ELECTRO STATIC MICRO POWER GENERATOR USING POTASSIUM ION ELECTRET FORMING ON A COMB-DRIVE ACTUATOR

M. Suzuki[1], H. Hayashi[1], A. Mori[1], T. Sugiyama[2] and G. Hashiguchi[2]
[1]AOI Electronics Co., Ltd., Takamatsu, Japan
[2]Research Institute of Electronics, Shizuoka University, Hamamatsu, Japan

Abstract: This paper reports the testing and the theory of an electro static micro power generator with silicon dioxide electret induced by highly doped potassium ions. This electret film was formed on the etched sidewalls of comb-drive electrodes. Oxide film on the side-wall incorporated potassium ions was grown by steam from bubbling KOH solution. To charge SiO_2 film, bias-temperature (BT) procedure was applied to the device at about 200 V and 700 K. We have confirmed about 90 V built-in potential. A maximum output power of approximately 50 nW is obtained at load resistance of 100 MΩ. Vibration acceleration is 0.6 m/s^2 and resonance frequency is 58 Hz. We obtained close agreement between the experimental and theoretical values of the electrical characteristics.

INTRODUCTION

These days, the field of energy harvesting that utilizes environmental energy has been advancing. One of the parts of the field, vibration-driven electret generator is expected to harvest energy from vibration energy of low frequency.[1] The comb-drive actuator is a device that converts energy efficiently between electrical and mechanical vibration. We assume that the comb-drive actuator with electret film formed at the opposing faces of the comb electrodes realizes a higher electro-mechanical conversion coefficient, and utilizable Electro Static Micro Power Generator devices with low output impedance.

In general the electret film retains electric charges semi permanently such as electret condenser microphones.[2] There are several methods to give electric charges to the electret films such as corona discharge[3], ion implantation[4], electron beam injection[5], or molecule ionization by X-ray radiation[6]. These methods, however, they are only applicable to open planar surfaces but not to sidewalls of deep trenches, so that to realize electret film formed at the opposing faces of the comb electrodes with a few micro meter gaps had ever been difficult.

However, articles we have reported above shows that electret film formed at opposing faces of comb electrodes has been realized by thermal oxidation with the nitrogen atmosphere including potassium ions[7]. Also this paper reports matching between testing results and theoretical equation of vibration-driven generation with silicon dioxide electret, which is induced by highly doped potassium ions formed at the opposing faces of comb electrodes.

SiO$_2$ ELECTRET USING POTASSIUM ION GREW AND CHARGED

Figure 1 (a) is an illustration of our oxidation set up. We examined the thermal oxidation as follows. Firstly, the oxidation furnace temperature was set at 1,203 K ~ 1,473 K. 40 wt% KOH solution was maintained at 358 K in a hot bath. The carrier gas of the bubbling was pure nitrogen gas with a flow rate of 2 L/min. The steam was floated through the furnace. The details of the oxidation setup are reported elsewhere.[7] These conditions were maintained for a few hours.
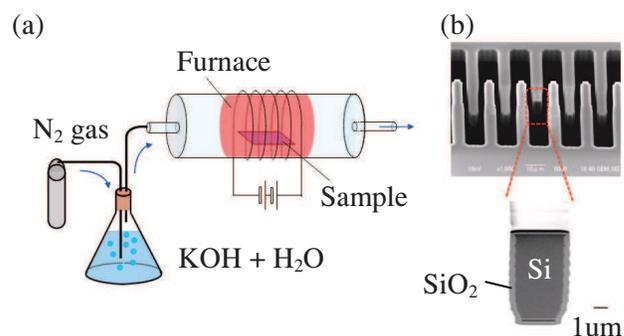

Fig. 1: (a) Oxidation setup with bubbling steam of KOH solution. (b) SEM images of the oxidized film on the silicon etched side wall. The magnified view shows a cross section of the comb electrode cut by a focused ion beam.

