Abstract
The electret condenser microphones (FilmECMs) with film lamination and silica agglomerates were fabricated and the influence of the silica agglomerates on the characteristic of the FilmECM was investigated. The silica agglomerates was formed on PFA (perfluoroalkoxy) films by the application of colloidal silica using inkjet printing. The silica agglomerates for spacers formed the microgaps between the insulation films in the gap. Eventually, The silica agglomerates drastically enhanced the sensitivity of FilmECM while the resonance frequency was decreased. The size and the interval of the silica agglomerates influenced on the sensitivity and the resonance frequency. Such a influence can be explained by the density of the contact points of the films and silica agglomerates in the gap of FilmECM. Thereby the FilmECM which had the comparable sensitivity with commercial ECM was obtained. The resonant frequency was much higher than audible frequency (around 50 kHz). Hence, a wideband ECM could be obtained using FilmECM if the poor sealing of the gap and the diffraction of the sound is eliminated.

Key words: Electret, Microphone, Silica Agglomerate, Perfluoroalkoxy, Microgap

1. Introduction
Electret Condenser Microphones (ECMs) have been used in many applications because they are inexpensive, small, and require no polarizing voltage \(^{1}\). They have a structure of a capacitor consisting of a diaphragm (front electrode), a spacer ring, and a back electrode; an electret polymer film is attached to either of them, as shown in Fig. 1. An electric field is emitted from the electret film in the capacitor. Then the motion of the diaphragm resulting from a sound is picked up as a variation of electric voltage across the capacitance. The sensitivity of the ECM against a sound \(\beta\) (V/Pa) is expected to be directly related to the electric field in the gap generated by the electret film \(E_g\), as \(^{2}\)

\[
\beta = \frac{E_g}{K_g} \tag{1}
\]

where \(K_g\) is the equivalent stiffness per unit area (Pa/m) of the gap. A microphone is usually required to show flat response against a sound within range of audible frequency. The resonant frequency of the microphone, therefore, must to be higher than audible frequency. Furthermore, a wideband (wide frequency range) microphone recently has been required because digital audio equipment that can measure and reproduce sound over...
audible frequency, has been developed \(^{(3)}\). The resonant frequency \(f_r\) for a single degree of freedom system of the ECM can be expressed by natural frequency of a spring mass system, as

\[
f_r = \frac{1}{2\pi} \sqrt{\frac{K_g}{M_g}}
\]  

(2)

where \(M_g\) is the equivalent mass per unit area (kg/m\(^2\)) of the vibration layer. Fig. 1(b) shows Schematic of ECM with insulated film lamination (FilmECM) \(^{(4)}\). The numerous micro-gaps are formed by the film lamination without bonding in the FilmECM. The micro-gap enhances the \(E_g\) because of the electrical breakdown strength in air was subjected to Paschen’s law, whereby the electric field strength increases concomitantly with the decrease in the gap length until the gap length is microscopic \(^{(5)}\). The micro-gaps in Fig. 1(b) also increase \(K_g\) from the macroscopic gap because of the increase in the density of contact points\(^{(4)}\). Hence, the \(f_r\) of FilmECM can be expected to be increased by the micro-gaps because of the increase of \(K_g\). On the other hand, the degradation of sensitivity due to the increase of \(K_g\) can be prevented by the enhancement of \(E_g\) according to Eq. (1). The FilmECM, therefore, could be expected to be a wideband microphone including ultrasonic frequency range maintaining the same sensitivity as commercial ECMs. Authors fabricated FilmECMs with perfluoroalkoxy (PFA) film lamination as shown in Fig. 1(b) in prior work \(^{(6)}\). The fabricated samples demonstrated -55 dB (0dB=1V/Pa) for the average sensitivity while the significant degradation of the sensitivity was not observed up to 50 kHz. The sensitivity of the FilmECM in prior work, however, was apparently lower than...
that of commercial ECM (around -45 dB (7)). The surface electric potential of the electret (PFA film with thickness of 12.5 µm) was set to -1 kV in prior work because this value was the upper limitation for the stable electret obtained by the corona charging (8). Hence, further enhancement of $E_g$ is difficult because such a high electric field emitted by the electret is gradually degraded in the long term.

