

Soft Electret Gel For Low Frequency Vibrational Energy Harvesters

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Abstract. A soft electret material was obtained by solidifying ionic liquid in a polymer network and immobilizing cations (+) on the surface. When a piece of soft electret gel is sandwiched between a pair of electrodes, a large amount of charge is induced in an electrical-double-layer capacitor ($1.0\text{-}10\text{ }\mu\text{F}/\text{cm}^2$) appearing at the interface of the electrode and the ionic liquid gel without an external voltage source. By retracting the electrode repeatedly, we obtained a current output of a few $\mu\text{A}_{\text{p-p}}/\text{cm}^2$ stably.

1. Introduction

There has been intensive investigation on MEMS vibrational energy harvesters due to their high applicability to IoT (Internet of Things) [1]. These inertial harvesters can be divided into three categories: piezoelectric, electromagnetic and electrostatic. Compared to the bulky electromagnetic type and limited-frequency-ranged piezoelectric type, electrostatic energy harvesters have several advantages. In particular, separating the spring and the power generation regions provides better design options for optimized performance. Although low frequency vibration ($<50\text{ Hz}$) is abundant in our daily life, e.g. motions by human body, infrastructure and transportation vehicles, most studies using electrostatic energy harvesters have been aiming at high frequency, e.g. vibrations generated by compressors or engines. The mismatch seems to stem from the fact that harvesters based on conventional MEMS technology are too fragile to achieve high-output power ($>100\text{ }\mu\text{W}$) at low frequency [2]. Therefore, to harvest energy at low frequencies while maintaining the advantages of electrostatic energy harvesters, it is necessary to develop a new method for capacitive power generation.

A triboelectric nanogenerator can obtain high-output power from low-frequency human motion [3]. However, compared to conventional devices, this type of device requires large external mechanical energy input such as pushing on a buzzer or stepping on the floor. In order to overcome this limitation, we employ a novel energy harvesting technique that changes the contact area between the soft electret gel having immobilized cations on the surface and the electrode. In this study, we demonstrated contact/retract operation of the electrode as a verification of our new power generation principle. This work improves the harvester based on the electrical double layer of ionic liquid reported at PowerMEMS 2014 [4].



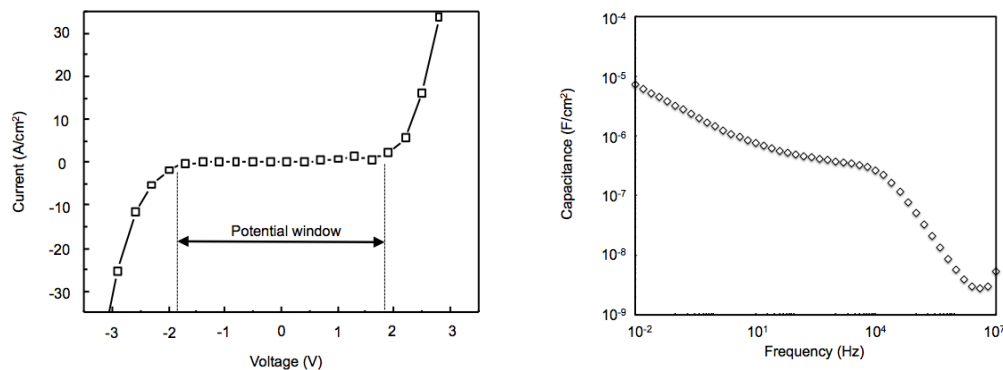


Figure 1. (a) The potential window of ionic liquid. (b) The capacitance of ionic liquid vs frequency.

2. Concept

2.1. Characteristics of the ionic liquid

Ionic liquids are composed of cations (+) and anions (-) with no other diluting solvent, and a wide variety of ionic pairs can be combined as desired. These ionic liquids have various unique characteristics, e.g. extremely low vapor pressure, resistance to high temperature, and the formation of an electrical double layer when a voltage applied across the material. Within these characteristics, we focused on the formation of an electrical double layer within the applied voltage range called the potential window (**Figure 1a**). An ionic liquid works as an insulator in the potential window, as it forms a 1 nm-thick electrical double layer on the interface between the ionic liquid and the electrode. Thus, it is capable of generating quite high capacitances in the order of 10 $\mu\text{F}/\text{cm}^2$ (**Figure 1b**).

