OHA Ceramic Electret for Vibration Energy Harvesting

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Abstract. With a motivation for developing oxy-hydroxyapatite (OHA) ceramic-electret applicable to vibration energy harvesting, the poling characteristics of OHA ceramics were investigated in terms of microstructure using thermally stimulated depolarization current (TSDC). OHA is a hydroxyapatite (Ca₁₀(PO₄)₆(OH)₂)-derivative material, in which the OH⁻ ions are partially substituted by O²⁻ ions and vacancies (Ca₁₀(PO₄)₆(OH)₂Oₓ/2). Patterned electret using 14-mm diameter OHA ceramic was prototyped with stripe-shaped electrodes, which serve as the electrostatic shield on the surfaces. The relationship between surface potential and the pattern width of the electrodes was experimentally examined, and the power generation characteristics were investigated.

1. Introduction
Energy harvesting is the technology to capture small amounts of ambient energy in order to realize maintenance-free standalone power source for low-power electronics. Its applications include automotive sensors such as tire pressure monitoring systems (TPMS), wireless sensors for structural health monitoring, and wearable devices [1]. At a low-frequency vibration range below 100 Hz, electret vibration energy harvester (EH) should have higher output power than electromagnetic or piezoelectric counterparts [2]. Recently, in addition to conventional electret materials such as polytetrafluoroethylene (PTFE) and SiO₂ [3], new polymer electret materials with higher surface charge density such as CYTOP-EGG [4, 5] and parylene AF4 [6] are proposed with a view of energy harvesting applications. On the other hand, inorganic electret has advantage for high thermal stability of charges. Tanaka et al. [7] proposed oxy-hydroxyapatite (OHA) ceramics as a promising electret material with extremely-high stored charges and high surface potential.

In the present study, we investigate the poling characteristics of OHA ceramics, and examine a patterning method of the surface potential for power generation of vibration EH prototype using OHA ceramic electret.

2. Poling characteristics of OHA
OHA is a hydroxyapatite (Ca₁₀(PO₄)₆(OH)₂)-derivative material, in which the OH⁻ ions are partially substituted by O²⁻ ions and vacancies (Ca₁₀(PO₄)₆(OH)₂Oₓ/2) [1]. Although OHA shows no piezoelectric property, our first-principle MD simulations demonstrated that the local flip of H⁺ and the exchange of OH⁻/O²⁻, OH⁻/vacancy and O²⁻/vacancy occur in the OH⁻ sites linearly arranged along the c-axis in the apatite structure (Fig. 1), showing the possibility for inducing poling within the OHA ceramics.

OHA ceramic disks (ϕ 10 mm, t=1 mm) were prepared by sintering hydroxyapatite powder compacts at 1250-1400°C for 2 h under air. Sintering temperature affects the degree of grain growth; the grain size of OHA ceramics is monotonously increased from ca. 2 to 12 μm. As shown in Fig. 2a, the OHA
ceramic “electrets” was prepared at 200°C for 1 h under the electrical field of 8 kV/cm. The field was kept during the cooling process to avoid the dipole relaxation [7]. The poling condition of the obtained OHA ceramics was investigated with a surface potential measurement and a thermally stimulated depolarization current (TSDC) technique (Fig. 2b).

**Figure 1.** Crystal structure and carrier dynamics for OHA estimated by first-principle MD simulation.

**Figure 2.** Schematic of (a) approach for preparing OHA ceramic electret and (b) TSDC technique.

**Figure 3.** Effect of the grain size on surface potential ($V_{sur}$) and stored-charge ($Q$) of OHA electrets.

**Figure 4.** Experimentally obtained TSDC curve (Ex.) of OHA electrets with the theoretical curves (Th.) calculated using $E_{dr}$ values of 0.3-1.2 eV.
3. TSDC Experiments

Figure 3 shows the surface potential $V_{\text{sur}}$ and the stored charges $Q$ versus the grain size. It can be seen that there is a positive correlation between $V_{\text{sur}}$, $Q$ and the grain size, supporting the effect of the grain boundaries on the dipole formation in the OHA ceramics. For the detailed understanding of dipole formation/relaxation mechanism of the OHA ceramics, TSDC measurements were made and compared with the activation energy obtained in the MD simulation as shown in Fig. 4. The results show that four different kinds of poling modes with different activation energies $E_{\text{dr}}$ exist in the OHA electret. The values of $E_{\text{dr}}$ are in good agreement with the activation energy for flip/migration of ionic carries determined by the MD simulation.

