Vibrational Energy Harvester based on Electrical Double Layer of Ionic Liquid

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Abstract. To boost the output of the vibration energy harvester an order of magnitude higher, we devised a high-performance energy harvester taking advantages of the two characteristics of ionic liquid, namely variable deformation of liquid and the electrical double layer between ionic liquid and metal. The electrical double layer is approximately 1nm thick and works as insulator within the voltage range of ±2.0V. Therefore, we can obtain quite high capacitance(1-10μ/cm^2). Squeezing and drawing ionic liquid between a pair of vibrating electrodes, we can obtain a μW-class energy harvester.

1. Introduction

The concept "Internet of Things[1]" is attracting much attention to realize a comfortable life with the data from wireless sensors installed in all places. Energy harvesting is a key for practical wireless sensor networks because it can eliminate periodical battery change. Energy harvesting is expected as the power source for sensor nodes because they work without maintenance and supply sensors with power until they get broken. Especially, the vibration type attracts much attention for its wide applicability.

There are 3 types of energy harvesters, a piezo type; a capacitive type; and an electromagnetic induction type. The electromagnetic induction type needs large magnets and structures and it becomes bulky. For this reason, this type is incompatible with MEMS device. To replace batteries of the wireless sensor nodes by energy harvesters, there are various difficulties such as low power generation and the narrow band width. Wireless sensor nodes consume 100μW to transmit data over 10m and the ambient vibrations associated with the bridge swing or human motion are composed of mainly low frequency under 10Hz[4][5]. Energy harvesters must generate power from such low frequency vibrations that exist abundantly in the environment. Due to its high spring constant and small mass, the resonant frequency of the piezo type tends to be high. To decrease the frequency, low spring constant and large mass are essential[2]. Thus, the structure becomes really fragile. Current devices cannot satisfy the requirement of generating large power from the low frequency source. We devised the capacitive type with ionic liquid to improve the robustness and output source. Taking the advantages of the characteristics of ionic liquid, the arbitrary deformation of liquid[6] and the high capacitance, we can fabricate a high-power energy harvester of the low resonant frequency and solve these problems. Just squeezing and drawing the ionic liquid, we can generate power. It is possible to eliminate a spring-mass structure and improves the robustness with ionic liquid. Furthermore, ionic liquid automatically forms electrical double layer of 1nm in thickness. It is unnecessary to make micro-gap like capacitive type based on the electrets[3]. The nano-gap makes the capacitance