2.2. Principle of power generation

The capacitance is utilized as variable capacitor whose contact area changes as the electrode is moves. In this way output current was obtained with the motion; this result was already reported in PowerMEMS 2014. However, this method has two primary problems: (1) Electrostatic attraction between the electrode and the ionic liquid prevented the change in contact area that is necessary for power generation and (2) external voltage source is needed to form the electrical double layer. Therefore, this work is the further extension of the previous study on utilizing the electrical double layer of ionic liquid while mitigating the aforementioned limitations.

Soft electret material was obtained by solidifying ionic liquid and immobilizing cations on the surface. When a piece of the soft electret gel is sandwiched between a pair of electrodes, large amount of charge are induced in an electrical-double-layer capacitor appearing at the interface of the electrode and the ionic liquid gel. By retracting the electrode repeatedly, we obtained the output-current (**Figure 2**).

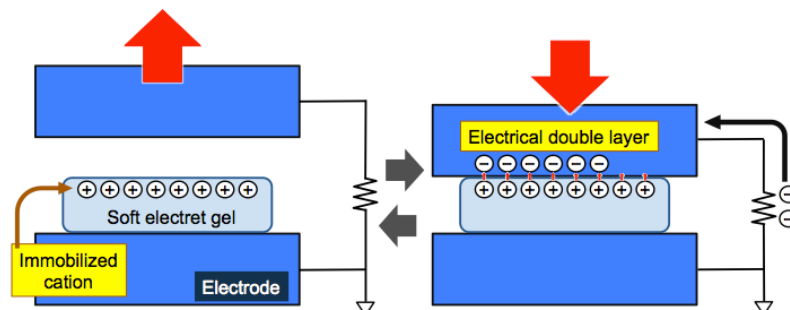


Figure 2. Schematic of principle of power generation by soft electret gel: Electrical-double-layer capacitance appearing at the interface of the electrode and the soft electret gel.

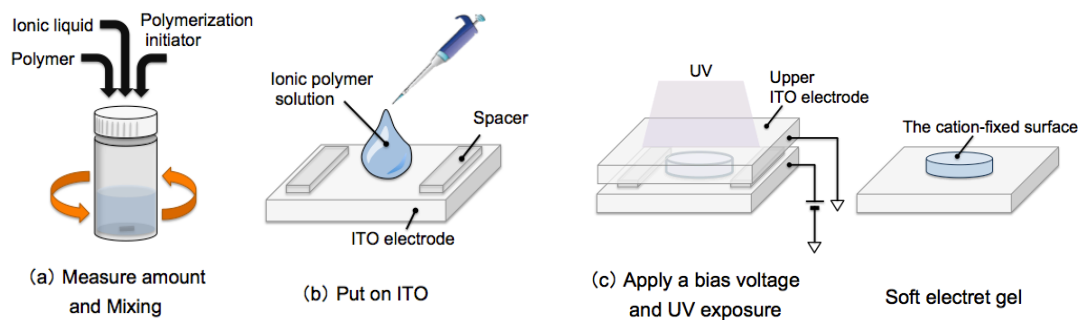


Figure 3. Schematic view of the soft electret gel manufacturing method: Cations of ionic liquid and fluid polymer have the same polymerizable functional group

3. Experimental section

3.1. Materials and manufacturing method

The soft electret gel consists of three materials: a base material, an ionic liquid and an initiator (**Figure 3a**). The base material is a fluid polymer with a polymerizable functional group. Accordingly, the ionic liquid has a cation with the same functional group for binding to the polymer. The initiator allows polymerization after mixing the appropriate amounts of constituent materials and exposing to UV light. First, we mixed and put the ionic polymer solution between a pair of transparent ITO (Indium Tin Oxide) electrodes with spacers to define the height of the gel (**Figure 3b**). We then applied a bias voltage within the solution's potential window (2 V DC) in order to form an electrical double layer. Finally, we exposed the sample to UV light (total about 45 min) for immobilizing cation ions on the surface of the gel (**Figure 3c**) while keeping the bias voltage.

