Electrostatic vibrational energy harvester with ionic liquid and potassium-ion-electret

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Abstract. This paper introduces an electrostatic vibrational energy harvester with an effective electrode distance of ~1 μm by utilizing the 1-nm-thick insulating gap that an ionic liquid forms, followed by a proof-of-concept with an AC current of 100 nA (peak-to-peak) and a voltage of 100 mV (peak-to-peak) generated from our prototype.

1. Introduction
Electrostatic vibrational energy harvesters attract increasing interest for their potential in miniaturization and low frequency operation towards application to IoT sensor nodes. MEMS technology and favorable scaling properties enable the miniaturization of the device, while uncoupled design freedom between the energy generating region and the mechanical suspension allows low frequency operation. The remaining issue is creating and maintaining an extremely narrow gap between moving and stationary electrodes to enlarge output power.

In this research, we have developed an energy harvester featuring ionic liquid between the electrodes. Ionic liquids are known to automatically form an extremely thin insulating gap called an electrical double layer, on the surface of charged electrodes. This thin gap may ultimately realize an effective electrode distance of ~1 nm without any specific fabrication, leading to a mechanically robust harvester with large output power.

2. Concept
2.1. Ionic liquid
An ionic liquid is a fluid salt composed only of organic cations and anions, around room temperature. Ionic liquids have unique chemical and physical properties, featuring (1) thermal and chemical stability, (2) negligible volatility, and (3) high ionic conductivity [1]. In this work, we focus on the electrochemical properties of ionic liquids, specifically the interactions that occur at the interface of ionic liquids and charged electrodes. A potential window is a voltage range within which cations or anions do not get reduced or oxidized, or in electrical terms, do not transfer charges to or from the
electrodes. Within this voltage range, electronic charges at the surface of the electrode attract counterpart ions in the ionic liquid (figure 1). These ions are not firmly anchored to the surface of the ionic liquid, but distributed near the surface keeping a gap of about 1 nm from the electrode surface. This structure, called an electrical double layer, provides very large capacitance of ~10 μF/cm² and high stored charge density [2].

2.2. Electrostatic vibrational energy harvester with ionic liquid

Conventional electrostatic vibrational energy harvesters are composed of a pair of electrodes, one of which is an electret with immobilized charge. They can be categorized into two main types: perpendicular or lateral displacement harvesters (figure 2). Perpendicular displacement harvesters feature a changing gap between the parallel electrodes, with the electrodes moving perpendicularly with respect to each other. Lateral displacement harvesters, however, feature overlapping surface area changes, with the electrodes moving laterally with respect to each other. In either case, charges flow through the circuit in order to compensate for the change in the capacitance between the electrodes. Another point in common is that the current flow can be increased by decreasing the width of the electrode gap during fabrication. However, there has been a limit in MEMS technology to fabricate increasingly narrow gaps while maintaining separation.

Therefore, in our device, ionic liquid is inserted between the electrodes (figure 3). Utilizing the overlapping surface area change with the electrodes moving in the perpendicular direction represents a novel method to generate a capacitance change for electrostatic vibrational energy harvesters (figure 2). The electrical double layer that the ionic liquid automatically forms leads to an effective electrode distance of ~1 nm, which is mechanically robust since the liquid is continuously touching the electrode. Furthermore, this thin insulating gap provides a large capacitance of ~10 μF/cm² which enlarges the output power in respect to the capacitance change.
3. Method

3.1. Components

3.1.1. Potassium-ion-electret. In order to initiate the formation of the electrical double layer within the ionic liquid, a potassium-ion-electret is used to induce fixed charges. The fabrication of a potassium-ion-electret was developed by Hashiguchi et al. First, through wet oxidization, K⁺ is doped in the ~1-μm-thick SiO₂ layer formed on top of a silicon wafer. After a bias voltage is applied under high temperature (500-600 °C) across the oxide layer, the redistribution of SiO⁻ and positive charges converts the material into a permanent electret with a surface voltage of ~-200 V. A SAM layer of HMDS covers the electret in order to prevent the gradual decay of the electret due to water vapor.

3.1.2. Protective layer covered ionic liquid. Initially, we placed the ionic liquid directly on the electret surface. The charges, however, disappeared in the area where the ionic liquid touched the surface (figure 4). Hence, a layer of parylene is deposited on the ionic liquid for protection (figure 5). To maintain the hemispherical shape of the ionic liquid during the deposition, a mold is made with a 1-μm-thick hydrophobic Cytop layer. Subsequently, a 1-μm-thick layer of parylene C is deposited on the top of the ionic liquid droplet. The diameter of the bottom area of the droplet is designed to be \( \phi = 5 \) mm.

3.2. Experimental setup.

After the components of our energy harvesting structure is assembled, vibration is applied to examine the power generation. While the upper electrode with potassium-ion-electret is fixed, the lower electrode with parylene covered ionic liquid is actuated by a frequency tuneable shaker (figure 6). The output current and output voltage is measured using a Digital multimeter (Keysight, 34410A) with a load resistance of 1 MΩ.

4. Experimental result and discussion

Potassium-ion-electret and parylene covered ionic liquid was fabricated according to the procedures mentioned in 3.1.1 and 3.1.2. When the amount of ionic liquid was 10 μL, the height of the droplet became 1.5 mm. An Au electrode with electret attached was fixed to a support, while an Au electrode with parylene covered ionic liquid was fixed to a shaker which provides the vibration (Figure 7).
Figure 7. Photograph of energy harvesting structure. Mold with \( \phi = 5 \text{ mm} \) filled with 10 \( \mu \text{L} \) of ionic liquid yields a 1.5 mm tall droplet.

![Photograph of energy harvesting structure](image)

Figure 8. (a) Measurement result of AC current generated from vibration of \( f = 1 \text{ Hz} \). (b) Measurement result of voltage generated from vibration of \( f = 1 \text{ Hz} \).

![Measurement results of AC current and voltage](image)

As a result, we successfully generated an AC current of 100 nA (peak-to-peak) and a voltage of 100 mV (peak-to-peak) from gently squeezing and relaxing the droplet with the electrode driven by the shaker at 1 Hz (Figure 8). This result verifies possible application of ionic liquid to electrostatic energy harvesting. Also, this result suggests that the SiO\(_2\) electret kept its charge.

5. Conclusion
We introduced a novel vibrational energy harvester with an ionic liquid droplet inserted between the electrodes, followed by a proof-of-concept measurement with a calculated output power of 10 nW. We are now conducting precise measurements with the aim of device miniaturization. In addition, we are working on the improvement of the protective layer between the ionic liquid and the electret to fully utilize the 1-nm-thick electrical double layer.

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