

Electrostatic Thermal Energy Harvester Using Unsteady Temperature Change

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Abstract: A model electrostatic thermal generator using unsteady temperature change is proposed. The device consists of a capacitor based on high-permittivity ceramics, and an electret layer serving as a permanent voltage source. Connecting them in series, permittivity change by temporal temperature change alters the amount of induced charges on the electrode thereby produces electric current in the external circuit. Optimum design parameters of the system have been obtained using a simplified circuit model. An early prototype using BaTiO₃ ceramic as the dielectric and SiO₂ as the electret is microfabricated, and its response is compared with the model prediction.

Keywords: Thermal energy harvesting, Electret, Permittivity change, BaTiO₃

1. INTRODUCTION

Thermal energy harvesting from waste heat or body heat is useful for powering low-power electronics such as wireless sensor nodes [1]. The Seebeck effect is usually employed for getting electric power from steady temperature gradients, where thermal impedance matching is an important design strategy [2]. MEMS thermoelectric devices with thermal insulation structures are developed for that purpose [3, 4]. On the other hand, transient temperature gradient is also relevant as energy sources. Moser et al. [5] propose thermoelectric harvesters from temperature difference between ambient air and large backside thermal capacitance such as road tunnel wall, and reported that the thermal cut-off frequency plays an important role in their design. Temporal temperature change during aircraft flights is also an interesting application, because the air temperature is decreased to -50 °C at the cruising altitude [6-8]. Samson et al. [7] developed a thermoelectric generator prototype using phase change material (PCM) as the backside thermal capacitance, and made a series of in-flight tests by installing the device on fuselage.

Pyroelectric is an alternative method to extract electricity from transient temperature change, where temporal temperature change can be directly used for energy conversion. Sebald et al. [9] made detailed comparison between thermoelectric and pyroelectric energy conversion, and reported that the conversion efficiency with pyroelectric can be much higher than that with thermoelectric. Thermal engines using pyroelectric device such as PZT or P(VDF-TrFE) are also proposed [10, 11].

In the present study, we propose electret-based electrostatic induction for thermal energy harvesting from unsteady temperature change. If compared with the pyroelectric principle, the present power generation principle should be more robust against excessive temperature variation.

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2. PRINCIPLE AND OPTIMIZATION

Figure 1 shows configuration of the present device with a capacitor (capacitance: C) using high-permittivity material and metalized electret (capacitance: C_e , surface charge density: σ_e) serving as a permanent voltage source. They are connecting in series with an external load R . The temperature change of the capacitor leads to the permittivity change, and the amount of induced charges on the electrode is changed. Thus, the external current I is produced when temperature of the dielectric is changed. A circuit model of the generator is developed based on the Kirchhoff's law, the Gauss's law, and the conservation law of charges:

$$V = IR = d_1 E_1 - d_2 E_2, \quad I = -S_1 \frac{d\sigma_1}{dt} = S_2 \frac{d\sigma_2}{dt}, \quad (1)$$

$$\sigma_1 = \varepsilon_0 \varepsilon_1 E_1, \quad \sigma_2 = \varepsilon_0 \varepsilon_2(t) E_2, \quad (2)$$

$$S_1 \sigma_e = -(S_1 \sigma_1 + S_2 \sigma_2), \quad (3)$$

where d_1 , S_1 , E_1 , σ_1 , and ε_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 , σ_2 , and $\varepsilon_2(t)$ are those of the dielectric. Eqs. (1-3) can be integrated into a first-order differential equation, i.e.,

$$\frac{d\sigma_1}{dt} = -\frac{1}{R} \left\{ \left(\frac{1}{C_e} + \frac{1}{C(t)} \right) \sigma_1 + \frac{1}{C(t)} \sigma_e \right\} \quad (4)$$

Eq. (4) can be non-dimensionalized with $t = RC_e t^*$, $\sigma_1 = \sigma_e \sigma_1^*$, $C(t) = C_e C^*(t^*)$, and we get

$$I^* = V^* = \frac{d\sigma_1^*}{dt^*} = - \left(1 + \frac{1}{C^*(t^*)} \right) \sigma_1^* - \frac{1}{C^*(t^*)} \quad (5)$$

For simplicity, capacitance of the dielectric is assumed to change linearly in time, i.e.,

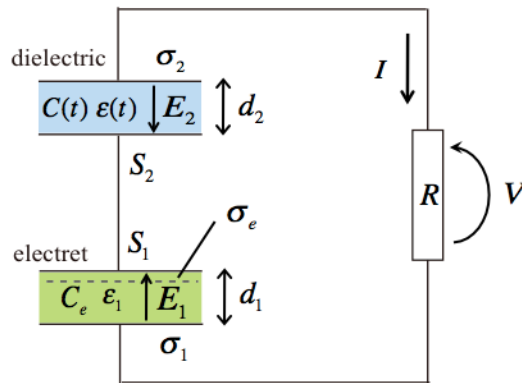


Figure 1. Circuit model of thermal electret generator.

