their limited lifespan and difficulty in maintenance. Energy harvesting refers to the process of capturing and transforming untapped ambient energy into the electrical energy. Such energy harvesters, acting as a replacement of conventional batteries or as a secondary power source, would be an invaluable alternative to provide sustainable energy for low-power wireless electronic devices [1].

Kinetic or mechanical energy is ubiquitously existed in our environment and readily available in various basic forms of activities and motions, such as human limb movements, structural and machinery vibrations. Thereby, it is an excellent candidate for energy harvesting. Generally, mechanical energy can be transformed to electricity by two strategies: exploiting the mechanical strain and making use of relative movement. For the strain-based harvesters, the energy can be extracted from the structural deformation by employing active smart materials with energy converting capabilities, such as piezoelectric materials. Piezoelectric harvesters generally work on the bending of some special piezoelectric materials such as PZT or PVDF. These materials are able to convert the mechanical strain fluctuation to charge movement via direct piezoelectric effect. As for the relative-movement harvesters, electrical energy can be created by the relative displacement of two components through electromagnetic, magnetostrictive electrostatic or triboelectric energy transduction mechanisms. Specifically, electromagnetic or magnetostrictive harvesters operate based on the Faraday's law of induction where electricity is generated due to the magnetic flux change in a circuit coil [2]. The magnetic flux change can be induced by a moving magnet or deformation of magnetostrictive materials. Electrostatic harvesters are developed based on the capacitance change of variable capacitors with a constant voltage bias. The bias can be provided either by an external source or pre-charged electrets. Triboelectric harvesters are based on triboelectric effect where electron migration is created when two materials with significantly dissimilar electron affinities are brought to physical contact.

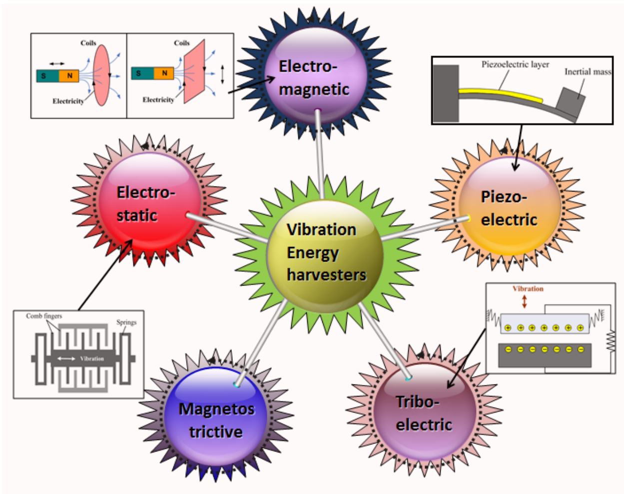

Figure 1: Five transduction mechanisms: electromagnetic, piezoelectric, electrostatic, magnetostrictive and triboelectric transductions to convert kinetic energy to electricity

Figure 1 summarizes the five basic transduction mechanisms to convert kinetic energy to electrical energy. Among these reported mechanisms, electret-based electrostatic and triboelectric energy harvesting devices are advantageous in terms of low cost, easy formation and long-term stability and therefore have great potential in energy harvesting to power wireless electronic devices and microsystems.

There are several issues need to be addressed before applying energy harvesting technologies in the real application. Firstly, the output power of the state-of-the-art MEMS-scale energy harvesters is still in nW to μW level, which limits their range of applications in our daily life [3]. Secondly, most electret-based electrostatic generators focus on silicon-based MEMS technology. This is beneficial for integration with semiconductor electronics and massive production [4]. Nevertheless, it may not be suitable for flexible and wearable applications due to the fragile properties of silicon materials. Further exploration of developing flexible and durable devices is needed. Thirdly, for triboelectric generators, the output performance is highly dependent on the charges created by contact triboelectrification effect [5]. The charge storage capability of contacting polymer materials is not fully exploited. Mechanical failure of nanostructured surface after long-term abrasion is also a concern.