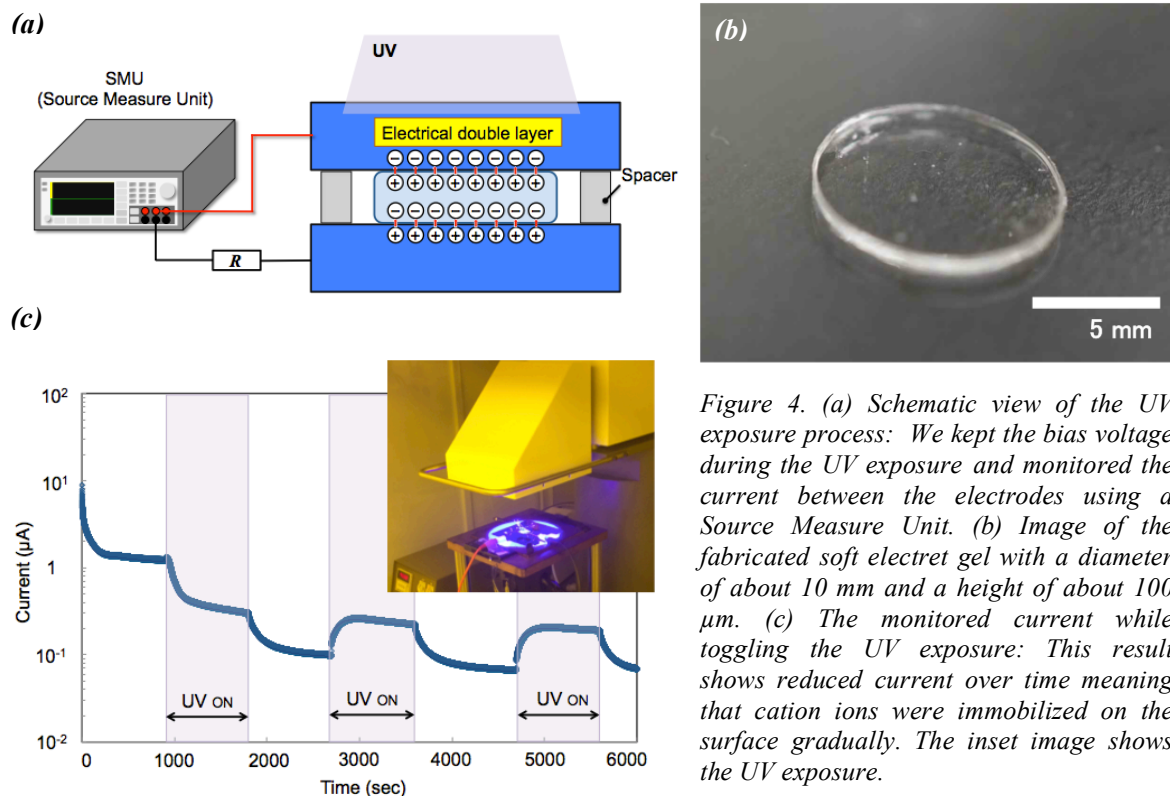


Figure 4. (a) Schematic view of the UV exposure process: We kept the bias voltage during the UV exposure and monitored the current between the electrodes using a Source Measure Unit. (b) Image of the fabricated soft electret gel with a diameter of about 10 mm and a height of about 100 μm . (c) The monitored current while toggling the UV exposure: This result shows reduced current over time meaning that cation ions were immobilized on the surface gradually. The inset image shows the UV exposure.

3.2. Immobilized cations

Through these processes, we monitored the current between the electrodes using a Source Measure Unit (SMU; Keysight B2900A, **Figure 4a**). **Figure 4b** shows the monitored current during cycles with and without UV exposure. This curve shows that the current reduced over time settling down to $0.1 \mu\text{A}/\text{cm}^2$, which means that cations were immobilized on the surface gradually. The soft electret gel was fabricated with a diameter of 10 mm and a height of $100 \mu\text{m}$ (**Figure 4c**).

3.3. Power generation principle verification

We prepared a pair of ITO electrodes and placed a sample of the soft electret gel between them (**Figure 5a**). Then, we used a Digital Multi Meter (DMM; Agilent 34410A) and LabVIEW-setup to monitor the output current between the electrodes (**Figure 5b**). The output current was measured using the $10 \text{ M}\Omega$ setting of DMM. When the gel surface with immobilized cations touched the ITO electrode, we obtained an output current.

4. Result and discussion

The output current peaked when we touched the cations-fixed surface with the electrode (**Figure 5c**). We measured up to $2 \mu\text{A}_{\text{p-p}}/\text{cm}^2$ from the soft electret gel by using a DMM and LabVIEW-setup.

Compared to previous study (PowerMEMS 2014), we were able to achieve an equivalent output current of $2 \mu\text{A}_{\text{p-p}}/\text{cm}^2$ without using any external bias voltage. This means the soft electret gel works as an alternative to the external power supply. In this study, we fabricated a relatively stiff sheet-like gel of about 10mm diameter and about $100 \mu\text{m}$ thickness. The shape, dimension and stiffness of the gel can be modified as desired allowing for optimization of the output current from a device.