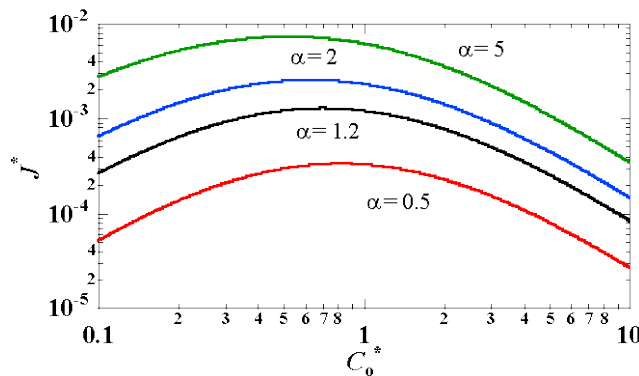


Figure 2. Nondimensionalized output power J^* versus capacitance ratio C_o^* .

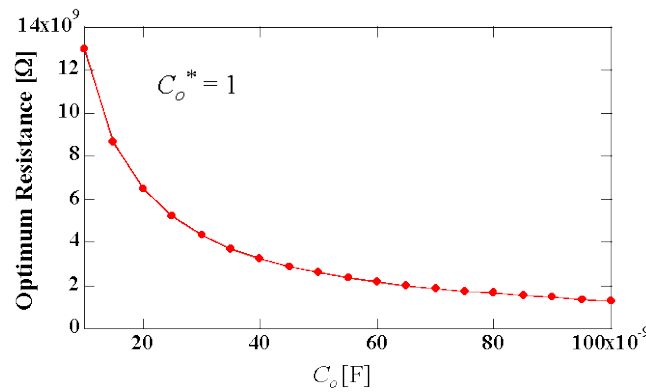
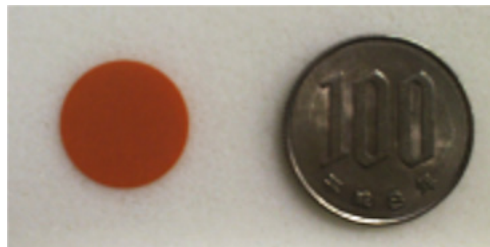
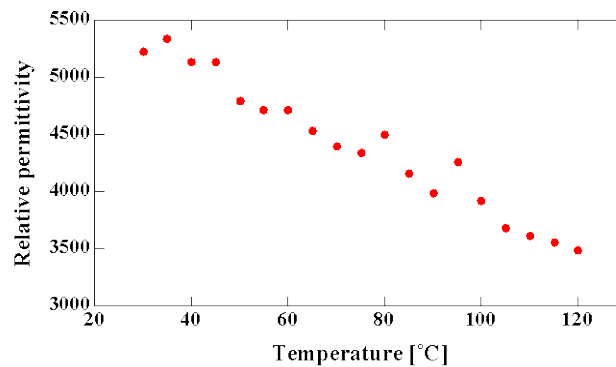


Figure 3. Optimum load resistance versus initial capacitance.

Figure 4. BaTiO₃ capacitor (15 mm dia., 0.1 mm in thickness).Figure 5. Relative permittivity of the BaTiO₃ capacitor versus temperature.

$$C^*(t^*) = \left(1 + \alpha \frac{t^*}{\tau^*}\right) C_o^* \quad (6)$$

where α , τ^* , and C_o^* are the capacitance increase rate, time scale of the temperature change non-dimensionalized with the time constant RC_e , and the initial capacitance ratio of the dielectric to C_e ($C_o^* = C_o/C_e$).

Figure 2 shows simulation results for the non-dimensionalized output power J^* ($= \varepsilon_1 \varepsilon_0 / d_1 S_1 \sigma_e^2 \cdot J$) versus C_o^* . It is found that the optimum C_o^* exists, and it is around unity for $\alpha=0.5$, and decreased with increasing α . In addition, when α increases, the output power is dramatically increased. As shown in Fig. 3, the optimum resistance is decreased with C_o , indicating that high-permittivity material is required for this type of generator.