In this paper, we present a novel electrostatic /triboelectric hybrid power generator using folded electrets, which addresses the above concerns and exhibits several advantages. Firstly, the whole device is constructed on a 3D multi-layered architecture which is not only bendable in the horizontal direction but also stretchable in vertical directions. It can be easily used in wearable applications due to its lightweight and good flexibility. Secondly, the multi-layered structure increases the contact area, which enhances both triboelectrification effect and capacitance variation for electrostatic energy generation and therefore multiplies the overall performance. Thirdly, by employing pre-charged electrets, power density in the electrets can be maximized and high output performance can be readily obtained without relying on complicated surface modification process. Therefore, several milli-watt power can be obtained and used to light up hundreds commercial LEDs simultaneously.

DEVICE CONCEPTUATION

A 3D schematic of the proposed hybrid power generator with folded multi-layered electrets is shown in Figure 2 (a). It consists mainly of two conductive sheets acting as two electrodes of the variable capacitors. One electrode is made of a conductive sheet comprising a copper/LCP/copper substrate, which has the merits of good conductivity, flexibility and excellent foldability [6, 7]. Micro/Nano sized copper particles are obtained by partially etched in the copper etchant. These particles could significantly increase the contact surface area of the both sides of the Copper/LCP/copper substrate, giving rise to enhanced performance of the overall triboelectrification effect.

The other electrode is sandwiched with FEP electret thin films on both sides. The FEP electret thin film could perform both as insulation layer between two conductive electrodes and as a biased voltage source to create electrostatic induction charges. Each layer could be regarded as a separate capacitor and the whole structure could be regarded as multiple capacitors connected in parallel. The entire hybrid generator is constructed as a 3D multilayer structure, which is beneficial to overall electrostatic induction effect within a compact and light-weight design. The capacitance variation and contact area can be multiplied by 2N (N is the number of plate layer). Thereby, high performance can be readily obtained without modifying the surface of polymer electrets.

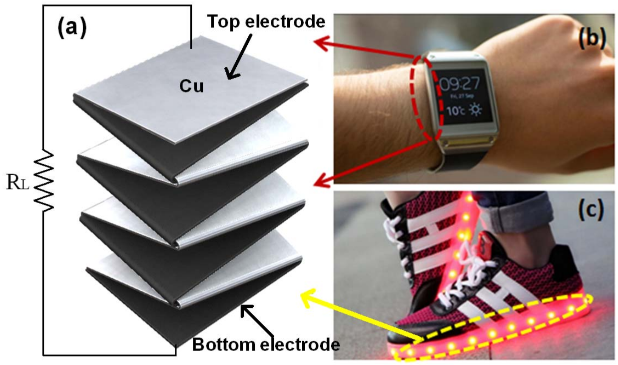

Figure 2: (a) 3D schematic of electrostatic/triboelectric hybrid power generator using folded multilayer electrets; potential applications of such generator for (b) digital watch; (c) shining shoes to improve comfortableness with no battery-replacement concern

Figure 2 (b) and (c) show the potential applications in a digital watch and shining shoes to improve comfortableness with no battery-replacement concern. The tiny multi-layered generator can be installed at the back of the digital watch. When relative movements between the watch and wrist occur, varying capacitance will convert the mechanical motion to electrical power. If the relative movement is large enough and induce the physical contacts between layers, the output of power can be further enhanced by triboelectric mechanism. The light-weight and flexible generator can also be installed on commercial shining shoes to replace electrochemical batteries without sacrificing the overall comfort level. Besides, the success of the proposed generator can be further applied to a broad range of applications such as biomedical sensing like heart beat/pulse sensing, finger print identification, mechanical triggering or keyboard tapping, etc.

OPERATING PRINCIPLES

Triboelectric energy harvesting works based on the coupling of triboelectrification effect and electrostatic induction. They operate mainly on four energy conversion schemes, such as vertical contact-separation scheme, lateral sliding scheme, single-electrode scheme and freestanding electrode scheme [8]. For vertical contact-separation scheme, the charge is created when the top electrode collides with bottom dielectrics with different electron affinity. The charge on the dielectrics would induce opposite charge in the back electrodes. The capacitance change would lead to charge flowing back and forth between the two electrodes.

