LIQUID METAL DROPLET BASED TUBE-SHAPED ELECTROSTATIC ENERGY HARVESTER

Haotian Chen[1], Yu Song[2], Mengdi Han[2], Bocheng Yu[2], Xiaoliang Cheng[2], Xuexian Chen[1], Dongmin Chen[1,] and Haixia Zhang[1,2,*]*

[1]Academy for Advanced Interdisciplinary Studies, Peking University, CHINA

[2]Institute of Microelectronics, Peking University, CHINA

ABSTRACT

This paper presents a liquid metal droplet (LMD) based tube-shaped electrostatic energy harvester, which for the first time, utilize LMD as tribo-electrification material. This device use double-helix electrodes around the tube to obtain cycle transferred charges which multiple output frequency and enhance efficiency tremendously. As using the tube-shaped structure, this generator can be wound up to user's wrist, which is very convenience to harvest energy from human movement. The voltage output can be reached to 3.52 V when user swung arm irregularly. It gives great potential to power up the wearable electronics.

INTRODUCTION

With rapid increasing number of portable electronics, the power supply has become an urgent problem around the world. Like automatic winding watch, collecting energy from human motion to charge wearable devices is a tempting way to solve the energy problem. Different methods based on different mechanisms, including electromagnetic [1, 2], piezoelectric [3-6], and electrostatic [7-10], have been exploited.

Integrating energy harvesters into devices is a common way to collect vibration energy. However, the amount of energy is limited due to the narrow space of wearable devices. Actually, there is still plenty of room in portable electronics such as wristband. Few people make full use of the bands because traditional energy harvesters can't deform into that shape. Thanks to its unique property, triboelectric energy generator (TEG), one of electrostatic energy harvester, based on contact electrification and electrostatic induction [11, 12], do not rely on specific materials such as permanent magnets or piezoelectric materials. Some researchers utilized liquid to fabricate a triboelectric energy generator [13]. Compared to solid TEG, liquid TEG can overcome the limitation of shape and space.

In this work, we design a tube shape TENG with a liquid metal droplet into it as one of triboelectric pair. On the one hand, the tube shape generator can be wound up into the shape of watch band or bracelet band and then connected to the main device, which can take full advantage of the space of band and save more space for the part of processor and battery. On the other hand, as the liquid metal has amorphous shape, it ensures the total contact and guarantees large amount of charges transferring.

EXPERIMENT

Structure of generator is illustrated in Figure 1. The main body of the generator is a polyethylene (PE) hollow tube. Double-helix-shaped copper electrodes are entwined around the tube. A droplet of liquid metal, Hg is injected into the tube. After that, two ends of the tube are concealed to prevent Hg evaporating. Due to the big surface tension, LMD can move freely in the tube. Specifically designed double-helix-shaped copper electrodes ensure that whatever direction and angle the droplet flows along, the device can generate the moving energy. The size of the device is displayed in Table 1

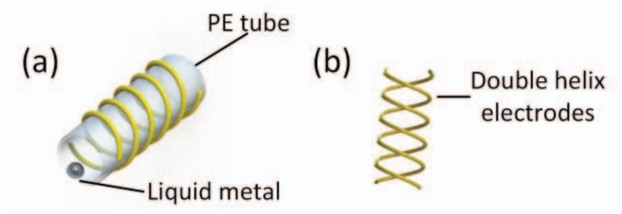

Figure 1: (a) Schematic illustration of the device. (b) Double-helix electrode.

Table 1. Parameters of the of the energy harvester

Electrode	**length**	**width**	**Screw pitch**
	3cm	2mm	2mm
PE tube	**Length**	**Outer diameter**	**Inner diameter**
	4cm	11.80mm	10.24mm
Liquid metal	**Mass**	**Volume**	
	0.7g	0.05cm^3	

Figure 2(a) illustrates the process of contact electrification. At first, there is no charge accumulated on the PE surface. Once the LMD is injected into the tube, according to their different abilities in attracting electrons, the interface of LMD will carry positive charges and corresponding PE surface will carry negative charges. Then the LMD move inside the tube, all the inner PE surface will gain negative charges and the same amount of positive charge will distribute on the LMD surface.