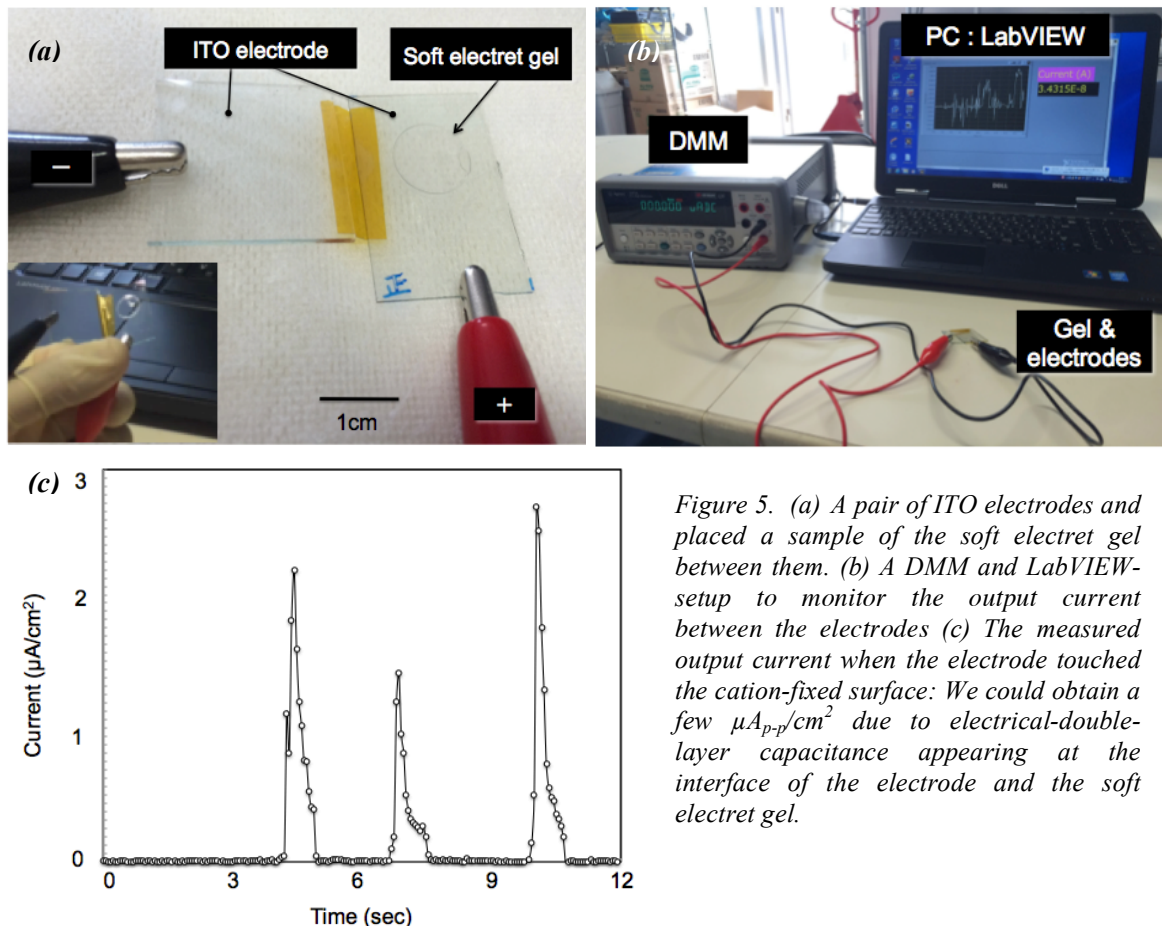


Figure 5. (a) A pair of ITO electrodes and placed a sample of the soft electret gel between them. (b) A DMM and LabVIEW-setup to monitor the output current between the electrodes (c) The measured output current when the electrode touched the cation-fixed surface: We could obtain a few $\mu\text{A}_{\text{p-p}}/\text{cm}^2$ due to electrical-double-layer capacitance appearing at the interface of the electrode and the soft electret gel.

5. Conclusion

In this study, we have developed a soft electret gel with immobilized cations on the surface. This technique provides robust devices by minimizing fragile regions. Unlike harvesters obtained by the conventional MEMS technology, the soft electret gel method shows superior performance at the low frequency range with low mechanical input power due to the characteristics of the ionic liquid based insulating material between the electrodes. Moreover, eliminating the external bias voltage to form an electrical double layer for high capacitance is crucial for low power applications. As a result, the proposed technology leads to a robust energy harvester at the low frequency range for low power applications such as wearable devices based on human motion. Currently, we are developing a MEMS energy harvesting device using this novel electret gel.

6. Acknowledgements

This work is partly supported by the New Energy and Industrial Technology Development Organization (NEDO).

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