This is how we realized SiO_2 film incorporated potassium ions at the opposing faces of the comb electrodes. Figure 1 (b) shows a SEM image of a cross-section of a comb electrode after 8 hours oxidation at 1,223 K. As shown here, thermal oxide was uniformly formed on even such small gap

structures, and the thickness was found to be approximately 500 nm as equal as the thickness of bulk silicon substrate. The secondary ion mass spectroscopy (SIMS) data showed that about 3×10^{17} cm^{-3} potassium ions are incorporated in the SiO$_2$ film while 1×10^{19} cm^{-3} potassium ions are trapped at the interface between silicon substrate and the SiO$_2$ film.

Electrodes pads were deposited with 500 nm thick SiN film to prevent pads from oxidation. The SiN film was selectively removed by reactive ion etching (RIE) using SF$_6$ gas after oxidation.

After these processes, we conducted bias-temperature procedure to move potassium ions in the SiO$_2$ film to the surface of the film. The sample was heated at 673 K to 1,073 K using a hot plate applied DC voltage of 200 V to 400 V.

After one hour of BT procedure, we turned off the hot plate and cooled down at room temperature with DC voltage on. After these processes, overlapping length between the opposing comb electrodes was increased with decreasing of DC voltage. This means that comb electrodes moved without applied external bias voltage.

Figure 2 shows time trace of quantity of charged electricity characteristics of device charged by this method. Furthermore, hydrophobic films are covered by HMDS (hexamethyldisilazane) film after BT procedure. This also shows that quantity of charged electricity at four device samples within six devices samples of A to F gradually decrease as time passes, while at other two device samples of E and F, quantity of charged electricity was maintained as it was.
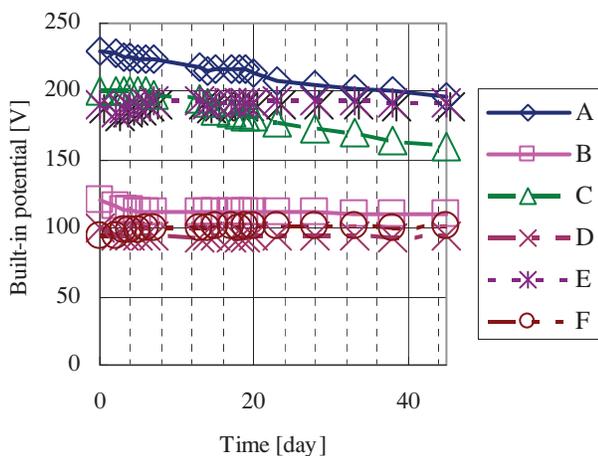

Fig. 2: Time trace of the built-in potential of SiO$_2$ electret covered by HMDS film.

EXPERIMENTAL AND RESULT

We have fabricated a prototype of Fig. 3 (a) to describe the performance of power generation caused by vibration of comb-drive actuator with comb electrodes formed with electret film. SOI (Silicon on Insulator) substrate with device layer of 100 μm thickness. The prototype has size of 12 mm-square, and 333 pairs of comb electrodes. The initial overlapping length of comb electrodes was 300 μm, and gap distance between the electrodes was 10 μm. The capacitance between the comb electrodes was 19 pF. Also the mass with effective mass of 2.4×10^{-5} kg was supported with spring with spring constant of 2.5 N/m. Using the oxidation methods we mentioned in section 2, we have oxidized the opposing faces of the comb electrodes. The comb-drive actuator was wet oxidized for 3.5 hours in the furnace set at 1,473 K. Thickness of the SiO$_2$ film was 1 μm. Cr and Au thin films were deposited on the surface of the electrode pads. BT procedure was examined with the hot plate temperature set at approximately 673 K, and applied DC voltage was 200 V.
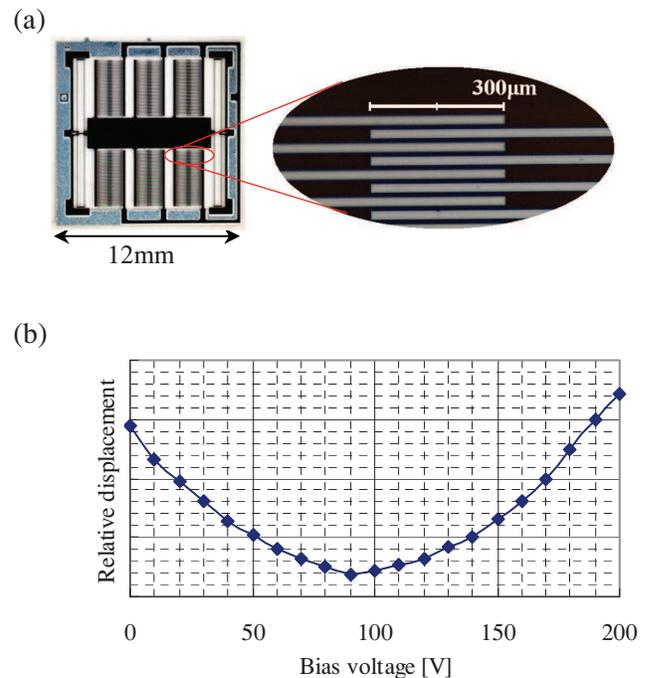
(a)

