

# NOVEL THROUGH-SUBSTRATE CHARGING METHOD FOR ELECTRET GENERATOR USING SOFT X-RAY IRRADIATION

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**Abstract:** A new charging method with soft X-ray irradiation has been investigated for MEMS electret generator. Since the radiation can penetrate through Si/glass substrate and generate ions inside air gap, electret can be charged even after assembling/packaging process. As proof of the concept, a CYTOP film was charged through the Al foil electrode using soft X-ray irradiation. We found that charging properties such as uniformity, stability and controllability are as good as those of electrets charged by conventional corona discharge. Although the charging time in air is longer than that for corona discharge, reduction of the charging time is possible by using higher-energy X-ray and other gases species with higher absorption factor to soft X-ray.

**Keywords:** Energy harvesting, Electret, Soft X-ray, CYTOP

## INTRODUCTION

In recent years, energy harvesting from environmental vibration attracts much attention from the perspective of its application to low-power electronic devices such as sensor network node [1,2]. Especially, power generation from human motion [3] is one of the key technologies for future green mobile electronics.

Electret power generator is suitable for converting low-frequency vibration below 100 Hz to electricity, if compared with other technique such as electromagnetic ones. So far, we have developed new high-performance polymer electret based on CYTOP, and demonstrated extremely-high surface charge density using corona discharge [4]. We have also prototyped a vibration-driven electret generator with low resonant frequency [5].

In the present study, we report a novel through-wafer electret charging method using soft X-rays, which enables charging even after assembling or packaging process, since soft X-rays can penetrate various materials and ionize gas molecules in the gap.

## SOFT X-RAY CHARGING METHOD

Corona discharge is one of the most popular charging methods for electrets, by which a high-voltage needle electrode is employed to produce corona ions and to implant stable surface charges in relatively short time. Since corona ions cannot penetrate substrates, electret should be charged prior to assembling/packing processes such as anodic

bonding, frit sealing, and solder reflow. This is problematic because polymer electrets cannot hold implanted charges at high temperature above 100 °C [4], which is required for most assembling/packing technologies.

In the 1970's, charging methods of electret using the Compton effects was studied [6] with X-rays or gamma rays, of which energy is several MeV. However, charging effect of lower energy irradiation have not been examined in detail.

Figure 1 shows the conceptual diagram of the present charging method using soft X-ray. Soft X-rays are electromagnetic radiation up to tens of keV, which can ionize gas molecules. When the soft X-rays up to 10 keV are irradiated to air, the ions such as  $\text{CO}_3^-$ ,  $(\text{H}_2\text{O})_2\text{H}^+$ ,  $\text{O}_2^-$ , and  $\text{H}_3\text{O}^+$  are produced from air

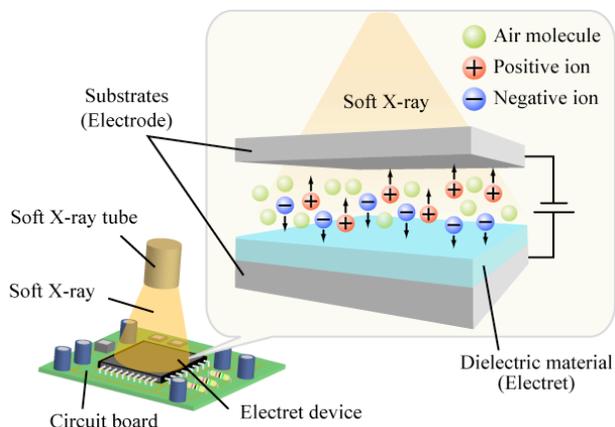


Figure 1. A conceptual diagram of charging method with soft X-ray irradiation.

molecules [7]. Soft-X-ray-induced ions are often used for the neutralization in semiconductor processing, since the particle contamination or the ozone production is less than that of a corona discharge neutralizer.

To implant charges, positive and negative ions generated with the X-rays are separated by applying an electric field to the irradiated region. When an electret film is formed on an electrode with positive potential, negative ions are dragged toward its surface and the charges are transferred to the electret.

In addition, soft X-rays can penetrate materials used in various MEMS components. For example, transmittance of 10 keV soft X-rays through a 0.4 mm-thick SiO<sub>2</sub> substrate is as large as 20 %. Therefore, the present method enables charging electrets inside assembled or packaged device on a circuit board.