Another idea is the improvement of the sensitivity by controlling the size of micro-gaps. The width of micro-gap and the contact density between insulation films can be easily controlled by printing spacers (particles or agglomerates) on the insulation film as shown in Fig.1 (c). Such a spacer must be formed by insulated material because the leakage current degraded the electric field in the gap. Silicon dioxide (silica) is known as highly insulated materials and several studies on silica electret have been reported (9). Furthermore, silica agglomerates can be easily printed to arbitrary position on a film by inkjet printing techniques (10). Piezoelectric inkjet printer forces a droplet of ink from the nozzle. Colloidal silica is suitable for the ink of inkjet printing. The silica agglomerates are formed after the evaporation of water from the printed droplet of colloidal silica.

In this study, lattice of silica agglomerates were printed on the PFA films using a piezoelectric inkjet printer. The printed films were laminated with the electret film and the FilmECMs were fabricated. The role of silica agglomerates as spacer was investigated and the possibility of FilmECMs as wideband microphone was discussed.

2. Experimental Procedures

Element of fabricated FilmECM was depicted in Fig.1 (c). The element of FilmECM can be divided into three parts, a top electrode (vibrating electrode), a gap layer with laminated films and micro-gaps, and an electret layer including bottom electrode, respectively. PFA films marketed by Junkosha Inc. with thickness of 12.5 µm were selected for the electret films and the laminated films in the gap. A PFA film as a top insulation layer was welded to a top electrode of aluminum film (40x40 mm) with thickness of 10 µm. Microgaps were formed between the top insulation layer and intermediate layer in the gap with spacers of silica agglomerates. A PFA film was also welded to a bottom electrode of aluminum disk with diameter of 22 mm and thickness of 0.5 mm. The PFA film on the bottom electrode was negatively corona charged and the surface electric potential was controlled at -1 kV by an electrostatic sensor (ZI-SD, Omron). All layers were laminated to fabricate a FilmECM element. The element was attached to an aluminum test fixture as shown in Fig 2. The element was put on a copper electrode bonded on an acrylic plate. Then a top aluminum plate with hole (diameter = 20 mm, thickness = 3 mm) was put on the element and the top plate of aluminum was fixed by screws. The electric output of FilmECM was obtained from the back electrode with amplification of FET (2SK2219).

An inkjet printing technique was used to form silica agglomerates as spacers on PFA films in the gap. Commercial colloidal silica of 20 mass% (20L, Nissan Chemical Industries) was used for this study. The droplets of colloidal silica were printed in a pattern of square grids by a piezoelectric inkjet printer (Labojet-300, Microjet Corp.). Several printing conditions (the volume of droplet and the interval of grid points) were selected as shown in Table 1. The printed droplets were dried in air at room temperature and the colloidal crystals of silica particles were formed as shown in Fig. 3.

The sensitivity of FilmECM was measured by the semi-anechoic box (home made). A speaker (LS-K703, Kenwood) and two test fixtures with measurement microphone (UC-54, Rion) and FilmECM were placed in the semi-anechoic box. The distance of the test fixtures from the speaker was set to 34 cm and they became a line symmetrical position to the radial axis of the speaker. The acoustic sound was generated by sweep waves from 100 Hz to 100 kHz and the signal outputs of measurement microphone and FilmECM against sound were
measured. The FFT analysis was done for all measured waveforms. Then, the receiving sensitivity of FilmECM was calculated by the intensity ratio of the FilmECM sample to the measurement microphone using the FFT spectrum. The sensitivity at the frequency from 0.1 to 10 kHz was then averaged to calculate the average sensitivity of FilmECM.

Fig. 2. Test fixture for FilmECM element

Table 1. Printing conditions of colloidal silica using inkjet printer.

<table>
<thead>
<tr>
<th>Droplet Volume, v [pl]</th>
<th>Silica agglomerate</th>
<th>Silica agglomerate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Interval, d [µm]</td>
<td>Diameter, D [µm]</td>
</tr>
<tr>
<td>130</td>
<td>150, 200, 250, 300, 400, 500</td>
<td>66-76</td>
</tr>
<tr>
<td>350</td>
<td>150, 200, 250, 300, 400, 500</td>
<td>44-56</td>
</tr>
<tr>
<td>720</td>
<td>250, 300, 400, 500</td>
<td>74-89</td>
</tr>
</tbody>
</table>

Fig. 3. Stereomicroscopic observation of typical lattice of silica agglomerates formed by inkjet printing (m = 130 pl, d = 100 µm).

