博士論文（要約）

Development of MEMS-based Vibration Energy Harvester with Vertical Electret
（垂直エレクトレットを用いたMEMS環境振動発電器の開発）

付　乾炎

The concept of vibration energy harvesting is to convert ambient environmental vibration energy into electricity for powering low-power-consumption electronics such as wireless sensor nodes, which will make significant contribution to the vision of Internet of Things (IOT). Among various energy conversion principles from kinetic energy to electricity, electrostatic/electret energy harvesters have attracted much attention for its high output power in small volumes and compatibility with CMOS/MEMS fabrication technologies. In electrostatic energy harvesters, the capacitance change should be maximized for enhancing output power, where comb drive is the most commonly used configuration for the MEMS variable capacitor. Actually, there are two different configurations of in-plane MEMS electret energy harvester with comb drives, that means the capacitance between two interdigitated fingers can be varied due to the overlapping-area-change (OV) or gap-closing (GC). Recently several research groups have concentrated on development of micro capacitive vibration energy harvesters with comb drives. However, at the authors' best knowledge, appropriate choice of the overlapping-area-change or gap-closing converters for maximizing output power under give conditions still remains unknown.

Another advantage of in-plane electrostatic/electret energy harvesters with comb drives is that it can be micro-fabricated through one-mask silicon-on-insulator (SOI) process without any assembling processes. Several microwatt level of output power can be obtained from the current electrostatic energy harvesters. However, external voltage source for the bias voltage applies is required for those electrostatic energy harvesters. The superiority of electret energy harvester is that it has built-in bias voltage. When properly charged, electret films can retain electrical charges for a long period. Several methods are proposed for charging the electret films such as contact charging, thermal poling, electron-beam injection, and corona charging. However, since corona ions cannot penetrate into such a small gap of a few micron-meters for the comb finger electrodes, it is not a straightforward process to charge vertical electrets on the sidewall of comb drives because of local charge accumulation near the gap opening. This is also true for other existing charging methods.

As explained before, in electrostatic energy harvesters, the capacitance change should be maximized for enhancing the output power. Also actually the output power is also directly linked to the electret's surface potential, and the vibration frequency when submitted to vibrations. However, since this is just a qualitative analysis, a complete electromechanical model of electret energy harvester with comb drives for mimic the response of the generators is required. A coupled simulation of electric circuits and a mechanical system in order to examine its performance under realistic vibration condition need to be built.

In the past decade, electret energy harvesters have been investigated and improved constantly. Boland *et al*. first developed a MEMS electret energy harvester using Teflon AF as the electret.

Lo *et al*. developed one prototype of parylene-based electret energy harvesters. The parylene-HT can provide a very high surface charge density of 3.7 mC^2/m^2 for a 7.3 µm-thick film. Up to 17.98 µW can be obtained at 50 Hz with the effectiveness of 0.05%. Matsumoto *et al*. examined power generation from forced oscillation using 480 µm wide CYTOP EGG electrets patterned on the substrate, and obtained maximum output power of 6 µW at 40 Hz with the effectiveness of 0.7%. Since the effectiveness for current proposed electret energy harvester are relatively low, MEMS-based vibration electret energy harvester with comb drives with high effectiveness is demanded.

Based on the above consideration, the objectives of the present research are

- To propose a design method for electrostatic/electret energy harvester with comb drives through comparison of the maximum capacitance change rate per unit area between overlapping-area-change and gap-closing interdigitated electrodes.
- To investigate surface potential distributions along a micron-gap soft-X-ray-charged vertical electret and apply the comb drive with vertical electret to a MEMS vibration generator for energy harvesting.
- To establish a complete electromechanical model of vibration-driven micro electret energy harvesters both for overlapping-area-change and gap-closing types of electret energy harvesters to accurately mimic the response of the electret energy harvesters.
- To propose the in-plane MEMS electret energy harvesters with overlapping-area-change or gap-closing types of comb drive electrodes for large output power and high effectiveness, and examine their electromechanical performances in a series of experiments.

A design method for in-plane MEMS electrostatic energy harvesters with comb drives has been proposed. The key design parameters of maximum capacitance change rate per unit area of the overlapping-area-change and gap-closing types are evaluated for the properly design of electrostatic generators. Dependent on the device layer thickness and the achievable aspect ratio of the deep-reactive-ion-etching (DRIE) process, either the overlapping-area-change or the gap-closing type converter has higher output power than the other. For thin device layers, the overlapping-area-change type is superior to the gap-closing type. On the other hand, for thick device layers, the gap-closing type is a better choice. The mapping of the thresholds for different aspect ratio seems a linear function of the aspect ratio. With increasing the aspect ratio, the region for the overlapping-area-change type is increased. For electret energy harvester with electret layer, the effective aspect ratio is increased, and thus the area of the overlapping-area-change type becomes broader with increasing the thickness of the electret film.

Surface potential distributions have been investigated along micron-gap soft-X-ray-charged vertical electrets. Parylene-C is proved to be applicable for vertical electret on the comb drives. The long-term stability of charge for parylene-C is examined. The surface potential only decreased to the 67% of initial surface potential even after 20-30 days. More stable electret material should be used for practical devices, but parylene-C electret can still be used for our proof-of-concept study. A novel charging method based on soft X-ray irradiation is applied to vertical electrets with micron-order gap. With the 130 V bias voltages, uniform surface potential of 60 V is obtained up to 70 μm in the depth direction for a 7 μm gap opening. Along the longitudinal direction along the comb finger, uniform surface potential is also confirmed.

Both overlapping-area-change and gap-closing types of MEMS electret energy harvester have been successfully micro-fabricated with the single layer silicon-on-insulator process without any assembly process. Mechanical response of the device shows that even after the parylene deposition, the quality factor of the structure is unchanged. The two prototypes of MEMS electret energy harvesters have been developed to verify the present design method. For the overlapping-area-change and gap-closing types of electret energy harvester, maximum output power of 1.79 μW and 0.973 μW are obtained at 1.9 g external acceleration, respectively. Since $\Delta C_r^* = 1.45$, the overlapping-area-change type has higher output power compared with that of the gap-closing type in the whole range of external acceleration. That means the present experimental data are in accordance with the numerical analysis.

The complete electromechanical models and corresponding comprehensive analysis have been conducted both for the overlapping-area-change and gap-closing types of vibration-driven MEMS electret energy harvesters. For both types of MEMS electret energy harvester with overlapping-area-change electrodes and gap-closing electrodes, the experimental data are in good agreement with the simulation results. Therefore, the present model is sufficiently accurate to mimic the response of electret energy harvesters.

Since capacitance of the gap-closing converters is inversely proportional to the displacement, and thus the gap-closing converter is suitable for large vibration acceleration. However, at small acceleration, the capacitance change diminishes. On the other hand, capacitance of the overlapping-area-change converters with a constant gap is linearly changed with the displacement, and thus its change is higher than that of the gap-closing type at low acceleration. Therefore, a novel electrode configuration combined with in-plane overlapping-area-change and gap-closing converters that provide relatively high output power both at low and high vibration accelerations has been proposed.

Finally, an early prototype of combined electrodes has been developed. Output power up to 1.6 μW at 266 Hz and 2 g has been obtained. For the device with the resonant frequency at 648 Hz, up to 3.6 μW has been achieved at 4 g. The effectiveness of the present device is 57%, which is higher than previous electrostatic/electret energy harvesters. Compared with the overlapping-area-change and gap-closing types of electret energy harvester, combined type of generator has higher output power.