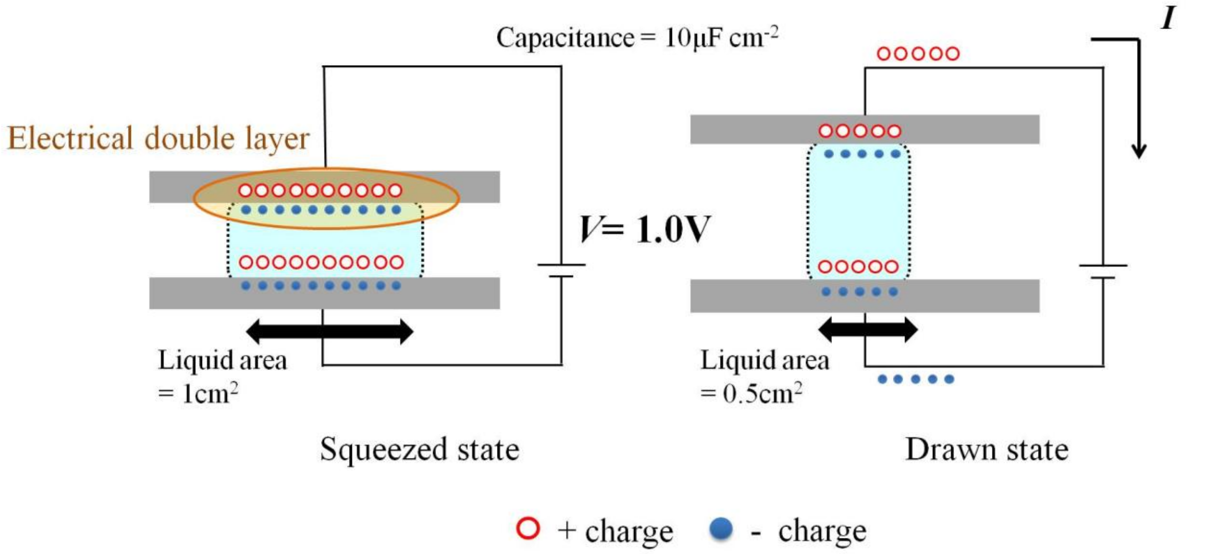

Figure 1. Schematic representation of the squeezed state and drawn state and calcuration. Narrow the gap and the contact area of the ionic liquid and electrodes changed. Thus, the charge at the electrodes changes and current occurs.

extremely high(μF) and we can obtain a large output. In this paper, we propose a new power generation principle based on ionic liquid.

2. Concept

Ionic liquid has various unique characteristics such as the formation of the electrical double layer, extremely low vapor pressure and resistance to high temperature. For this reason, remarkable attention has focused on devices using ionic liquid. The thickness of the electrical double layer is only 1nm and ionic liquid works as insulator within the voltage range called potential window. Thus, ionic liquid has quite high capacitance in the order of 10μF cm^{-2}[7]. Based on the large capacitance and its variable deformation, we devise a new energy harvester. Figure 1 shows the device structure and power

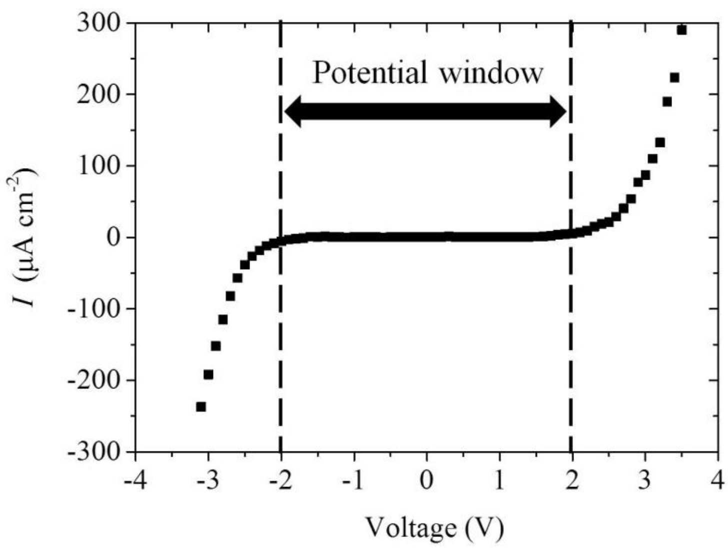

Figure 2. The potential window of the ionic liquid. ($[DEME]^+[TFSA]^-$)
potential window -1.9V to 1.9V : In this range, ionic liquid works as insulator.

