Soft-X-Ray-Charged Vertical Electrets and Its Application to Electrostatic Transducers

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ABSTRACT
A novel charging method for vertical electrets in narrow gaps using soft X-rays has been developed. Electrets can be charged up to the depth 20–30 times of the gap opening. With the present charging technology, MEMS electret transducers can be fabricated using a single wafer without assembling process. We demonstrate performance of vertical electrets using early prototype of in-plane accelerometer. Under 18.7 µm-p external oscillation at 500 Hz, 30 mV output has been obtained without external bias voltage. Surface potential for 80 µm-deep vertical electrets is estimated to be 52 V.

INTRODUCTION
Electret is a dielectric material with quasi-permanent charges. Eguchi [1] first developed carnauba wax electret using a thermal polarization method. Since then, various applications of electrets such as acoustic/mechanical transducers and air filter have been proposed [2]. Recently, electrets also are applied to various micro devices including MEMS microphone [3], vibration-driven power generator [4-9], radiation dosimeter [10], gap control with electrostatic levitation [11], and droplet manipulation using liquid dielectrophoresis [12]. We have also developed new high-performance polymer electret based on CYTOP (Asahi Glass), which enables extremely high surface charge density of 1.5 mC/m² [13].

However, in most electret devices, assembling process is necessary after charging the electrets. Recently, we have developed a new charging method using soft X-rays [14, 15]. When soft X-rays up to 10 keV are irradiated to air, positive and negative ions equally generated in the gap. They are dragged toward electrets with an electric field across the gap, and the charges are transferred to the electrets. Since soft X-rays can penetrate into narrow gaps, even ‘vertical’ electrets on the sidewall of high-aspect-ratio structures can be made as shown in Fig. 1b.

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VERTICAL ELECTRETS CHARGED WITH SOFT X-RAYS
Corona discharge is a conventional charging method for electrets, in which corona ions emitted from a high-voltage needle transfer their charges onto the electret film when they arrive at the surface. However, corona ions cannot penetrate substrates or narrow gaps due to charge build-up near the opening. Therefore, after charging, the substrate with electrets should be assembled with the other substrate as shown in Fig. 1a, prohibiting the use of electrets in single-wafer approach.

In the present study, we develop ‘vertical’ electrets by using the soft X-ray technology, which can be used for in-plane single-wafer electret transducers. We also demonstrate the performance of vertical electrets with microfabricated accelerometer prototype.

Figure 1. a) Conventional fabrication method of electret transducers with assembling after charging, b) In-situ charging method for ‘vertical’ electrets using soft X-ray irradiation enabling single-wafer electret transducers.
To begin with, surface potential of ‘vertical’ electrets charged through the narrow gap is examined using a setup shown in Fig. 2a. In the present study, parylene-C is used as the electret material [16], since it can be coated on complex 3D structures with CVD. Here, 2-µm-thick parylene-C is coated on one side of copper substrates. The gap between the parylene-C electret and a counter electrode made of a copper substrate is defined with the thickness of an olefin spacer film. Soft X-ray tube of 9.5 keV is used for irradiation. The bias voltage and the irradiation time are respectively chosen as 100 V and 10 minutes. Figure 2b shows the surface potential measured with an electrostatic voltmeter (Monroe Electronics, model 244A) versus the distance from the opening. Note that surface potential below 2 mm is unavailable due to low spatial resolution of the electrostatic probe. The surface potential near the opening reaches more than 90 V, which is nearly equal to the bias voltage applied during charging. The surface potential is almost constant up to the distance 20~30 times of the gap opening. Therefore, almost uniform surface charge distribution on vertical electrets should be available up to the depth of 100 µm for gap opening of a few µm.

**DESIGN OF ELECTRET ACCELEROMETER PROTOTYPE**

To demonstrate the performance of vertical electrets, an accelerometer prototype using electrets on comb fingers was designed. An SOI wafer with an 80-µm-thick device layer was used. The length of suspension beam is 450 µm with a cross section of 80 µm x 6 µm. The comb length and width are respectively 6 µm and 30 µm, while the gap between facing combs is 5.5 µm. 1.5-µm-thick parylene-C is used as the electret. The proof mass is 2.8 mm x 1.9 mm. The resonant frequency and the capacitance of the comb fingers are estimated to be 2.2 kHz and 1.4 pF, respectively.

**MEMS FABRICATION**

Fabrication process of the present in-plane electret accelerometer prototype is shown in Fig. 4. Process starts with EB evaporation of Cr/Au/Cr layers (10/200/10 nm) onto a 4” SOI wafer (Fig. 4a), followed by standard lithography of the metal layers to pattern the structures (Fig. 4b). Springs and comb fingers are then etched into the 80-µm-thick device layer with DRIE (Fig. 4c). The handle layer is also etched with DRIE from the backside to release the structure and to avoid stiction of the proof mass during parylene deposition (Fig. 4d). After the SiO₂ layer is stripped with vapor HF (Fig. 4e), 1.5-µm-thick parylene-C is coated by CVD on the whole structure forming electret films on both sides of the comb fingers (Fig. 4f). The device is fixed on a PC board and wired. Figure 5a shows the device with a proof mass supported with 6-µm-wide Si beams, and Fig. 5b shows the close-up view of the comb fingers with parylene-C electrets.
EXPERIMENTAL RESULTS

Parylene-C electret is charged with soft X-ray of 9.5 keV with the bias voltage of 100 V for 30 minutes. The device is fixed onto an electromagnetic shaker (LW-140-110, Labworks), and in-plane oscillation is applied to the device. The amplitude is measured with a laser displacement meter (LC-2430, Keyence).

Figure 6 shows the output voltage signal for 18.7 µm_p-p external oscillation at 500 Hz. Amplitude of the proof mass is estimated to be 1.2 µm. In this measurement, the comb drive is shunted with a 10 MΩ resistor, and the voltage across the resistor is measured as shown in Fig. 6. Hum noise is removed with a high-pass Fourier numerical filter. The output as large voltage as 30 mV has been obtained without any electrical amplification. Figure 7 shows voltage amplitude versus external vibration amplitude. The output voltage is almost linearly increased with the external amplitude, and its trend is in good agreement with the present model described above. Surface potential estimated by the curve fitting is 52 V. The surface potential is a half of the charging bias voltage, since long-term stability of charges in parylene-C electrets is much less than that of CYTOP.

CONCLUSIONS

‘Vertical’ electrets have been proposed based on a novel charging method with soft X-ray irradiation. Surface potential can be precisely controlled with the bias voltage, and electrets are formed on the sidewall inside narrow gaps. The depth of vertical electrets
can be 20–30 times of the gap opening. Early prototype of single-wafer in-plane electret accelerometer is designed and successfully fabricated. At 500 Hz, voltage amplitude of 30 mV has been obtained without any amplification. Output voltage is almost linearly changed with the external amplitude, and estimate of surface potential is 52 V. It is believed that the present approach can open up a new field of MEMS electret transducers.

The authors thank Dr. Y. Yasuno and Dr. H. Kodama in Kobayasi Institute of Physical Research and Mr. K. Kidokoro in RION Co., Ltd. for fruitful discussion during the course of this work. Photomasks are made using the University of Tokyo VLSI Design and Education Center (VDEC)’s 8-inch EB writer F5112+VD01 donated by ADVANTEC Corporation.

REFERENCES