(b)

Fig. 3: (a) image of the comb-drive actuator with SiO$_2$ electret film. (b) Relative displacement between the opposing comb electrodes when Bias Voltage (DC) is applied to the fixed comb electrode.

Firstly, external DC voltage was applied to the electrode pads connected to the fixed comb electrodes to confirm the potential difference between the opposing comb electrodes, and electrode pads connected to the opposing movable electrodes was

connected to ground. Figure 3 shows relative-displacements observed as the function of applied DC voltage. Movable comb electrodes are pulled-in from the initial position at the state without charged to the side of fixed comb electrodes by the electric field induced by electret film. After that, movable electrodes are pulled-in again. External applied bias voltage at which movable electrodes move to the initial point is equal to the potential difference between the opposing electrodes. Therefore we assume that the potential difference is arisen at approximately 90 V.

Next, experiment of power generation is examined using configuration of Fig. 4. A voice coil was used as the source of vibration. Amplitude the stage of the voice coil vibrates is proportional to the amplitude of output signal of function generator. The plate is set vertically to the stage to fix the electro static micro power generator over the plate. And, electrode pads of the device connected to the fixed electrodes was connected to the ground, while electrodes pads connected to the movable electrodes was connected to the load resistance. We applied the vibration to the device to measure the potential arisen between both terminals of the load resistance.
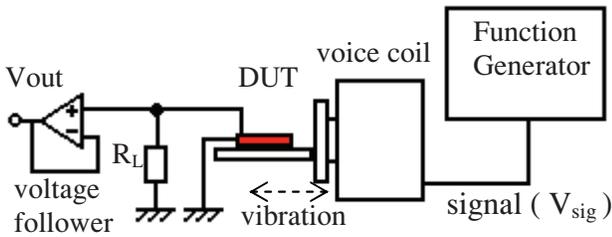
Figure 5 shows the frequency dependence of vibration acceleration of the voice coil measured by a laser Doppler velocity meter. The measured value was a constant of about 0.6 m/s^2. Figure 6 shows the time trace of the output voltage measured at load resistance of 100 MΩ. We obtained output voltage of approximately 6.4 V_{p-p}. Also Fig. 7 shows the output voltage and current and power for each load resistance. A maximum output power is approximately 50 nW at the load resistance of 100 MΩ.
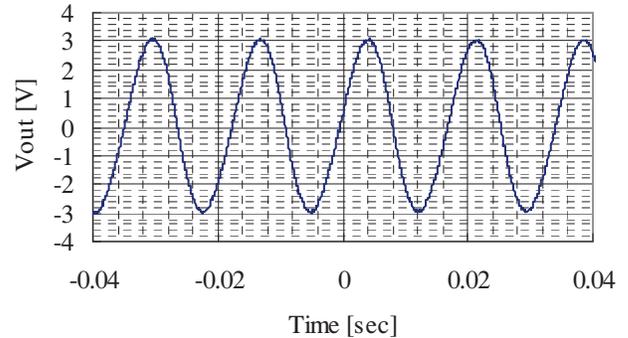

Fig. 6: Time trace of the output voltage (Vout) at f = 58Hz and R_L = 100 MΩ.

Fig. 4: Schematic diagram of the experimental setup for power generation.