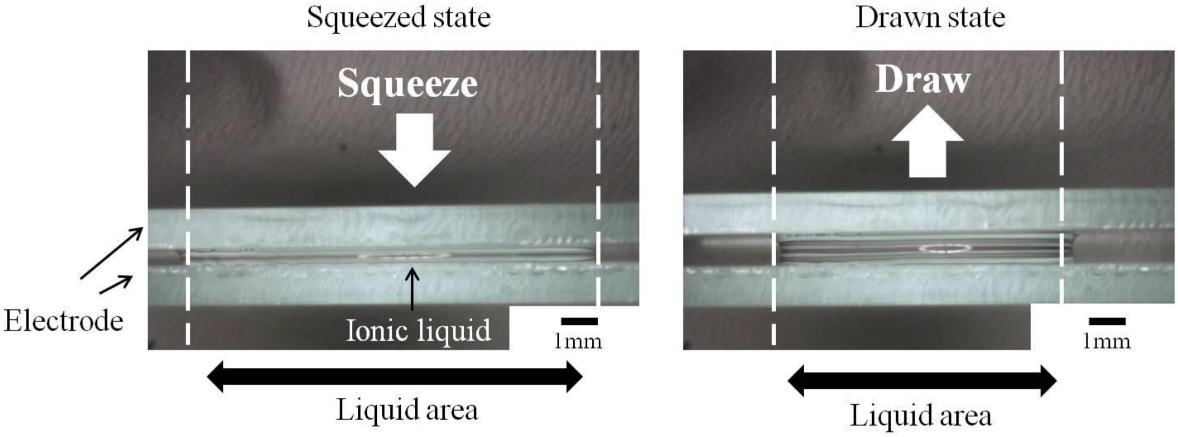

Figure 3. Photographs of the squeezed and drawn states.
Squeezed state: gap= 0.5mm, contact area= 1.6cm^2
Drawn state: gap= 1.0mm, contact area= 0.55cm^2

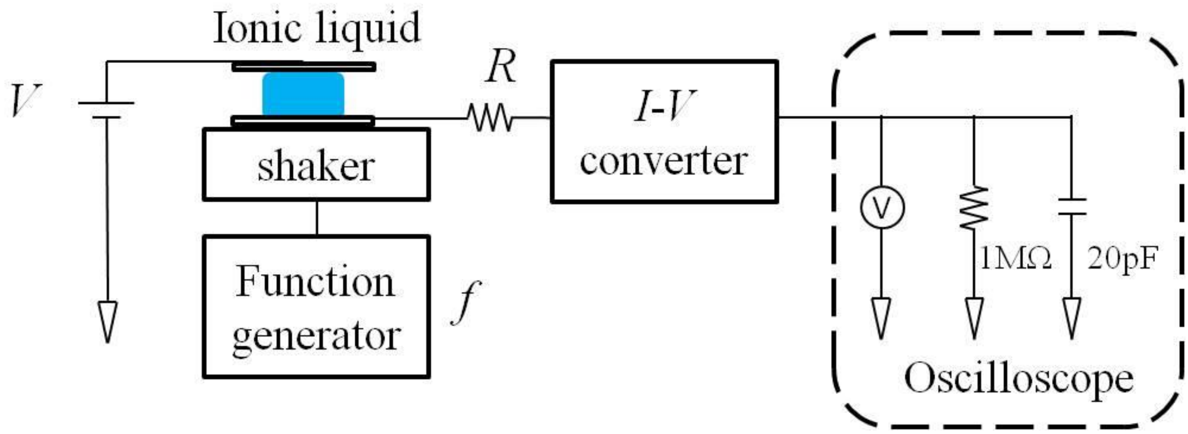

Figure 4. Schematic diagram of the experimental setup (*R* represents a loading resistance).
We applied sinusoidal movement periodically on the ionic liquid(+/- 250μm). The output current was measured by an oscilloscope and an I-V converter.

generating principle. The principle is quiet simple. Only squeezing and drawing the upper electrode, we can generate power. We put ionic liquid between electrodes and applied voltage. The voltage range is 0.5-2.0V within the potential window where the ionic liquid works as insulator as shown in Fig.2 (Please note in the real harvester the voltage source must be replaces by an electret). By drawing the upper electrode, the contact area decreases, and the capacitance between the liquid and the electrode also decreases. This change causes charge transfer and the current flows. Figure 3 shows the ionic liquid between two electrodes. To estimate the expected current ouput, we calculate the current with a simple model. In the setup in Fig. 1, let us assume the capacitance of ionic liquid in squeezed state is 10μF at V_{bias}= 1.0V. The squeezed state turns into the drawn state by the external vibration and the contact area decreases from 1.0cm^2 to 0.5cm^2. At the same time, the capacitance decreases from 10μF to 5μF. The change of the stored charge is 5μC. If this duration time is 1s, the output current will be 5μA. Based on this calculation, we prepare the setup and measure the output current. The experimental setup is shown in the Fig.4. We prepared a 90μl-droplet of ionic liquid (*[DEME]$^+$[TFSA]$^-$)* shown in Fig.3. One electrode was fixed and the other was attached to a shaker with the initial gap of 1mm. The ionic liquid was squeezed and drawn periodically by the vertical sinusoidal vibration. The gap