The peak frequency of the fabricated elements of FilmECM was investigated by a two-probe-method (6), (11). Two FilmECM samples with same fabrication condition were prepared for transmitter and receiver. These samples with test fixtures were placed in the semi-anechoic box face to face in distance of 17 cm. The FET amplifiers were removed from both samples. The input-output signals of the transmitter and the receiver were
transmitted via BNC cable (1 m). The burst waves (5 waves) with 300 V of peak to peak amplitude were generated as the transmitting signal by a function generator and bipolar power supply. The burst electric waves were input to the transmitter and the emitted acoustic waves from the transmitter were detected by the receiver. The signal intensity of the receiver in each frequency was measured when the burst waves at frequency from 20 to 200 kHz were input into the transmitter. The resonant frequency for a single degree of freedom system of the sample was then defined as the frequency at which the maximum signal intensity was obtained.

3. Results and Discussions

3.1 Sensitivity

Relationship between the average sensitivity $\bar{\beta}$ and the printing interval $d$ was shown in Fig. 4 (0 dB = 1 V/Pa). The application of the silica agglomerates drastically enhanced the sensitivity of FilmECM regardless of the printing conditions of colloidal silica. The microgaps were supported by the dry contact points between PFA films in the gap when the droplets of colloidal silica were not printed on the film. The density and interval of the contact points of these samples, therefore, were not controlled.

On the other hand, the silica agglomerates played a role as a spacer, i.e. contact points, between the PFA films in the gap when the droplets of colloidal silica were printed on the PFA film in the gap. Thereby, the density and the interval of the contact points could be easily controlled by the design of the printing pattern. Hence, Fig. 4 indicated that the application of silica agglomerates decreased the density of contact points between PFA films in the gap and enhanced $\bar{\beta}$ compared to the samples without the application of the silica agglomerates.

Such a decrease of the density of contact points should soften $K_g$ and thus enhance $\bar{\beta}$ according to Eq. (1). This model indicates that the further enhancement of $\bar{\beta}$ could be achieved if the density of contact points is decreased by expanding the interval of silica agglomerates $d$. The expanding of $d$, however, degraded $\bar{\beta}$ when the droplet of printed colloidal silica was 130 pL as shown in fig. 4 (a). The possible reason why $\bar{\beta}$ was degraded by expanding $d$ is the direct contact of PFA films without silica agglomerates. The top electrode with the melted PFA film is attracted to the electret because the electrostatic force generates in the the gap. Hence, the top electrode between the silica agglomerates is deflected to the electret. The upper PFA film on the top electrode will directly contact to the lower PFA film without the silica agglomerates if the electrostatic force is so strong that the deflection is larger than the height of silica agglomerates. Consequently, fig.4 (a) reveals that the top electrodes directly contacted to the lower PFA films for all samples and eventually, the sensitivity of FilmECM with silica agglomerates was monotonically decreased with the increase of $d$ because the direct contact points of PFA films were increased.

The direct contact of PFA films can be avoided if the height of silica agglomerates is higher than the deflection of the top electrodes due electrostatic force. Fig.4 (b) shows that $\bar{\beta}$ was increased from 150 to 250 $\mu$m of $d$. The height of the silica agglomerates in fig.4 (b) was increased 10 $\mu$m when the volume of the printed droplet of colloidal silica was changed from 130 to 360 pL. Eventually, $\bar{\beta}$ was enhanced by controlling $d$ because the direct contact of PFA films was avoided.

Such a enhancement of $\bar{\beta}$ by the increase of the height of the silica agglomerates, however, was not observed when the printed droplet of colloidal silica was 720 pL as shown in fig.4 (c). The silica agglomerates was too large to be rigidly stuck on the PFA film when the droplet was 720 pL. The Fig. 5 shows the observation of the silica agglomerates on the PFA film when the top electrode was removed after the measurement of the
sensitivity and the resonant frequency. Most of the silica agglomerates were moved or dropped from the original position because of a friction between the films in the FilmECM.