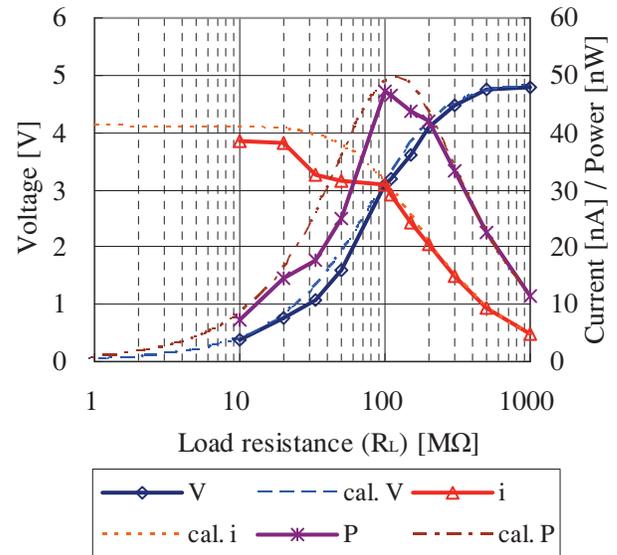*Fig. 7: Power output versus external load resistance (R_L) at f=58 Hz.*

DISCUSSION

We have observed the vibration-driven electret power generation of the comb-drive actuator with SiO$_2$ film oxidized with the steam of bubbling KOH solution. We now examined the adaptability of the comb-drive actuator to the linear electro-mechanical equation. The linear equation is represented by

Fig. 5: Vibration acceleration of the voice coil versus frequency.

$$\begin{pmatrix} f \\ i \end{pmatrix} = \begin{pmatrix} r_f + j\omega m + \dfrac{k}{j\omega} & -\dfrac{C_0 E_0}{X} \\ \dfrac{C_0 E_0}{X} & j\omega(C_0 + C_s) \end{pmatrix} \begin{pmatrix} v \\ e \end{pmatrix}, (1)$$

where j is an imaginary number, ω is the angular frequency, f is the external force applied to the comb-drive actuator, v is the root-mean-square (RMS) vibrating velocity of the comb-drive actuator, r_f and m are the mechanical resistance and the effective mass, k is the spring constant, X is the initial overlapping length of comb electrodes, i and e are the RMS current and the voltage of two electrode pads, and where each of C_0 and C_s are capacitances between the opposing electrodes and parasitic capacitances, respectively. f is given by f = ma, where a is RMS value of the vibration acceleration of the comb-drive actuator. Also, load resistance was connected between two opposing electrode pads and equation of the power consumed with load resistance derived from equation (1) is given by

$$P = \frac{R_L}{2} \frac{A^2 \cdot f^2}{\left[\begin{cases} r_f + A^2 R_L + k(C_o + C_s)R_L \\ -\omega^2 m(C_o + C_s)R_L \end{cases}^2 + \left\{ \omega\big(m + r_f(C_o + C_s)R_L\big) - \dfrac{k}{\omega} \right\}^2 \right]}, \qquad (2)$$

where A is the electro-mechanical conversion factor, which is given by A = $C_0 E_0/X$. We substituted the designed value and each experimental values (a = 0.6 m/s^2, E_0 = 90 V, $\omega = 2\pi \times 58$ Hz) to eq. (2). Figure 7 also shows the calculated power (cal. P), current (cal. i) and voltage (cal. V). We obtained close agreement between the experimental and theoretical values of the electrical characteristics.

CONCLUSION

We obtained close agreement between experimental result of power generation of the electro static micro power generator with silicon dioxide electret film induced by highly doped potassium ions with the opposing faces of the comb electrodes and the calculated result of theoretical equation. We conclude that we will be able to develop a new device with a high efficiency of power generation based on out early prototype.

Furthermore, this charging method we examined is different from the conventional methods, and using this method we can control the quantity of charged electricity selectively, so that this method is conducted to confirm the potential differences arisen between electrodes. And this method can be mass produce having batch molding and uniformly charging attributed to the MEMS process.

Also, this result is applicable to the electro static micro transducer.[8]

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