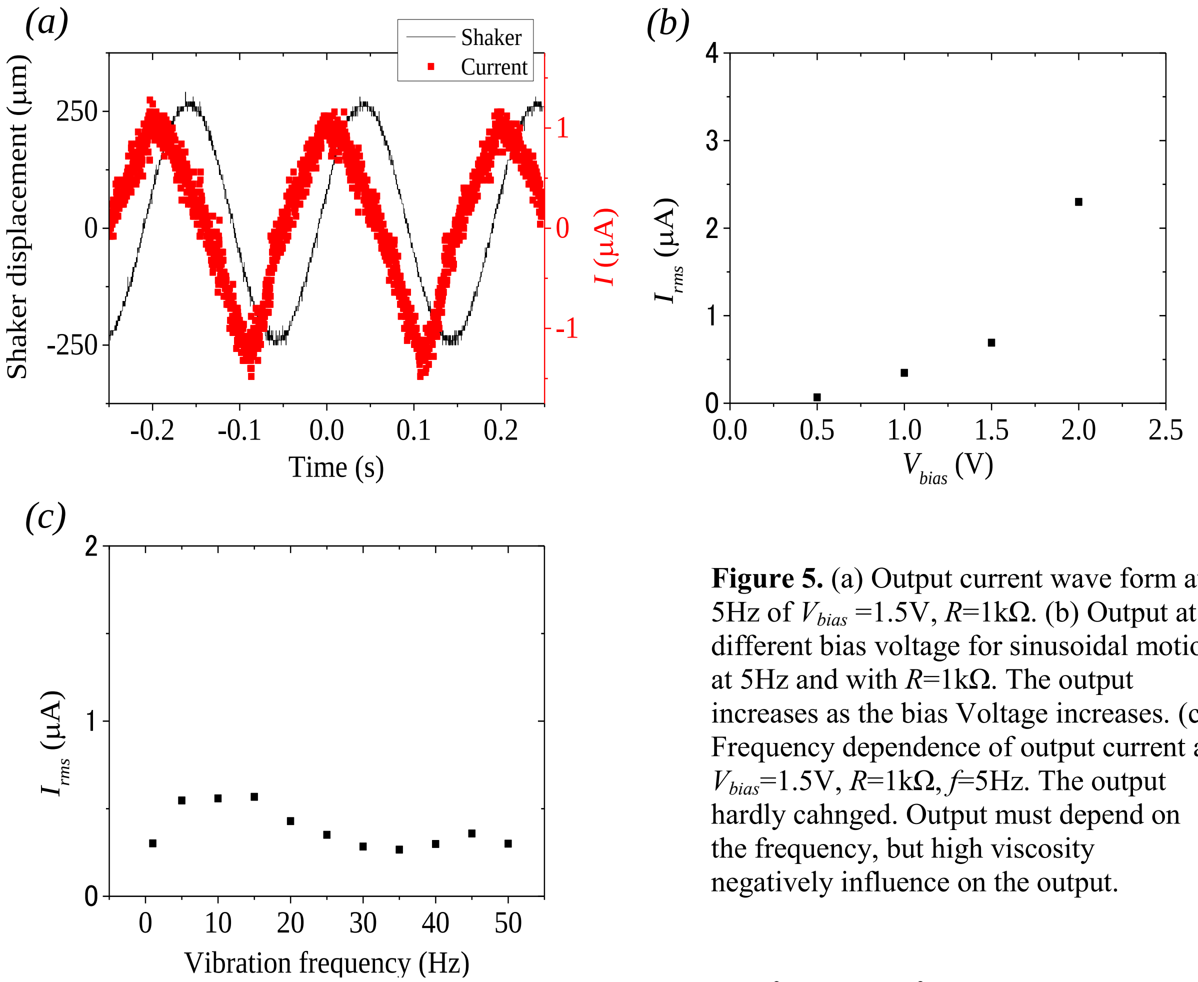

Figure 5. (a) Output current wave form at 5Hz of V_{bias} =1.5V, R=1kΩ. (b) Output at different bias voltage for sinusoidal motion at 5Hz and with R=1kΩ. The output increases as the bias Voltage increases. (c) Frequency dependence of output current at V_{bias}=1.5V, R=1kΩ, f=5Hz. The output hardly cahnged. Output must depend on the frequency, but high viscosity negatively influence on the output.

changed from 0.5mm to 1.0mm. The contact areas were 0.55cm^2 and 1.6cm^2 at squeezed and drawn states respectably. The output current was measured with an oscilloscope and an I-V converter.

3. Result & discussion

The peak value of the output current was 1μA (Fig. 5-a). We succeeded in power generation by squeezing and drawing ionic liquid and obtained sinusoidal output. The output in μA and the shaker motion in μm are expressed by 1.1sin(10πt+1.34)μA and 250sin(10πt)μm, respectively. There is a phase lag (61°) between them. Compared with the simple calculation, this output was smaller than we expected. Because of the wettablity, the spread ionic liquid could not be pulled back to the original state. This negatively influenced on the power generation.

The graphs 5-b and 5-c show output vs. bias voltage and vibration frequency, respectively. As bias voltage increased, we could obtain maximum effective current of 2.3μA at 5Hz, with a loading resistance of 1kΩ (Fig. 5-b). As the V_{bias} increased, the charge increased as well. Therefore large flow of electrons occurred in the circuit. Then, we swept the frequency from 1to 50Hz, at 1V with R of 1kΩ. We obtained output within the range (Fig. 5-c). As we swept the frequency of the shaker, the output did not increase as we expected. Because of its high viscosity, ionic liquid could not keep up with the motion of the shaker.

4. conclusion

