POWER OUTPUT ENHANCEMENT OF VIBRATION-DRIVEN ELECTRET GENERATOR USING CONCAVE ELECTRODES

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Abstract: We fabricated a compact vibration-driven electret generator that excels at power output. It succeeded in the operation of the wireless sensor module only on electricity from its electret generator. Our compact vibration-driven electret generator can supply enough power to operate a wireless sensor module without external power source. It was necessary for enabling this operation to enhance power output of our electret generator. We enhanced power output of our electret generator by decreasing parasitic capacitance. To decrease parasitic capacitance, we prepared a collector substrate using concave electrodes. We decreased parasitic capacitance from 25 pF to 17 pF. As a result, the power out of our generator is enhanced from 40 μW to 100 μW considerably at an acceleration of 0.15 g (1.47 m s^{-2}) and a resonance frequency of 30 Hz.

Keywords: energy harvesting, electret, parasitic capacitance, wireless sensor module

INTRODUCTION

There is a problem on power supply as one of the factors which obstructs the spread of ubiquitous wireless sensor network. In case of using power line, high cost for installation and wiring will be a problem. In case of using battery, cost for maintenance will not be small. As a solution, we have developed a vibration-driven electret generator.

We succeeded in operating a wireless sensor module only on electricity from our electret generator. It was necessary for enabling this operation to enhance power output of our electret generator and achieved it by decreasing parasitic capacitance. To decrease parasitic capacitance, we fabricated concave electrodes on a collector substrate.

In this paper, we present how we decreased parasitic capacitance in our electric generator to achieve operation of a wireless sensor module without external power source.

HEALTH MONITORING FOR MOTORS

Fig. 1 shows the appearance and the block chart of our wireless sensor module. This module is composed of an electret generator, rectifying and charging circuits, energy storage devices, power supply control circuits, a wireless transmitter and an accelerometer.

Rectifying and charging circuits convert the AC current power output from the electret generator into DC current and step down to a target voltage. The energy storage devices convert the constant output in the order of micro-watts into the intermittent output in the order of milli-watts. The power supply control circuits control power supply to the wireless transmitter and the accelerometer to be efficient.

Fig. 2 shows outline and results of an experiment on our wireless sensor module. In this experiment, we expect to apply our wireless sensor module for health monitoring for motors. We verified whether our wireless sensor module work only with the electrical
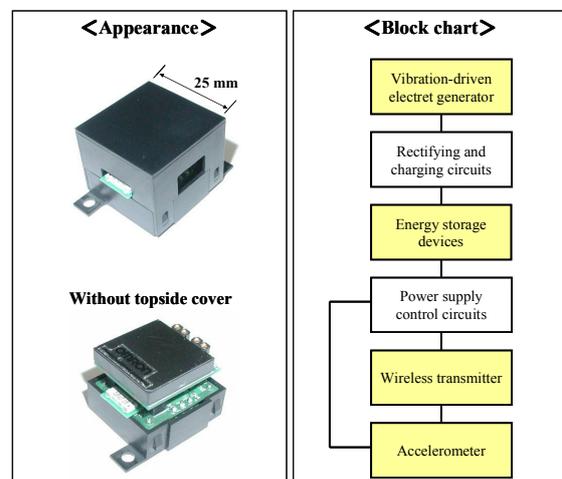

Fig. 1: Appearance and the block chart of the wireless sensor module.

energy generated by actual vibration from a motor. We obtained excellent verification results that our module was able to transmit the data on vibration of the motor (256 Byte) every 5 minutes at a distance of 10 meters in a room. This experiment was run in a room surrounded by concrete wall because motors are used in such room in real situation. Because the concrete indoor environments become a great stumbling block for wireless telecommunications, the transmission distance was 10 meters. For our health monitoring system for motors, we need at least one data on vibration of the motor in every ten minutes. The result of our experiment shows that data can be sent every 5 minutes. This result indicates that our wireless sensor module can be used for our health monitoring system for motors in real situation. Our system is useful for maintenance and inspection of the motors installed over a wide area or operated for a prolonged period. The surplus electricity in the module can be used to increase the number of sensing data or to extend the

transmission distance. We can choose how to use the surplus electricity according to the system requirements and the usage.
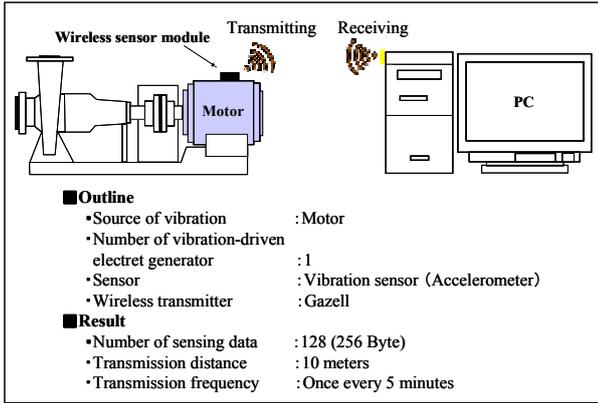