### EXPERIMENTAL SETUP

Electret properties charged with soft X-ray irradiation were examined to evaluate the present method for electret generators. Figure 2 shows a photo of the experimental setup using soft X-rays. As the proof of concept, an aluminum foil with the thickness of 12 μm was used as the top electrode, and the sample was irradiated with soft X-rays through the aluminum foil. The target material of X-ray bulb is tungsten and the energy range is from 3 to 9.5 keV. From the measurement with the photosensitive film badges (Nagase Landauer, Ltd., Luxel), dose equivalent is estimated to be 61 Sv/h when the bulb current is 200 μA and the bulb-to-sample distance is

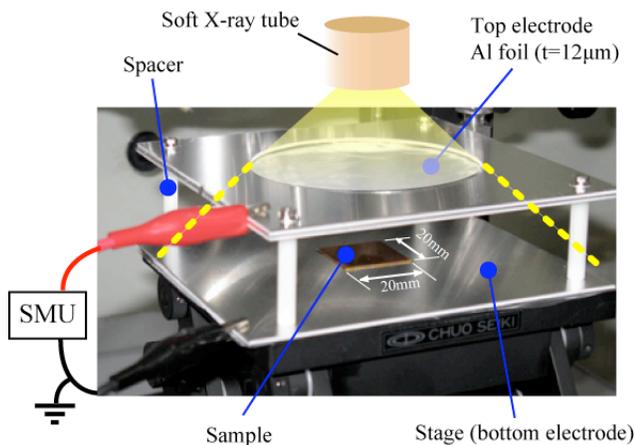


Figure 2. A photo of the experimental setup for the present charging method. In order to separate ions and drag negative ions to electrets, positive potential was applied to the bottom electrode.

20 mm. To apply an electric field and measure the ion current, source measure units (SMU, Keithley Instruments Inc., Model 2410) was used. CYTOP (Asahi Glass, CTL-M) film with the thickness of 15 μm is formed on Cu substrates with spincoating as electret samples. Sample was charged at room temperature, and no annealing was made after the charging. Surface potential of the charged electret sample was measured with the electrostatic voltmeter (Monroe Electronics Inc., model 244A).

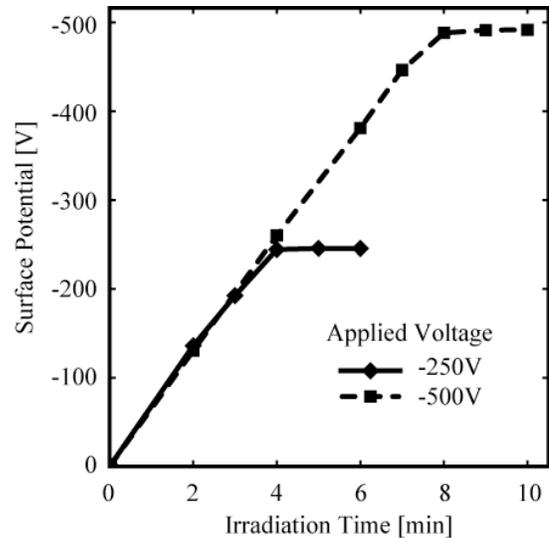


Figure 3. Surface potential versus irradiation time (gap = 3 mm). The data are average value of 9 points in the central 6 × 6 mm<sup>2</sup> area.

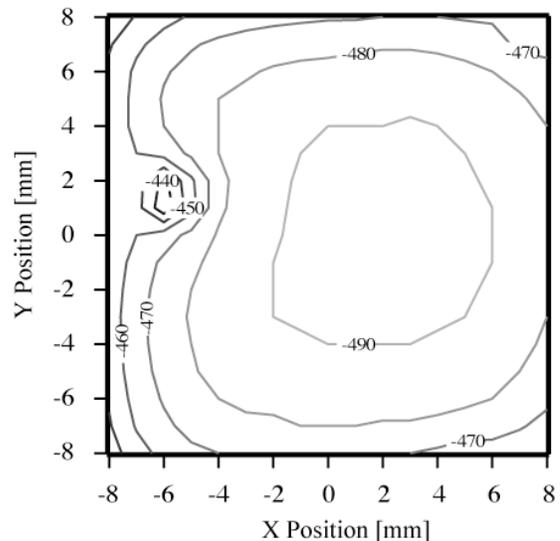


Figure 4. The contour map of surface potential of charged electret (irradiation time = 8 min, top electrode voltage = -500 V). Distance between the sample stage and the soft X-ray bulb is about 70 mm.