Consequently, The FilmECM showed the highest average sensitivity, -46 dB (0dB = 1V/Pa) when the droplet of 360 pL was printed at the interval of 250 µm. This FilmECM is comparable in sensitivity to commercial ECM.

![Fig. 4. Influence of the interval of silica agglomerates on the average sensitivity of FilmECM, triangle symbols in (b) represent the hydrophobized samples by HMDS treatment; the printed droplet was (a) 130, (b) 360 and (c) 720 pL.](image)

The PFA films with silica agglomerates of some samples were surface-treated with hexamethyl disilazane (HMDS) to investigate the influence of hydrophilic silanol of silica agglomerate on the sensitivity of FilmECM. HMDS is known to modify the surface of silica and reduce the hydrated silanol groups (6). The PFA films with silica agglomerates were placed in desiccator along with a beaker containing HMDS. The desiccator was then pumped down with a house vacuum and the films are exposed to HMDS vapor for 24 hr.
Fig. 4 (b) reveals that the sensitivity of the FilmECM apparently was degraded by the surface treatment of HMDS. This result indicates that the hydrophilic silanol groups have the important role for FilmECM to obtain the sensitivity comparable to a commercial ECM. Such a role of the silanol groups can be explained by the polarization of silica agglomerates by absorbed water molecules on the silanol groups. It has been observed that absorption of water enhances the surface electrical conductivity of silica gel \(^{(12)}\). The conduction mechanism is ionic and a protonic model surface conduction has been proposed \(^{(12)}\). The electric field is generated in the gap of FilmECM by the electret. Eventually, the polarization by the ionic conduction should occur in the silica agglomerates in the gap as shown in fig. 6.

![Image](a)

![Image](b)

![Image](c)

**Fig. 5.** Stereoscopic observation of the silica agglomerates on the PFA films of FilmECMs; the printed droplet was (a) 130, (b) 360 and (c) 720 pL

If the volume of microgaps is so small that the dielectric constant of the gap can be approximated as that of PFA, the capacitance of the gap will be equal to that of the electret. Then, \( E_g \) can be expressed as following,

\[
E_g = \frac{V_g}{w_g} = \frac{V_s}{w_g + w_e}
\]

where, \( V_g \) and \( V_s \) are difference of electric potential between the ends of the gap and surface electric potential of the electret, respectively. \( w_g \) and \( w_e \) are width of the gap and electret parallel to the electric field, respectively.

If the ionic conduction on the surface of the silica agglomerates is diminished by HMDS treatment, the polarization of the silica agglomerates would be too small to neglect low dielectric constant of the silica agglomerates. Thereby, \( E_g \) would be lower than the value calculated by eq. (3). Hence, the sensitivity of FilmECM would be degraded according to eq. (1). The further study should be required for a validation of this model: the influence of the silica agglomerates in the gap on the capacitance of the FilmECM will be investigated elsewhere.
Fig. 6. Polarization of silica agglomerates in a gap of FilmECM.

Fig. 7. Influence of the interval of silica agglomerates on the resonant frequency of FilmECM; the printed droplet was (a) 130, (b) 360 and (c) 720 pL.
3.2. Resonant Frequency

Fig. 7 shows the relationship between \( f_r \) and \( d \) of the fabricated FilmECMs. The \( f_r \) of FilmECM was increased with the degradation of the sensitivity. Such tendency can be expressed the equation derived from eq. (1) and (2),

\[
f_r = \frac{1}{2\pi} \sqrt{\frac{E_g}{M_g \beta}}
\]

(4)

According to eq. (4), \( f_r \) should be inverse proportional to square root of the sensitivity. The relationship between \( \beta \) and \( f_r \) estimated from eq. (3) and (4) is shown in Fig. 8. Assuming that only the top electrode (including the melted PFA layer) was vibrated by the sound pressure, \( M_g \) was calculated from the mass of the top electrode. The relation between \( \beta \) and \( f_r \) of the FilmECM without silica agglomerates well agreed with the estimated curve. The \( f_r \) of the FilmECM with silica agglomerates, however, showed lower value than the curve. This mismatch reveals that the size of microgap formed by the silica agglomerates was too large to ignore compared with the gap layer because the eq. (3) assumes that the volume of microgaps is negligible. The increase in the volume of the microgaps results the increase in \( w_g \) followed by the degradation of \( E_g \) and \( f_r \).