Fig. 2: Outline and results of the experiment on the wireless sensor module for motor health monitoring.

Fig. 3: Photos and schematic of electret generator. (a)Appearance, (b)Schematic of electret generator with the electret and collector substrate, (c)Electret substrate with patterned electret electrodes, (d)Collector substrate in the electret generator.

ELECTRET GENERATOR

The electret generator that we developed is a very compact, lightweight device. Fig. 3(a) shows the external view of an actual electret generator packaged in our wireless sensor module. Its size and weight are respectively $20 \times 20 \times 4$ mm^3 and 3.7 g. An internal structure is mainly composed of two functional parts. One is an electricity-generating part (electret substrate and collector substrate) fabricated by MEMS process and the other is a mechanical part (spring and slide mechanism element) by high-precision processing technology. An advantage of our electret generator is high durability. High reliability is obtained because the electricity-generating part and the mechanical part are separated, and vibrating stress doesn't apply to the electricity-generating part. Because it is possible to lighten with a simple mechanism and the vibrating stress can be reduced, the stress deterioration can be suppressed. In addition, the downsizing is also excellent because the electrode can be fabricated by MEMS process. Fig. 3(b) − (d) show schematics of electricity-generating parts and the patterned electret substrate and collector substrate. The mechanism how electret generators provide output power can be explained as follows. First, when electret electrodes with minus charges are opposed and overlapped to collector electrodes, plus charges is generated by the electrostatic induction on the collector electrodes in overlapping area. Then, if electret electrodes or collector electrodes are transferred by the extraneous vibration, the induced charges of the collector electrodes change. Power output of the electret generators is theoretically known for [1, 2]

$$P_{max} = \frac{\sigma^2 \cdot n \cdot A \cdot f}{2 \cdot \dfrac{\varepsilon_E \cdot \varepsilon_0}{d} \left(\dfrac{\varepsilon_E \cdot g}{d} + 1 \right)} \quad (1)$$
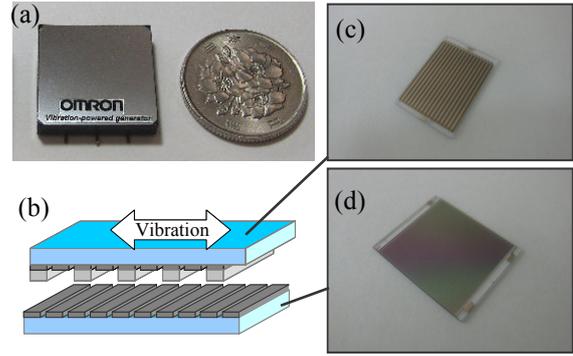
where σ is charge density, n is the number of electrodes, A is overlap area, f is frequency, ε_E is relative permittivity of electret, ε_0 is vacuum permittivity, d is electret thickness, g is separation gap. To obtain the large power output from environmental vibration with constant frequency, 1) giving high surface potential to electrets, 2) narrowing the separation gap between electrets and collector electrodes or 3) increasing the number of electrodes make advantage. However, in the case of 1), there is a problem that the charge retation becomes unstable when the electret surface potential is raised. In the case of 2), there is a problem that inner structure doesn't move because of the electrostatic force when the separation gap is too narrow [3]. Moreover in the case of 3), there is a problem that power output doesn't enhance because the parasitic capacitance influences harmfully when the number of the electrodes is increased. Therefore, it is important to handle parasitic capacitance [3, 4]. Technical details of reducing the parasitic capacitance are described.

