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 $\mu m_{p\text{-}p}$ 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/m^2 [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-ray irradiation, and revealed that surface potential and thermal stability of electrets charged with the soft X-ray method are as good as those with corona discharge [14, 15].

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 acceleromer prototype.

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.

Recently, we have developed a new electret 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.

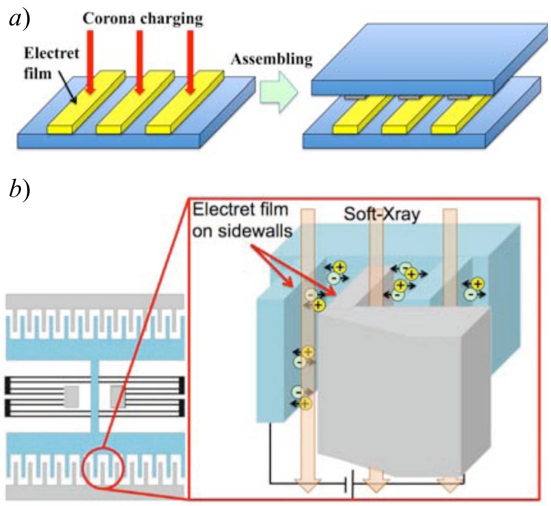

Figure 1. a) Conventional fabrication method of electret transducers with assembling after charging, b) In-situ charging method for 'vertical' electrets using soft X-ray irradiation enabling single-wafer electret transducers.

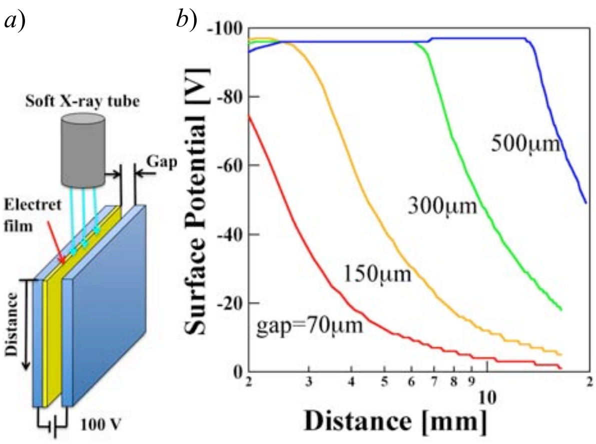

Figure 2. Soft X-ray charging tests in narrow gap.

To begin with, surface potential of 'vertical' electrets charged through the narrow gap is examined using a set up 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 paryelne-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.

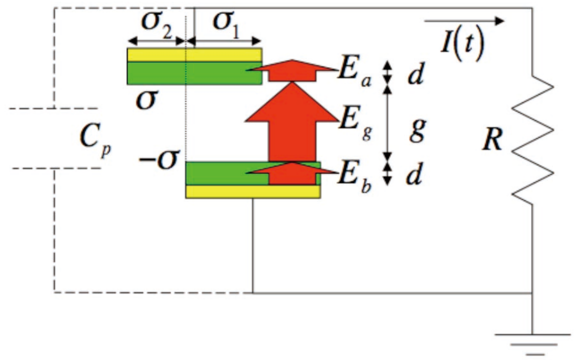

Figure 3. Numerical model assumed one-dimensional electrostatic field.

Figure 3 shows a numerical model of the present electret accelerometer based on one-dimensional electrostatic field [17], where d, g, and σ are respectively thickness of electret, the gap between electrets, and the surface charge density. σ_1 is the charge density induced on the upper electrode facing the bottom electret, while σ_2 is the induced charge density on the upper electrode without overlap with the bottom electret. Based on Gauss' and Kirchhoff's laws, the charge conservation equation leads to

$$\frac{d\left(A_1\sigma_1\right)}{dt}+\frac{d\left(A_2\sigma_2\right)}{dt}+C_pR\frac{dI}{dt}+I=0\,,$$

where C_p, R, and A_1 are respectively the parasitic capacitance, the external load, and the area of the upper electrode facing the bottom electret, while A_2 is the upper electrode area without overlap with the electret. As in the present experiment, parameters are chosen as d=1.5 μm, g=5.5 μm, C_p=50 pF, and R=10 MΩ.

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 SiO_2 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.