![Graph showing the relationship between sensitivity and resonant frequency of FilmECMs.](image)

Fig. 8. Comparison of the relations between the sensitivity and the resonant frequency of FilmECMs; open squares represent experimental data and solid curve is estimated from the measured \( \beta \) and eq. (4).

The all FilmECMs in this study had the value of \( f_r \) over 50 kHz. Hence, the wideband microphone of which frequency range reaches ultrasonic frequency can be expected using FilmECM. The frequency characteristic of the FilmECM with the average sensitivity of -46 dB is shown in Fig. 9. The degradation of the sensitivity at less than 200 Hz is caused by the poor sealing of the jig used in this study. The sound pressure will leak into the gap of ECM if the sealing is poor. Such a leak becomes more significant at lower frequency. Eventually, the vibration due to the sound pressure is suppressed by the poor sealing of ECM capsule at low frequency. On the other hand, The diffraction from the edges of the jig and/or cavity effect in front of diaphragm should affect frequency characteristic because the size of the jig and the thickness of the top plate was not negligible (13).

A sharp peak around 20 kHz was observed for all samples regardless of size and interval of silica agglomerates. This peak should be caused by the diffraction of sound from the edge of a jig or the cavity effect before the top electrode because the fabrication conditions of silica agglomerates in the gap did not influence on the frequency of this peak. The measurement microphone used in this study has wide frequency range up to 100 kHz and the diameter of this microphone is 6.4 mm (1/4 inch). On the other hand, the diameter of most of commercial ECMs is less than 6mm (7). Hence, this peak could be eliminated by
the use of a small capsule for a commercial ECM instead of the jig used in this study. Additionally it is possible to form microgaps using the silica agglomerates as spacer for such a small ECM because the interval of the silica agglomerates is much smaller than the diameter of the small capsule. The another peak around 50 kHz corresponded to the resonance frequency. The sensitivity of the fabricated FilmECM, therefore, should show the comparatively flat characteristic to near 50 kHz if the poor sealing of the gap and the diffraction and/or the cavity effect of the sound is eliminated. Consequently, it can be concluded that the FilmECM has the potential of a wideband ECM from audible to ultrasonic frequency.

4. Conclusions

The electret condenser microphones (FilmECMs) with film lamination and silica agglomerates were fabricated and the influence of the silica agglomerates on the characteristic of the FilmECM was investigated.

(1) The silica agglomerates for spacers of the microgaps drastically enhanced the sensitivity of FilmECM while the resonance frequency was decreased.

(2) The size and the interval of the silica agglomerates influenced on the sensitivity and the resonance frequency. Such a influence can be explained by the density of the contact points of the films and silica agglomerates in the gap of FilmECM. Thereby the FilmECM which had the comparable sensitivity with commercial ECM was obtained.

(3) The resonant frequency obtained by a two-probe method showed lower value than the value estimated from the sensitivity, the surface potential of the electret and the thickness of the films. The resonant frequency, however, was much higher than audible frequency (around 50 kHz). Hence, a wideband ECM could be obtained using FilmECM if the poor sealing of the gap and the diffraction of the sound is eliminated.

Appendix: Derivation of Eq. (3)

$V_g$ can be expressed using capacitance of electret and gap, $C_e$ and $C_g$ as

$$V_g = \frac{C_e}{C_e + C_g} V_s \quad (A1)$$

$C_g$ can be expressed in the term of equivalent capacitance of PFA films layer and microgap (air gap) layer, $C_p$ and $C_a$ connected in series as
If $C_a \gg C_p$ because the width of microgap is much smaller than that of PFA films layer, we can approximate $C_g = C_p$. Therefore, $C_g$ and $C_e$ can be expressed using dielectric constant of PFA, $\varepsilon_p$ as

$$C_g = C_p = \varepsilon_p \frac{A}{w_g} \quad (A2)$$

$$C_e = \varepsilon_p \frac{A}{w_e} \quad (A3)$$

Using Eqs. (A1), (A2) and (A3), $E_g$ is expressed as Eq. (3).

References