For electret-based electrostatic energy harvesting, the electrical power is generated due to the varying capacitance between two electrode plates. Electret materials serve as a negative/positive permanent surface voltage source. Similar to the triboelectric power generators, electret-based electrostatic harvester normally operates in two configurations: in-plane overlap varying type [9, 10] and out-of-plane gap closing type [11, 12].

In this work, we introduce corona-charged electrets into conventional triboelectric harvester and form the hybrid generator. The pre-implanted charges play an important role in the whole energy generation process. The charge circulation during the contact-release cycles is shown in Figure 3. At the original state, the counter electrode is separate from the charged electrets/bottom electrode (Figure 3(a)). When the counter electrode moves downward due to the external excitations, charge is created in the counter electrode due to the electrostatic induction by the pre-implanted charges in the electrets (Figure 3(b)). As the counter electrode moves further and collides with the FEP electrets, the triboelectric effect takes place. It accompanies with the enhanced electrostatic induction (Figure 3(c)). Once released, the counter electrode moves back due to the restoring force, resulting in the induced charges flowing back to the bottom electrode (Figure 3(d)).

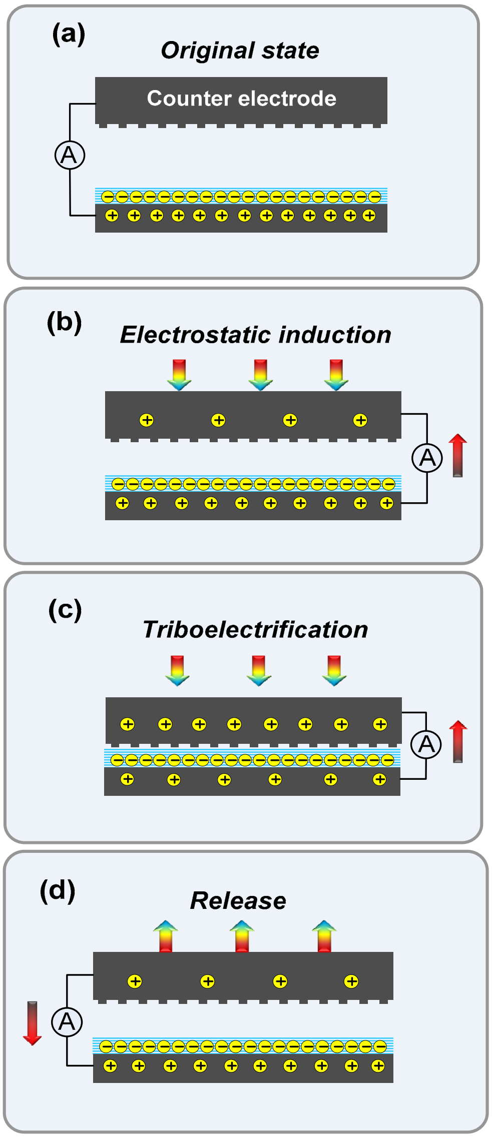

Figure 3: Schematic illustration of charge flow by hybridizing triboelectrification and electrostatic induction effects for high-energy conversion efficiency

DEVICE FABRICATION

Currently, there are several methods used to form electrets via charge implantation, such as thermal poling, contact charging, corona charging, electron gun injection and electron beam irradiation. Among these, corona charging is one of the most widely adopted technologies in both laboratories and industries. Figure 4 shows a schematic of the triode-needle-grid corona charging setup. In negative corona charging process, negative ions (CO_3^-, NO_3^-, NO_2^-, O_3^-, O_2^-) are generated around the needle with high negative voltage. The charges are then driven into the electrets by the strong electric field formed between the bottom electrode and the grid. FEP is used as electret materials for corona charging since it has very high dielectric strength up to 2.6×10^8 V/m, much higher than the breakdown electric field of the air (3×10^6 V/m). In the current experiment, the FEP thin film with thickness of 50 μm is mounted on the two sides of the copper electrodes.