PARASITIC CAPACITANCE

Parasitic capacitance is generated between a conductor carrying AC current and neighborhood conductor. According to this behavior of the parasitic capacitance, we considered that parasitic capacitance was generated between comb electrodes on the collector substrate where the induced charges by electret electrodes were harvested as AC current. Fig. 4 shows the schematic of various capacitances in electret generator. Because electric charges induced by electret electrodes and accumulated in C_1 leak to this C_3, electricity cannot be efficiently taken out of external load. As a result, it leads to the power output decrease. The result of actual measurement indicate that C_3 value of 25 pF is large compared to C_1 and C_2 (5 − 8 pF). To obtain the large power output, it is necessary to decrease the C_3. We calculated the capacitance model of C_3 as

$$C_3 = \frac{\pi \cdot \varepsilon}{\log(D-t)/0.5t} \cdot l \cdot n \qquad (2)$$

where π is circular constant, ε is relative permittivity, l is length of electrode, D is creepage distance between collector electrodes, t is film thickness. This calculation model is modified from a calculation of capacitance between the parallel transmission lines. C_3 is generated by capacitive coupling from the side of the collector electrodes mainly through the substrate part where the relative permittivity is higher. To decrease the C_3 from this Eq. (2), 1) extending the creepage distance D between collector electrodes, 2) lowering the relative permittivity of substrate or 3) reducing the thickness of collector electrodes make advantageous.
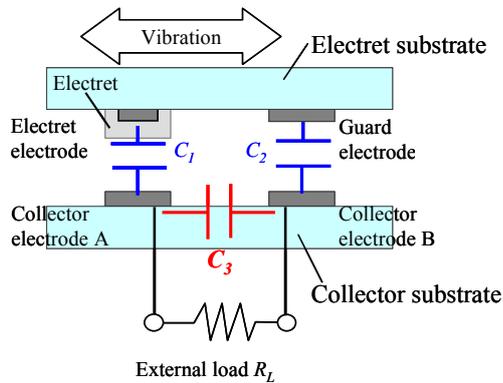

Fig. 4: Schematic of the electret generator with various capacitance. Capacitance C_1, C_2 and C_3 are generated in the gaps between the electret and collector electrodes, between the guard and collector electrodes and between the collector electrodes.

FABRICATION

We explain the method to extend D that is particularly-effective in decreasing C_3. There are three kinds of specific method for changing electrode geometry: "straight-line," "concave" and "salient" electrodes. A straight-line type is the electrodes with simply-extended D. A concave one is the electrodes with trenches between collector electrodes. On the other hand, a salient one is the electrodes with convex shapes between collector electrodes. A straight-line type is undesirable because the size of electret generator tend to be larger. A salient has the problems that it has the possibility the lines of electric force penetrates in the material whose relative permittivity is higher than that of air, and the fabrication process is difficult. We employ the concave because it can be easy to fabricate and surely take the D without enlarging the generator.

As a method of fabricating the concave electrodes, the blast method was adopted from the viewpoint of mass production and the aspect ratio. The boron carbide particle of mean particle diameter 10 μm was used for the blast. The quartz substrate ($\varepsilon_r = 4.0$) with low relative permittivity was prepared as a collector

substrate. As a result of optimizing film thickness of collector electrodes, Cr /Au (50 / 50 nm in thickness, t = 100 nm) thin film were deposited on the quartz substrate.

On the other hand, for electret electrodes, CYTOP (Asahi Glass Co., Ltd.) that was amorphous perfluoropolymer compatible with MEMS process was deposited. The CYTOP can be made with spin coat, and its thickness could be about 15 μm by multiple spin-on. It was also easily patterned by O_2 plasma etching. The corona electric charging was processed to these electret electrodes, and the surface potential of about -700 V was charged.

EXPERIMENT

We fabricated the concave electrodes on the collector substrate by blast method shown in Fig. 5. Fig. 5(b) shows the magnified cross-sectional photograph at A-A' line in Fig. 5(a). We could obtain the concave electrodes with 80 μm in depth using the blast method in the case of fabricating the substrate area between the gaps (65 μm) of collector electrodes. We confirmed that blast method was able to process concave electrodes of aspect ratio about 1.2.
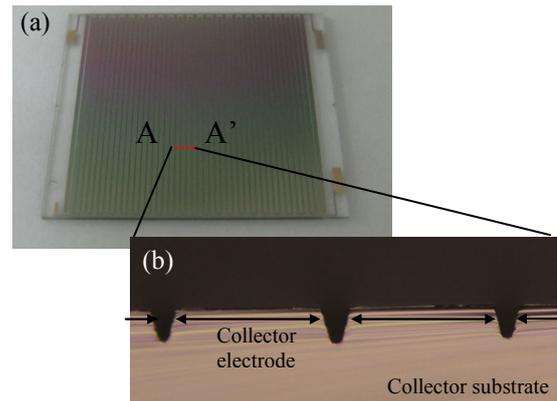

Fig. 5: Photos of the collector substrate that is same as Fig. 3(d). (a)Appearance, (b)Magnified cross-sectional view at the A-A' line with concave electrodes.

