MEMS Rotational Electret Energy Harvester for Human Motion

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Abstract. This paper reports the development of MEMS rotational electret energy harvester (EH) for capturing kinetic energy of human motion. Optimal design method of rotational electret EH is proposed by considering both the rate of overlapping-area-change and the parasitic capacitance. A rotational MEMS electret EH with embedded ball bearing has been successfully developed. Up to 3.6 µW has been obtained at 1 rps rotation with an early prototype.

1. Introduction
Output power of resonance-type vibration energy harvesters (VEH) is limited by the velocity-damped resonance generator (VDRG) limit [1], and it is not a straightforward process to design VEH with large output power from human motion due to its very low vibration frequency. On remedy is to enlarge the vibration amplitude of mass [2, 3], but the dimension of the device in the vibration direction should be enlarged. Another approach is to use a moving “rotor” without tethers [4-6], but its advantage over the resonance generators in terms of the output power remains unclear.

On the other hand, rotational generator is widely used as the perpetual power source of wristwatches [7], and prototypes with electromagnetic [8] and piezoelectric [9] principles are also proposed for capturing both linear and rotational accelerations. A gyroscopic device is also proposed [10]. At low rotational speed, the electret generator should have higher output power than electromagnetic or piezoelectric ones [11]. The objective of the present study is to develop a MEMS rotational electret EH prototype.

2. Design of Rotational MEMS Electret Generator
Figure 1 shows the concept of MEMS rotational electret EH. Fan-shaped electret and guard electrodes are patterned on the rotor, and interdigitated electrodes are formed on the stator for collecting the induced charges. The rotor is connected to the stator with a miniature ball bearing, and can be rotated freely around its center. The rotor has an eccentric added mass, which makes the center of gravity of the rotor off-centered.
In order to maximize its output power, number of poles \( N \) and the gap between the interdigitated electrodes \( \delta \) should be optimized. With increasing \( N \), the rate of change of the overlapping area between electret and electrode is increased. On the other hand, with decreasing \( N \), the parasitic capacitance \( C_p \) is increased, which deteriorates the generator performance [12, 13]. Similarly, with increasing \( \delta \), effective electrode area is decreased, while \( C_p \) is increased with decreasing \( \delta \).

In the present study, in order to determine the optimum \( N \), we employ the analytical formula for the output power of rotational electret generator including the effect of \( C_p \) [12]. For \( C_p \), we employ the analytical formula for interdigitated electrodes [14]. On the other hand, \( \delta \) at the innermost radius is chosen as 30 \( \mu \)m based on the requirement of the present MEMS process.

In this analysis, the rotational speed, the outer radius of the rotor, the innermost diameter of the electrodes, the air gap between the top and bottom substrates, and the surface charge density are assumed to be 1 Hz, 20 mm, 9 mm, 100 \( \mu \)m, and 1 mC/m\(^2\), respectively. The relative permittivity of the stator substrate is assumed to be 3.2, since a thick SU-8 layer is formed on the stator as explained below. The external load is optimized for each \( N \). Figure 2 shows the parasitic capacitance \( C_p \) and the output power versus number of poles \( N \). It can be seen that \( C_p \) is increased with \( N \), and the output power is maximized at \( N=213 \), where the output power of 206 \( \mu \)W can be obtained. Based on this analysis, \( N \) is chosen as 220, by which the output power is unchanged.
3. Fabrication Process

Figure 3 shows MEMS fabrication process using 1.5 mm-thick Si wafers with thermal oxide. On the rotor side, the SiO₂ insulation layer is patterned for the first mask of the bearing housing, and Cr/Au/Cr interdigitated electrodes are patterned on the SiO₂ layer. Then, 15 µm-thick CYTOP EGG (Asahi Glass) electret layer is formed, and then Cu hard mask for CYTOP and Al mask for bearing housing are patterned. The center part of CYTOP is removed with O₂ plasma. This is followed by two-step DRIE for forming the stepped bearing housing; the first mask is the bottom SiO₂, and the second mask is the Al layer. Finally, CYTOP is patterned with O₂ plasma and the Cu mask is stripped.

On the stator side, an Al mask is patterned for the bearing housing, and 100 µm-thick SU-8 is formed. Thickness of SU-8 is determined for minimizing $C_p$ [13]. Then, Cr/Au/Cr interdigitated electrodes and another Al hard mask are patterned on the SU-8 layer. The center part of SU-8 is removed with O₂/SF₆ plasma. This is followed by two-step DRIE for forming the stepped bearing housing; the first mask is the bottom Al, and the second mask is the top Al layer. Finally, the Al mask is stripped.

Figure 4 shows the rotor and stator substrates successfully microfabricated. A 2 mm-high miniature ball bearing is successfully buried into the Si wafers, and the rotor can be smoothly rotated with very low friction. The measured value of $C_p$ is around 200 pF, which is slightly higher than the present estimate of 176 pF.
4. Experimental Results

In the present early prototype, the gap between the rotor and the stator is unfortunately non-uniform, and around 100 $\mu$m. This is because the ball bearing is not well-fitted to the housing due to the rough bottom surface of the housing. In addition, the surface potential is about -160 V, which is much lower than the target value of the surface potential is -700--800 V. This lower surface potential could be solved by using a thicker SiO$_2$ insulation layer and/or improved design of the interdigitated electrode suppressing discharge.

Figure 5 shows the output voltage with an impulse rotational force across 1 M$\Omega$ load resistance. The waveform in Fig. 5 with about 1 rps is extracted, and re-plotted in Fig. 6. The peak-to-peak voltage amplitude is about 5.5 V, which corresponds to 3.6 $\mu$W power generation. The experimental data are in reasonable agreement with the simulation result of 4.1 $\mu$W. With the optimum load of 3.3 M$\Omega$, the output power in simulation is 7.2 $\mu$W. Since the output power is proportional to the surface voltage of the electret squared, the output power in accordance with the designed value of 200 $\mu$W can be obtained with the present generator.

5. Conclusion

MEMS rotational electret energy harvester (EH) for capturing kinetic energy of human motion is developed. Optimal design of number of poles is proposed by considering both the rate of overlapping-area-change and the parasitic capacitance. A prototype with embedded ball bearing has been successfully developed. Up to 3.6 $\mu$W has been obtained at 1 rps rotation with the early prototype.
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Photo-mask is made using The University of Tokyo VLSI Design and Education Center (VDEC)’s 8-inch EB writer F5112+VD01 donated by ADVANTEST Corporation.

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