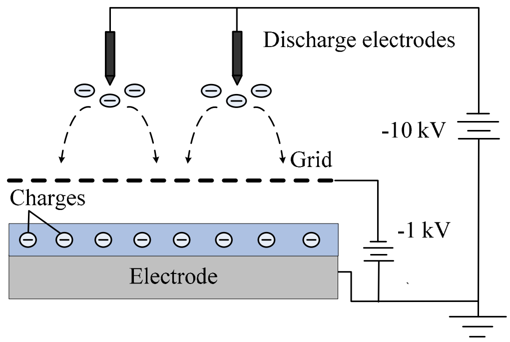

Figure 4: Schematic of triode-needle-grid corona charging setup

After corona charging the FEP thin films on both sides of the Copper/LCP/Copper substrate, the 3D hybrid power generation device is constructed through a simple paper folding process. The output power of electrostatic induction itself has a relationship with V and dC/dt as $P \propto V^2 \cdot dC/dt$, where V is the electret surface potential and dC/dt is the capacitance variation rate. Thereby, the output power from the developed 3D multi-layer structure is 2N times larger than that of a conventional electret-based electrostatic energy harvester, where N is the layer number. This will be further enhanced once contact and triboelectrification occur.

TESTING RESULTS

The fabricated electrostatic/triboelectric hybrid power generator is simply characterized by gentle finger tapping. The two terminal electrodes are connected to an external resistor and the electrical output signal is acquired by a data acquisition module (NI USB-6289 M series). Figure 5 shows the output voltage by continuous finger tapping. It can be seen that the peak-to-peak open-circuit voltage can go as high as 1000V. The short-circuit current can reach 0.11 mA. The performance of the hybrid generator is then evaluated by directly delivering energy to LEDs connected in series without any extra power conditioning circuit. With gentle finger tapping on the top of the fabricated device, the generated power can easily light up hundreds of

LEDs. It demonstrates the feasibility and huge potential of the proposed hybrid generator as power supply for low-power wearable devices. The finger tapping experiment process with the fabricated device is shown in Figure 6 (a). Figure 6 (b) is one snapshot of flashing 120 LEDs by gentle finger tapping to demonstrate the power generation capability of the fabricated device. The hybrid generator will be tested for other wearable devices in the future.

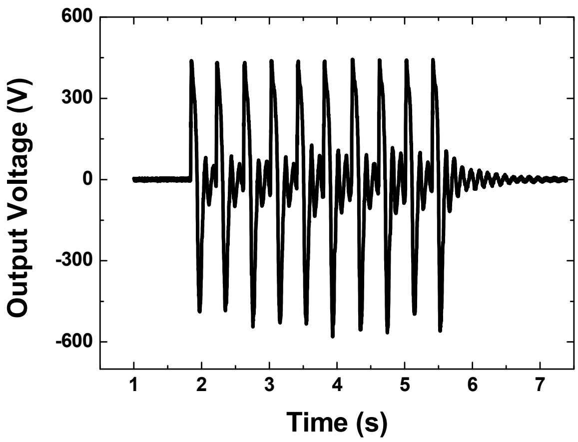

Figure 5: Output voltage of the proposed hybrid generator by continuously finger tapping

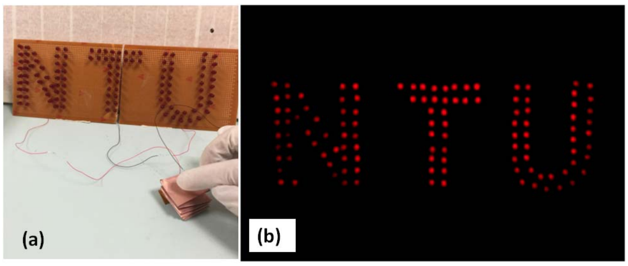

Figure 6： (a) Demonstration by tiny finger tapping of hybrid power generator; (b) Video demonstration of lighting up 120 LEDs

CONCLUSIONS

In this paper, a flexible multilayer generator hybridizing triboelectrification and electrostatic induction effects has been successfully developed. By gentle finger tapping, several mili-watt power is generated, which is able to light up hundreds commercial LEDs simultaneously without any extra power conditioning circuits. The generator is both bendable and stretchable, which indicates great potential to integrate them as power source for wearable and portable electronics.

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