## RESULTS & DISCUSSION

### Surface Potential

Figure 3 shows the surface potential of CYTOP film. The surface potential initially increases in proportion to the irradiation time of soft X-rays, and is independent of the applied voltage. After the surface potential reaches closer to the applied voltage, the surface potential becomes constant. This is because the surface potential of electrets neutralizes the electric field so that no more ions are dragged to the electrets.

Figure 4 illustrates the surface potential distribution of charged electret. The surface potential near the center is slightly higher than surroundings, showing a concentric distribution due to angular dependency of the X-ray radiation. The average value and the standard deviation of the surface potential within  $16 \times 16 \text{ mm}^2$  is 474.8 V and 12.6 V, respectively. This result is as good as one charged by corona discharge [8].

### Charging Rate

Boland *et al.* [9] reported that the spacing between the electrets and the counter electrodes has large effect on the power output of electret generators; the smaller the spacing is, the higher the power output [9]. However, external breakdown (arc discharge) easily occurs if the gap distance of air exceeds the limit value determined from the Paschen's curve. Therefore, we usually use the spacing of about 100  $\mu\text{m}$  in air, when the surface voltage of electrets reaches 1000 V.

Figure 5 shows dependence of the air gap on the surface potential of CYTOP film for the 1-min irradiation. When the gap is 20 mm, the surface potential as large as -536 V has been obtained, which is almost the same as our previous data with corona charging [8]. However, as the spacing was decreased to 1 mm, the surface potential was only -18 V. This is because absorption of soft X-rays to air molecules become less and the number of ions contributing to charge the electret is reduced due to smaller distance between the top electrode to electrets. From the present results, it is estimated that it would take at least several hours to complete the charging with the present condition if the gap is 100  $\mu\text{m}$ .

When the path length of 6-keV X-ray, which is peak energy of the present X-ray bulb, is 100  $\mu\text{m}$  in air, the absorption factor is approximately only 0.03 % [10]. If the gap is filled with other gas with higher absorption factor, the number of ions generated in the gap will increase. Figure 6 shows the comparison of the absorption factor for several gases.

For example, the absorption factor of  $\text{SF}_6$  and Xe is respectively 0.5 % and 3.5 %, which are 16 and 125 times higher than that of air [10]. Therefore, we can expect to improve the charging rate with the introduction of such gas into the gap, provided that external breakdown does not occur.

Moreover, it is possible to charge more effectively using such gases in combination with higher-energy X-ray, which can penetrate through substrates with little absorption loss, because absorption spectra of higher-mass gas broaden to higher-energy range in contrast to air. With theoretical analysis of transmittance spectra in  $\text{SiO}_2$  and absorption spectra in  $\text{SF}_6$  gas, we found that the optimum energy of X-ray is about 15 keV when the electret placed in 0.1 mm-thick gap filled with  $\text{SF}_6$  is charged through 0.4 mm-thick  $\text{SiO}_2$  substrate.

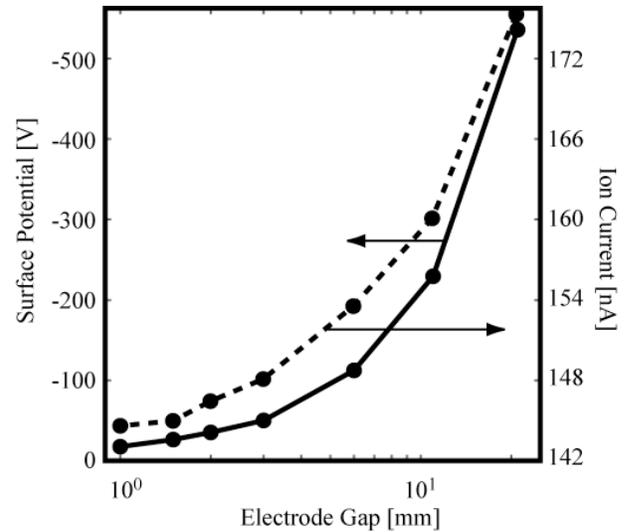


Figure 5. Surface potential and ion current versus electrode gap (irradiation time = 1 min).