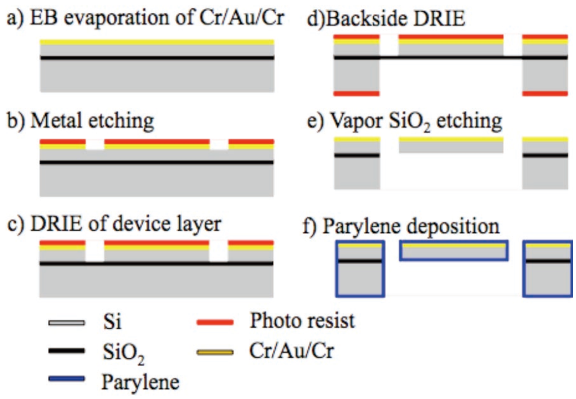

Figure 4. Fabrication process of the electret accelerometer prototype.

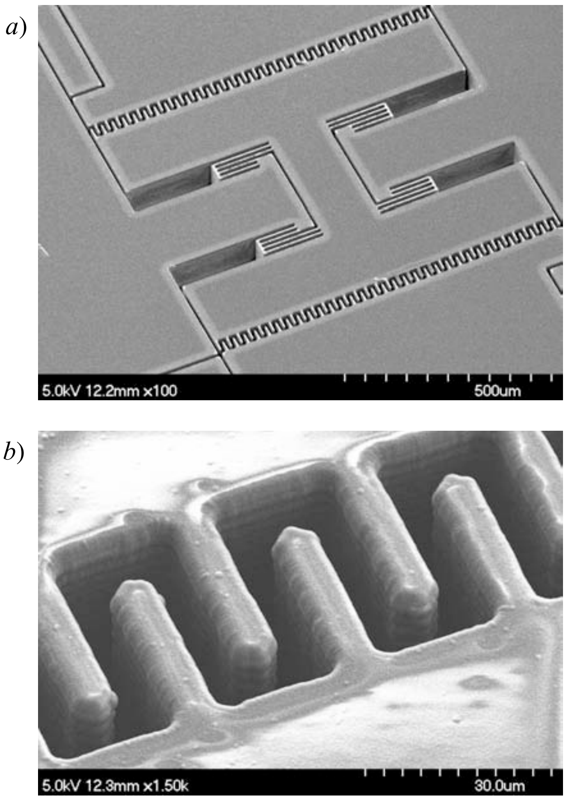

Figure 5. SEM images of in-plane accelerometer prototype with 'vertical' electrets. a)Overview, b)Close-up view of comb fingers with paryelne-C electrets.

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).

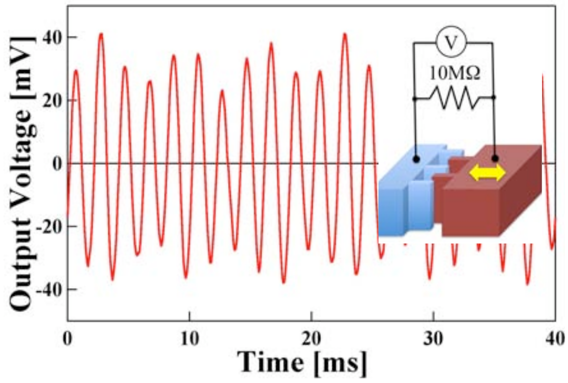

Figure 6. Output voltage signal across a 10MΩ shunt resistor for 18.7 μm$_{p\text{-}p}$ external oscillation at 500Hz.

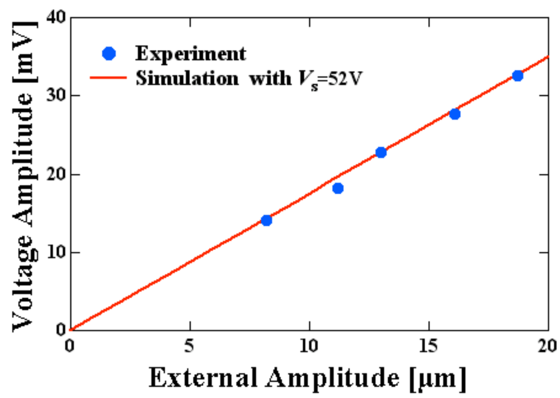

Figure 7. Output voltage versus amplitude of external vibration at 500Hz.

Figure 6 shows the output voltage signal for 18.7 μm$_{p\text{-}p}$ 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.

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