There are two working conditions. One of them is that LMD moves in a horizontal direction along the wall of the tube. Figure 2(b) describes its working principle. Initially, the LMD is located on the left electrode and negative charges accumulated on it due to electrostatic induction. When the LMD flows from electrode 1 to electrode 2, the moving droplet affects the charges distribution, driving electrons moving from electrode 1 to electrode 2 and generate a transient current. With double-helix-structured electrodes, when flowing along the tube, LMD drives electrons transferring between two electrodes several times, which up-convert output frequency and enhance efficiency dramatically. This working condition plays a leading role of energy harvesting.

The other condition is that LMD moves up-and-down in the tube, which occurs as accessional condition of the main working condition because it is very easy for LMD to slip on the PE surface. Figure 2(c) describes this process. At first, LMD stays on the electrode 1. When there comes a shake, the droplet bounces up and approaches to the electrode 2 thanks to the double helix electrodes design. During this process, changed position of the LMD leads electrons flow from electrode 1(bottom electrode) to electrode 2(top electrode), there generates a current flow from electrode 2 to electrode 1.

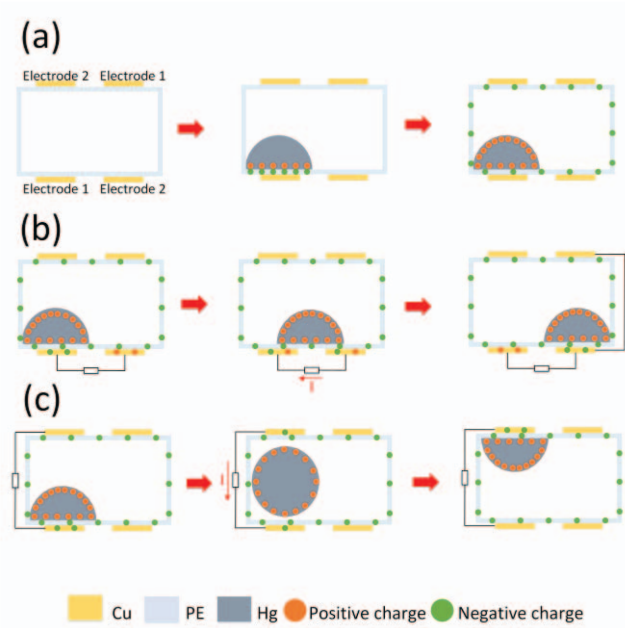

Figure 2: (a) Surface charge formation process. (b) Working principle of horizontal mode. (c) Working principle of vertical mode

SIMULATION

The output performance of this device is analyzed by FEM method using 2D electrostatic model. The parameters of the model are specifically defined following the actual size of the generator as shown in Table 1, except surface charge density and the size of LMD. Surface charge density is defined according to previous literatures and shape of LMD is approximatively abstracted into a rectangle.

The open-circuit outputs of both working conditions are first investigated. Figure 3(a)-(d) demonstrate the first working condition. It can be seen that open-circuit voltage changes periodically as the LMD slips along the tube. When LMD is approaching electrode 1, the output keeps increasing until the droplet covers the electrode totally. After that, output begins to decline before the LMD reaches the location of electrode 2. The process repeats as the LMD moves, which means that LMD moves from one end to the other can result in electrons transferring several times. If we increase the screw number and add a rectifier to connect the device, the efficiency will increase dramatically. The other working condition is simulated as Figure 3(e)-(h). Obviously, the extreme values are reached when the LMD fully contacts lower surface and upper surface, respectively.

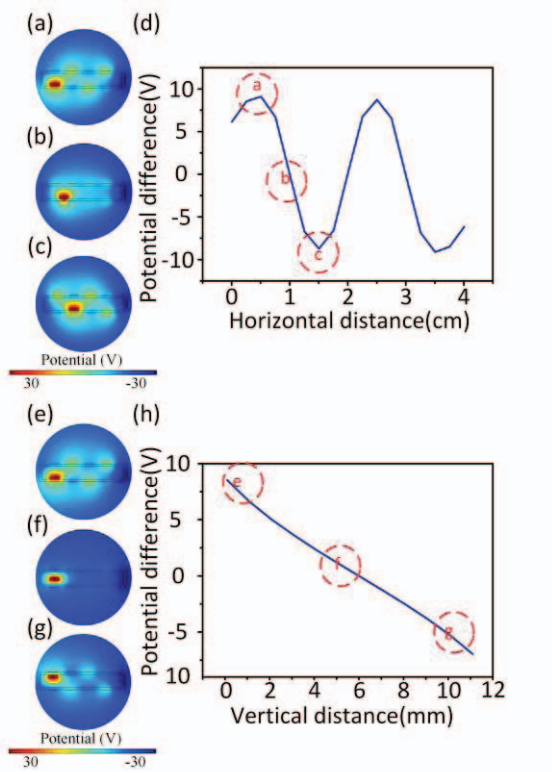

Figure 3: Simulation results of potential difference. (a)-(c) Hg located at X=0.5, 1, 1.5cm. (d) Sliding process. (e)- (g) Hg located at Y=0, 5, 10mm. (h) Rising process.