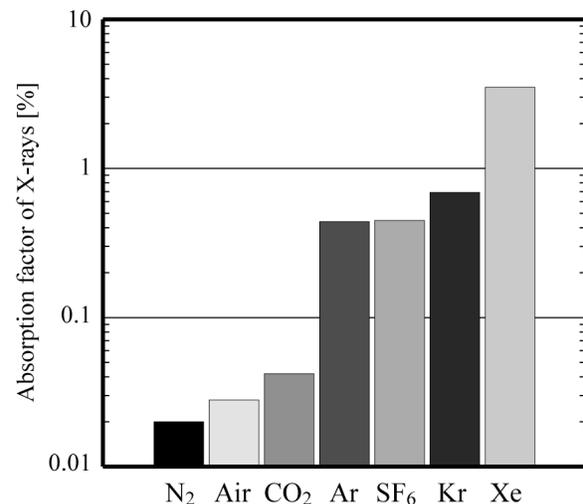


Figure 6. Absorption factor of soft X-ray of 6 keV for several gases (100  $\mu\text{m}$ , at 1 atm., 295 K).

## Stability

Figure 7 shows the time trace of surface potential after charging. It is observed that decay of surface potential is only 3 % for 8 days, indicating the charge retention property with the present method is as good as one charged by corona discharge [4].

Figure 8 shows a thermally stimulated discharge (TSD) spectrum of CYTOP electrets with two different charging methods at a temperature increment of 1 K/min. The present data indicate that peak temperature of both samples is almost the same, showing that the soft-X-ray-charged CYTOP electret has almost the same thermal stability as the corona-charged electret [4].

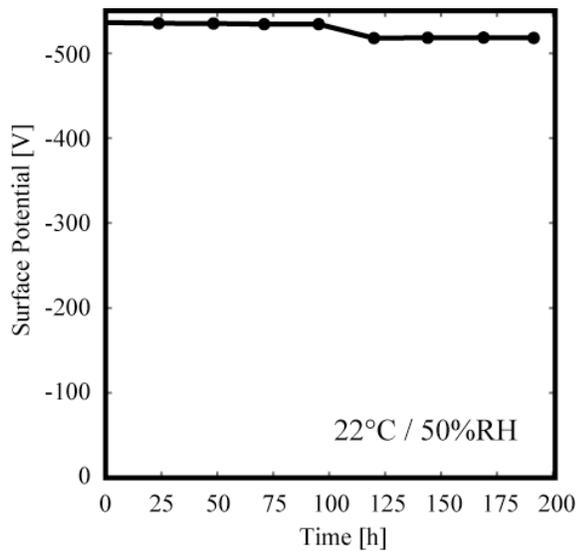


Figure 7. Time trace of the surface potential of CYTOP electret film.

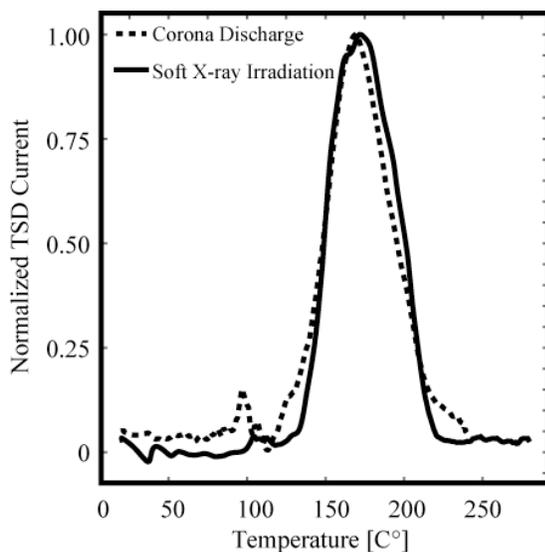


Figure 8. Thermally stimulated discharge (TSD) spectra of CYTOP electret films.

## CONCLUSION

A new charging method of polymer electret with soft X-ray irradiation has been demonstrated for the first time. The present method is available to charge electrets inside assembled/packaged electret generator.

Surface potential of the electret is controllable by adjusting the applied voltage to the top electrode. The charging properties such as uniformity or stability are as good as that of corona discharge. Although it takes somewhat long time to complete charging for small air gap, the charging time can be reduced using higher-mass gas and higher-energy soft X-ray.

We believe that the present charging method enables various fabrication/assembly processes of MEMS electret generators.

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