Electret-based Unsteady Thermal Energy Harvester using Potassium Tantalate Niobate Crystal

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Abstract: An electret-based unsteady thermal energy harvester is proposed using potassium tantalate niobate (KTa\(_{1-x}\)Nb\(_x\)O\(_3\), KTN) as a dielectric for the capacitor. By connecting in series the capacitor and an electret serving as a permanent voltage source, the capacitance change with temperature fluctuations alters the amount of induced charges thereby produces the external current. By using KTN having extremely-large temperature coefficient of permittivity together with the CYTOP electret, the output power of 572 nJ has been obtained from one heating cycle, which corresponds to 20 times higher output power than the previous result with BaTiO\(_3\).

Keywords: Thermal energy harvester, Electret, Potassium tantalate niobate, Permittivity

1. Introduction

Thermal energy harvesting is a promising energy source for low-energy consumption devices like wireless sensor nodes for Internet of Things (IoT) [1]. Various thermoelectric generators based on the Seebeck effect are prototyped for power generation from the steady temperature gradient [2]. On the other hand, ambient temperature fluctuations can be another possible energy source for thermal energy harvesting. Thermoelectric harvesters with thermal capacitor are considered for transient thermal fields [3]. Pyroelectric materials such as PZT or PVDF, in which change of spontaneous polarizations within the crystal structure is used, has higher energy conversion efficiency [4, 5].

We previously proposed an electret-based electrostatic unsteady thermal energy harvester [6], and obtained the output power of 30 nJ by heating the BaTiO\(_3\) from 20 to 100 °C in 300 s. The performance of the device was limited by the temperature sensitivity of the dielectric constant, although no heavy metal such as lead and cobalt is used for the electret and the capacitor.

In present study, an electret-based thermal energy harvester has been proposed with potassium tantalate niobate (KTa\(_{1-x}\)Nb\(_x\)O\(_3\), KTN) crystal [6] with much higher temperature sensitivity.

2. Working principle

Figure.1 shows the working principle of the electret-based energy harvester [7]. The device consists of three parts; the electret serving as the permanent voltage source (capacitance: \(C_e\), surface charge density: \(\sigma_e\)), the capacitor with temperature-sensitive dielectric (capacitance: \(C\)), and the external load. By connecting them in series, the permittivity of dielectric changes as ambient temperature varies, which leads to change of the amount of the induced charges. Thus, the external current is produced by the temperature fluctuations.

Based on the circuit model shown in figure 1, we employ the Kirchhoff’s law, the Gauss’s law and the conservation of charges:
where \( d_1, S_1, E_1, \sigma_1, \epsilon_1 \) are the thickness, the area, the electrical field, the induced charge and the permittivity of the electret, while \( d_2, S_2, E_2, \sigma_2, \epsilon(t) \) are those of the dielectric. After the non-dimensionalization with \( t^* = t/RC_e, \sigma^* = \sigma/\sigma_e, C^*(t) = C(t)/C_e \), we can get the differential equation:

\[
I^* = V^* = \frac{d\sigma_1^*}{dt^*} = -\left\{ (1 + \frac{1}{C(t^*)})\sigma_1^* + \frac{1}{C(t^*)} \right\}
\]

And the output power \( J \) can be written as,

\[
J = V_{charge}^2 C_e J^*
\]

where \( V_{charge}, C_e, \) and \( J^* \) are the surface voltage of electret, the capacitance of the electret, and the normalized output power derived from the non-dimensionalized differential equation, respectively. Therefore, the output power of the present unsteady energy harvester is mainly controlled by two main independent parameters, i.e., temperature sensitivity of the dielectric, and the surface potential of the electret.

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**Figure 1:** Circuit model of the electret-based energy harvester.

**Figure 2:** Normalized output power for different \( \alpha \).

**Figure 3:** Permittivity change of the KTN crystal.

**Figure 4:** TSD spectra of the CYTOP electret.
Figure 2 shows the normalized output power versus the capacitance ratio $C_0^* = C_0/C_e$ ($C_0$: initial capacitance of the dielectric) for different permittivity increase ratios $\alpha$, defined by the ratio of the maximum and minimum capacitances during one temperature change cycle. The normalized output power increases dramatically with $\alpha$. In our previous study with a BaTiO$_3$ dielectric, $\alpha$ is as low as 0.5 [7]. Figure 3 shows the relative permittivity of the KTN crystal presently used in the temperature range between 20 °C and 80 °C. KTN shows very high permittivity change near its phase transition temperature [6], and its permittivity increase rate $\alpha$ is as high as 11 for heating and 13 for cooling.

![KTN crystal](image1)

Figure 3: Relative permittivity of the KTN crystal presently used in the temperature range between 20 °C and 80 °C.

![Experimental setup](image2)

Figure 5: a) KTN crystal (size: 6 mm × 6 mm, thickness: 0.27 mm), b) Experimental setup for power generation.

![Temperature and permittivity](image3)

Figure 6: Temperature and permittivity for the KTN capacitor for different heating rates.

![Voltage output](image4)

Figure 7: Voltage output during the single heating cycle.
3. Experimental set up and Results

Figure 5a shows the 0.27 mm-thick KTN crystal used in the present study. The size of the metalized area is 6 mm × 6 mm. 15 µm-thick CYTOP EGG [8] with double sides of electrodes on a silicon wafer is used as the electret, of which area is 23 cm². Thermal charging [9] at 120 °C with the bias voltage of 400 V is applied. To specify the charge properties of the electret, thermally-stimulated discharge (TSD) experiment [10] is used. The heating rate is 1 °C/min. Figure 4 shows the result of TSD experiment. By integrating the TSD current over the elapsed time, the stored charge density for the CYTOP electret is estimated to be 53 nC/m², which corresponds to the surface voltage of $V_{\text{charge}} = 43$ V.

Figure 5b shows the present experimental setup. A lamp bulb was used as the heating source of the KTN capacitor. Temperature of the KTN capacitor is monitored by a thin thermocouple attached to the surface. Permittivity is also monitored by measuring the capacitance.

Figure 6 shows the temperature and permittivity changes for the present KTN capacitor. With the distance between the KTN crystal and the lamp of 0.1 cm and 0.5 cm, different initial temperature gradients of 1.74 °C/s and 0.98 °C/s are achieved. Figure 7 shows the output voltage with the external load of 610 MΩ. With the heating rates of 1.74 °C/s and 0.98 °C/s, the output power of 572 nJ and 363 nJ have been obtained, respectively. With the higher heating rate of 1.74 °C/s, the output power is 20 times higher than that in our previous study [7]. In Fig. 6, at around $t = 10$ s, the time derivative of the relative permittivity is 1.5 times higher for the heating rate of 1.74 °C/s, which results in the higher output voltage and thus the higher output power as shown in Fig. 7. Because the surface voltage of the present CYTOP electret is much lower than its limit [8], much higher output power can be expected with improvement of the charging process.

4. Conclusion

An electret-based thermal energy harvester using KTN crystal has been proposed. The determining factors of the total output power are better illuminated by combining the simulation results and experimental data. KTN crystal is applied as temperature-sensitive dielectric with much higher permittivity change for the temperature variation. Surface voltage of 43 V is achieved by thermal charging of CYTOP. Up to 572 nJ output has been obtained in one heating cycle with the CYTOP electret, which is 20 times higher than our previous result with BaTiO₃.

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