4. Patterning OHA Electret

Figure 5 shows a schematic of an in-plane vibration energy harvester using the OHA electret. In order to increase the changing rate of overlapping area and thus the output power, strip patterns are usually employed for in-plane vibration EH. Because it is difficult to physically etch OHA, conductive strip patterns, which serve as the electrostatic shield on the surface, are formed on the surface of OHA. In the present study, poled OHA ceramic disks ($\phi$ 14 mm, 1 mm thickness) with the surface potential of about -2400 V are used, and 1-2 mm wide Au patterns were formed by sputtering through a hard mask. The surface electrodes are grounded to ensure zero potential on the electrodes. We employ an Electrostatic Force Microscopy (EFM) [8] to measure the surface potential profile in between the electrodes.

Figure 6 shows the surface potential distribution across the strip patterns on the OHA electrets. It is found that the surface potentials are much lower than that of the plain OHA ceramic disk (~-2400 V), and decreased with decreasing the width of the strip patterns. With the 2 mm-wide electrodes, the peak value of the surface potential near the center is -1400 V, but the potential is decreased toward the edge of the electrodes. Because thinner pattern is advantageous for vibration power generation, more detailed investigation is necessary to clarify this issue.

5. Power Generation Experiment

The OHA ceramic electrets with Au strip were bonded on a glass plate as shown in Fig. 7a. For power generation experiments, the OHA electrets is fixed onto a stage connected to an electromagnetic shaker, and in-plane sinusoidal motion is applied. A glass plate with current-collecting counter electrodes with the same electrode width with the electret is prepared. It is fixed onto a 5-axis stage to precisely adjust the alignment and the air gap between the surface of the OHA electret and the counter electrodes. The vibration frequency is 10 Hz. The peak-to-peak vibration amplitudes are set to 1 mm for the 1 mm-wide electret/electrode, and 2 mm for the 2 mm-wide electret/electrode. Figure 8 shows the output voltage waveforms across a 400 M$\Omega$ load, and the output power versus the load resistance with different air gap. The peak-to-peak voltage amplitude up to 50 V and the output power of 0.9 $\mu$W with the 200 M$\Omega$ load.

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![Figure 5](image-url) **Figure 5.** Schematic of the vibration electret EH using stripe-shaped Au electrodes as the electrostatic shield.

![Figure 6](image-url) **Figure 6.** Surface potentials of OHA ceramic electrets with patterned Au electrodes on the surface.
is obtained with the 2-mm wide electret. Higher output power can be achieved by optimization of the strip width for electrostatic shielding and by using thinner air gap.

6. Conclusion

The poling characteristics of OHA ceramics were investigated in terms of microstructure using TSDC techniques. A patterning method of the surface potential of OHA electret is examined by using stripe-shaped electrodes on the surface. It is found that the surface potential becomes much lower than the plain electrode, and is decreased with the pattern width. Preliminary power generation experiment using in-plane vibration is made, and up to 0.9 \( \mu \)W output power is obtained with 10 Hz and 2 mm oscillation.

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References

[1] S. Roundy et al., Comp. Commu., 26, pp. 1131-1144, 2003
[2] Y. Suzuki, IEEJ Trans. Electr. Electr. Eng., 6, pp. 101-111, 2011
[3] G.M. Sessler, Electrets, 3rd ed., Laplacian Press, 1998
[4] Y. Sakane et al., J. Micromech. Microeng., 21 104011, 2008
[5] K. Kashigami et al., J. Micromech. Microeng., 21 125016, 2011
[6] H.-W. Lo, and Y.-C. Tai, J. Micromech. Microeng., 18 125016, 2008
[7] Y. Tanaka, et al., J. Appl. Phys., 107 014107, 2010
[8] D. Sato et al., Imaging Conf. Jpn. 2014, pp. 255-258, 2014