The size of LMD influences the output, which is one of important parameters to design the device. As the second working condition is accompanied by the first working condition, we only focus the horizontal mode here. The size of the tube and electrode is fixed while the length of LMD changes. We define the length of electrode as el, the gap between electrode as g and the length of LMD as l. We analyze the open-circuit voltage when l=0.5el, el, el+0.5g, el+g, 1.5el+g and 2el+g, as shown in Figure 4(a). It can be concluded from the simulated results that as the length of LMD increases, the voltage increases at first and then decreases and reaches the maximum when l equals el+g. The location where the device gets the most output also shifts as the length of LMD changes. Increasing length of LMD also leads to decreasing number of cycle. So there exists an optimum length for the device to operate at the most efficient condition.

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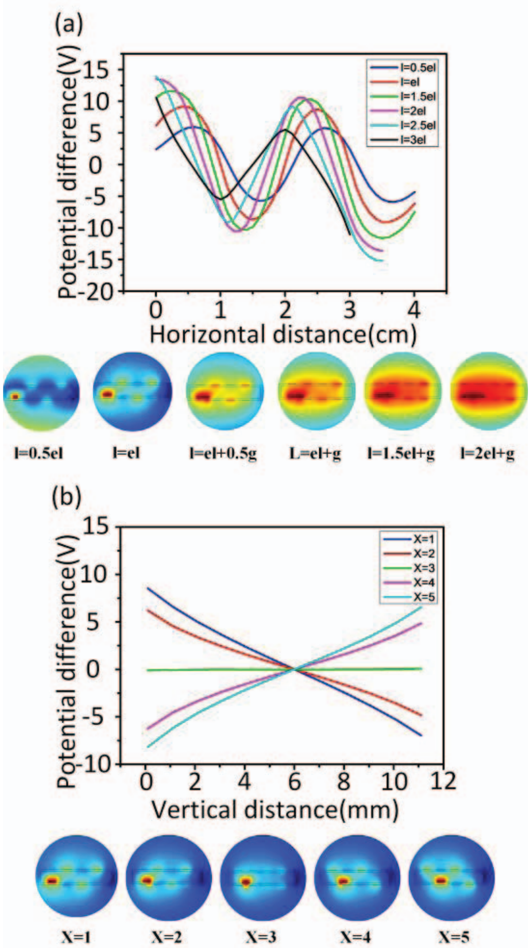

Figure 4: (a) Different sizes of LMD influence the open-circuit voltage in the first working condition. (b) Different positions of LMD influence the output performance in the second working condition.

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The location where LMD bounces also influences the performance when second working condition happens. The simulated results are displayed in Figure 4(b). X is the symbol of LMD's position, which represents the position is totally above the electrode 1, partly above the electrode 1, right above the gap between electrodes, partly above the electrode 2 and totally above the electrode 2, respectively. It is obvious that voltage output is much higher when LMD is close to the electrodes.

RESULT AND DISCUSSION

Experimental measurement was operated using a vibration system, which includes an oscilloscope with wave generation module (Agilent DSO-X 2014A), a modal shaker (JZK-10), and a power amplifier (SINOCERA YE5871A).

Figure 5(a)-(b) presents the device's output voltage and current waveform. 30.6 V peak-to-peak voltage and 298 nA peak-to-peak current can be obtained. Figure 5(c) shows waveform of a single cycle output voltage, which proves that alternative electrodes can multiply frequency.

To study how volume of liquid metal influences the output, we inject 0.7g and 1.4g Hg into the PE tube, respectively. 0.7g Hg ensures that the diameter of the contact area of LMD and the tube satisfied the condition where the length of LMD equals to the sum of electrode's length and gap length. Larger volume decreases the output voltage because enlarged volume results in enlarged contact surface, which reduces the voltage potential difference between neighboring electrodes. This result supports the simulation result.

The generator can charge a 1 μF capacitance to 1.81 V in 150 s at 2 Hz (Figure 6(a)). Average power of 727 nW can be obtained at 100 MΩ load (Figure 6(b)).