Fig. 6 shows calculated values and measured values of C_3 as a function of D. The calculated C_3 was plotted based on Eq. (2). The measured C_3 was plotted with accompanying microphotograph of the cross sectional images. The measured values match up to the calculated values. Our generator was able to reduce C_3 from 25 pF to 17 pF as a result of extending D from 45 μm to 180 μm by changing the way for fabricating the collector electrodes from the straight-line type to concave one.

We prepared electret generators with various values of C_3 (C_3 = 17, 20, 25 pF) shown in Fig. 6, and measured power output of the elecrtet generators at an acceleration of 0.15 g (1.47 m s^{-2}) and a resonance frequency of 30 Hz. Fig.7 shows the measured power output versus external loads. The power output of our generators were enhanced to 40 μW, 65 μW and 100 μW as C_3 values were reduced to 25 pF, 20 pF and 17

pF. There was as much as 60% contribution to the power output enhancement by the C_3 reduction of 8 pF. In addition, the higher power output was always obtained for all external loads by reducing C_3. The electret generator with lower resistive load can be designed by the reduction of C_3.
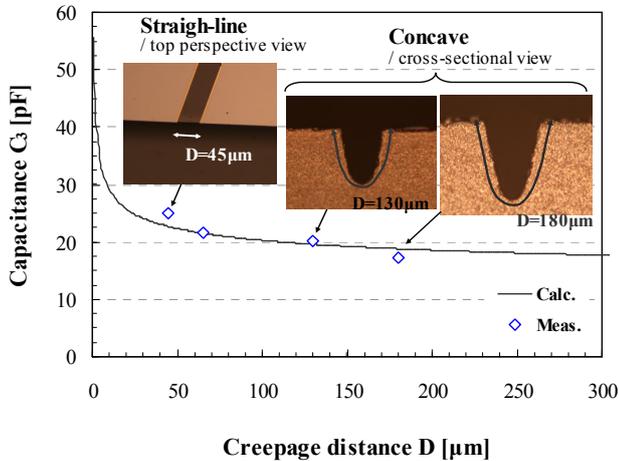

Fig. 6: Creepage distance D versus parasitic capacitance C_3 between the collector electrodes. C_3 is calculated with Eq. (2). Accompanying photos are the top perspective view with the straight-line electrodes and the cross-sectional views with the concave electrodes of various depths.
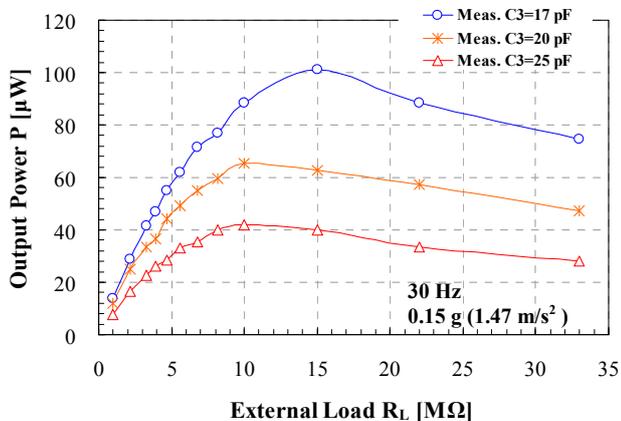

Fig. 7: Comparison of the measured output power versus external load resistor for various C_3 values in the collector substrates.

CONCLUSION

We fabricated a compact vibration-driven electret generator that excels at power output. It succeeded in the operation of a wireless sensor module only on electricity from its electret generator. It was necessary for enabling this operation to enhance power output of our electret generator.

We enhanced power output of our electret generator by decreasing parasitic capacitance. To decrease parasitic capacitance, we prepared a collector substrate using concave electrodes by blast method. We could decrease parasitic capacitance from 25 pF to 17 pF. As a result, the power out of our generator is enhanced from 40 μW to 100 μW considerably at an acceleration of 0.15 g (1.47 m s^{-2}) and a resonance frequency of 30 Hz.

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