A prototype of high-power energy harvester based on ionic liquid was reported in this paper. We succeeded in power generation with ionic liquid. The output is several nW and it was small compared with the power which wireless sensors need. However, the device generated quite high output current(μA) at this point. By improving the wettablity, the electrical circuit, and by optimizing the load resistance, it will be possible to generate a few tens of μW.

From the results, following conclusion can be drawn.

- The change of the capacitance generated power with the simple structure. Ionic liquid can eliminate complex structure from energy harvesters. It also improves the robustness of structure.
- The output depends on the bias voltage. If we utilize ionic liquid with a large potential window, we can apply high voltage on it and obtain high power generation.
- Ionic liquid driven by vibration generates power at the frequency range from 1 to 50Hz. From the results, the high viscosity negatively influenced on power generation. Ionic liquid with low viscosity must improve the frequency characteristic.

Our next steps are (1) replacement of the external power source with electrets, (2) improvement of the frequency characteristic for more efficient power generation from the environmental vibration which has wide spectrum in low frequency range, (3) optimization of the design of structures. We want to realize μW energy harvester with ionic liquid to replace the battery of wireless sensor nodes.

References

[1] Hecht J 2014 *Nat. Phys.* **10** 538
[2] Shen D, Park J H, Ajitsaria J, Choe S Y, Wikle H C and Kim D J 2008 *J. Micromech. Microeng.* **1** 055017-24
[3] Suzuki Y, Miki D, Edamoto M and Honzumi M 2010 *J. Micromech. Microeng.* **20** 104002-10
[4] Lombaert G, Conte J P and Asce M 2012 *J. Eng. Mech.* **138** 816-25
[5] Gwin J T, Gramann K, Makeig S and Ferris D P 2010 *J. Neurophysiol.* **103** 3526-34
[6] Strani M and Sabetta F 1984 *J. Fluid. Mech.* **141** 233-247
[7] Lockett V, Horne M, Sedev R, Rodopoulos T and Ralston J 2008 *J. Phys. Chem. Chem. Phys.* **12** 7486–95.