As copper electrode is double-helix-structured, the device can be bent with little influence on conductivity. In this way, the device can be wound up and become a shape of wristband. Figure 7(a) demonstrates that people can easily wear around his wrist. Just like traditional self-winding watch, whenever people swing his arm, the LMD will be driven to flow along the tube by inertia. In this way, the moving LMD leads electrons transferring between electrodes and harvests the energy. Figure 7(b) is the test result when researchers swung his arm irregularly. The voltage output can be reached to 3.52 V.

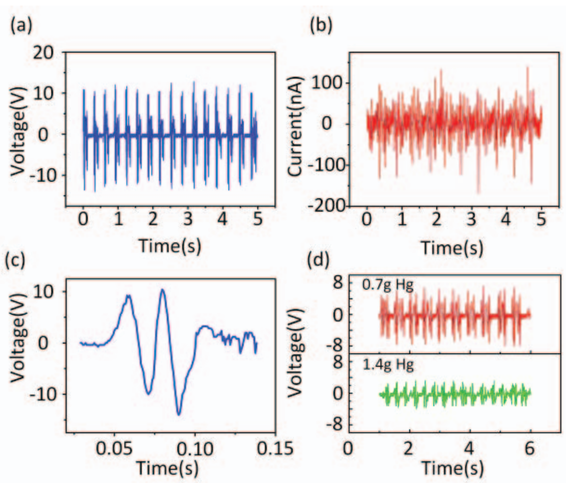

Figure 5: (a) Waveform of output voltage. (b) Waveform of output current. (c) Single cycle of output voltage. (d) Output voltages of different volumes of liquid metal.

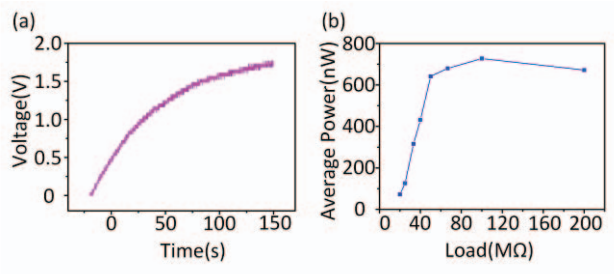

Figure 6: (a) Charging for 1uF capacitance. (b) Average output power under different external resistance loads

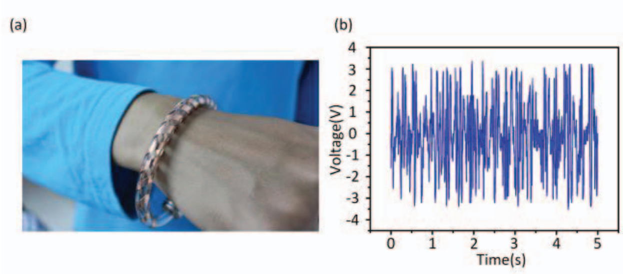

Figure 7: Output voltage of the device winding around human wrist

CONCLUSIONS

In summary, we design and fabricate a triboelectric energy generator, which utilizes LMD as one of triboelectric pair. The unique tube shape combines the LMD making it suitable to wear around wrist to harvest the energy from human motion. The double helix structured electrodes ensure the device can work no matter what direction the LMD flows or bounces. Two working conditions are analyzed. One is the horizontal mode. LMD flows along the tube and drives electrons flowing between two electrodes alternately due to that LMD carries positive charges and PE tube carries negative charges. The size of LMD will impact the performance of this working condition. When the length of LMD is equal to the sum of electrode's length and gap length, the open-circuit voltage can get its maximum value. The length of LMD also influences the number of cycle when it flows from one end to the other. The other working condition is vertical mode. LMD bounce up and down due to outer shake. This mode is usually accompanied by the former one. The location of LMD will deeply influence the output in this working mode. The more area the LMD covers above the electrode, the better performance the device obtains. Testing results show that this TEH can produce peak output voltage of 30.6 V and current of 298 nA at 100 MΩ external resistance, with a corresponding power density of 727 nW. Benefiting from its tube shape and double-helix-structured electrodes, it can be wound around a user's wrist to harvest the energy from human motion with little decline of output performance.

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CONTACT

*H.X. Zhang, Tel: +86-10-62767742;
zhang-alice@pku.edu.cn
*D.M. Chen, Tel: +86-10- 62757181;
dongminchen@pku.edu.cn