3. PROTOTYPE DESIGN AND EXPERIMENTS

Figure 4 shows the BaTiO₃ capacitor (Chiba Ceramic MFG, 15 mm dia., 0.1 mm in thickness) used in our preliminary experiment. Pure BaTiO₃ has its Curie temperature at around 130 °C, where

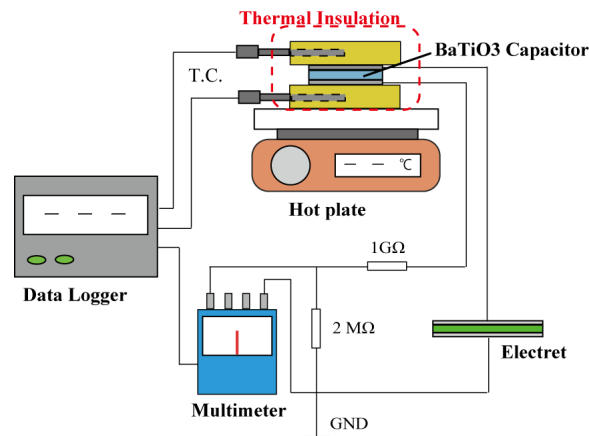


Figure 6. Schematic of the experimental setup.

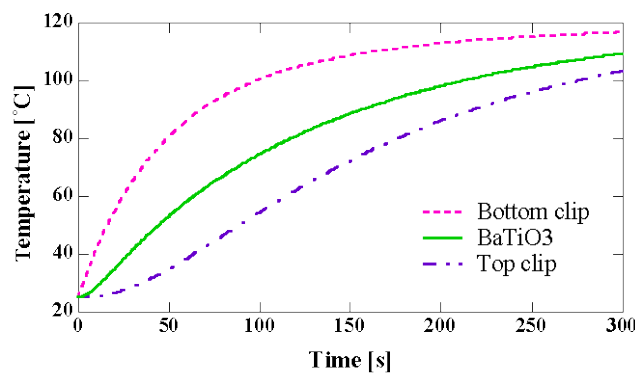
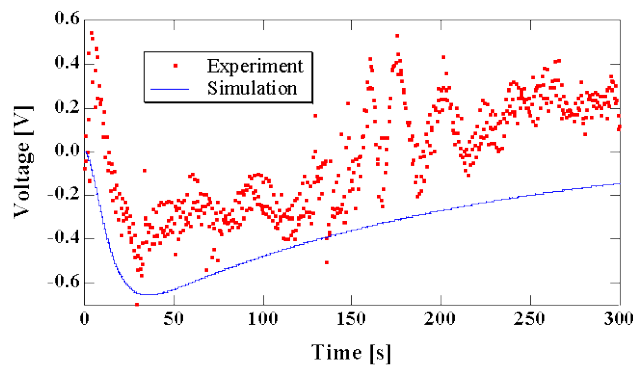
Figure 7. Estimated temperature of BaTiO₃ capacitor versus elapsed time.

Figure 8. Output voltage versus elapsed time.

the permittivity is drastically changed. Figure 5 shows the DC permittivity of the BaTiO₃ capacitor versus the temperature. Due to additives into the present BaTiO₃, α is not so high and about 0.5.

An electret plate is fabricated using a 4 cm square Si substrate with 1.5 μm -thick thermally-grown SiO₂. After corona charging, the surface potential is 420 V, which corresponds to the surface charge density σ_e of 9.5 mC/m². The metalized electret is formed by stacking another Si substrate with 1.5 μm -thick SiO₂ onto the electret plate. In the preliminary experiment with the present BaTiO₃ and electret plates, $C_0^*=0.2$, which is far from the optimum design.

Figure 6 shows the experimental setup. The BaTiO₃ capacitor is sandwiched with copper plates and heated on a hot plate. Temperature of the copper plates is measured with thermocouples, and the BaTiO₃ temperature is estimated using one-dimensional heat conduction equation with contact

resistance. Figure 7 shows the measured temperature of the top/bottom copper plates and the estimated temperature of the BaTiO₃ capacitor, which is increased from 20 to 100 °C in about 300 s.

Figure 8 shows the output voltage across a 1 GΩ resistive load. Up to 0.6 V is obtained, corresponding to about 30 nJ in 300 s. Although amount of the generated power in this early prototype is limited, the results are in accordance with prediction of the circuit model. Thus, the output power can be much increased by using the optimum C_0^* , much higher α , and higher surface potential with CYTOP electrets [13, 14]. It is also noted that the Currie temperature of Zr-added BaTiO₃ could be as low as 60 °C, and α can be as large as 5.

4. CONCLUSION

A new electret thermal generator using temporal temperature change has been proposed. A simplified circuit model is developed for parameter optimization. It is found that the optimum capacitance ratio is around unity and the output power is significantly increased with the capacitance increase rate. A preliminary experiment using BaTiO₃ ceramic as the dielectric layer is carried out. It is demonstrated that the experimental data are well predicted with the present model.

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