P(VDF-HFP) Polymer as Sensing Material for Capacitive Carbon Dioxide Sensors

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Abstract — P(VDF-HFP) polymer is investigated through both theoretical and experimental approaches as a sensing material for capacitive CO₂ sensor applications. Analysis based on the Clausius-Mossotti model shows that larger CO₂ solubility and larger dielectric constant contribute to high CO₂ capacitive sensitivity, which shows that P(VDF-HFP) polymer has significantly higher CO₂ sensitivity compared to Teflon when they have comparable CO₂ solubility, which is supported by subsequent experimental demonstration. Cross-sensitivity to humidity and temperature are evaluated and discussed for both P(VDF-HFP) and Teflon polymers. Fourier Transform Infrared spectroscopy (FTIR) analysis further reveals that the electrostatic interaction of P(VDF-HFP) with CO₂ is stronger than Teflon. The theoretical analyses and experimental demonstration indicate that P(VDF-HFP) is a promising sensing material to be applied for capacitive CO₂ sensors operated at room temperature.

Index Terms — capacitive sensors, carbon dioxide, dielectric, fluoropolymers, gas sensors, P(VDF-HFP)

I. INTRODUCTION

Carbon dioxide (CO₂) is the primary greenhouse gas produced by human activities. Monitoring and control of indoor CO₂ concentration is important for the well-being and comfort of people. There are many methods explored or used to detect and monitor the CO₂ concentration in environment, such as infrared-based methods [1-4], acoustic and resonance based methods [5-18] and electrical impedance and capacitance based methods [19-23].

For CO₂ sensors based on electrical impedance and capacitance, both metal oxides and polymer materials have been used as sensing materials. Some impedance and capacitance based CO₂ sensors use inorganic metal oxides as sensing materials, such as CuO-ZnO and CuO-BaTiO₃. The main disadvantage of the metal oxide based CO₂ capacitive sensors is the high operating temperature. For examples, the typical operating temperature is 366 °C for CuO-ZnO, and 456 °C for CuO-BaTiO₃ [14,15]. The high operating temperature and hence the high power consumption are not compatible with many low power electronics and not suitable for long-term CO₂ monitoring applications. Another group of impedance and capacitance based CO₂ sensors uses organic materials, particularly polymer materials, for CO₂ sensing. Based on the nature of interactions between CO₂ and the sensing materials, the polymer materials used for impedance and capacitance based CO₂ sensing can be further categorized into two subgroups, i.e., polymer materials based on physical absorption of CO₂ and those based on chemical reaction. The representative materials based on the physical absorption are Teflon polymers [7-12,16], and the representative materials based on chemical reaction with CO₂ are polymers with amine group, amidine group and/or carboxyl group, such as 1,2 diphenylethylenediamine (DPED) polymers [24-38]. The use of polymer materials for impedance and capacitance based CO₂ sensing are attractive for wide CO₂ monitoring applications, with their advantages of low power consumption, low cost, capable of operating at room temperature and compatibility with manufacturing of semiconductor devices for further miniaturization and electronic system integration. Polymer materials based on chemical reaction with CO₂ usually exhibit large magnitude dielectric change attributed to the change in the molecule structures due to the chemical reaction. However, the polymer materials based on chemical reaction usually have the highly chemically reactive groups, and thus poor long-term stability and high cross-sensitivity to humidity and temperature. The durability, reliability and cross-sensitivity to humidity and temperature are great challenges in practical long term CO₂ monitoring applications for this type of polymers. The other group of polymers based on physical absorption of CO₂ possesses superior chemical stability and can potentially overcome the stability and durability problem, but they usually have much lower sensitivity to CO₂. Polymer sensing materials

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with high CO\(_2\) sensitivity based on physical absorption are highly demanded. Poly(vinylidene fluoride-hexafluoropropylene) (P(VDF-HFP)) is a type of fluropolymer which has been explored for potential gas sensing applications. Daneshkhah et al. (2015, 2017) [39-40] presented three P(VDF-HFP) composite based sensors for detecting acetone, water, ethanol, isoprene, and 2-ethylhexyl acetate. The P(VDF-HFP) based composites were based on P(VDF-HFP), carbon black and carbon nanotubes. Ishizu et al. (2013) [41] reported the use of ionic gel for CO\(_2\) sensors, where 1-tetrafluoroborate ([EMIM][BF4]) ionic liquid was used as the active sensing materials with P(VDF-HFP) for forming the semi-liquid gel. P(VDF-HFP) polymers were also reported to be used for applications in absorption or separation of CO\(_2\) [42,43]. However, no research work has been reported to investigate the use of P(VDF-HFP) polymers as sensing materials for capacitive CO\(_2\) sensors.

In this paper, we report superior performance of P(VDF-HFP) polymers for use in capacitive CO\(_2\) sensors. To understand the factors that affect the sensitivity of capacitive CO\(_2\) sensors, Clausius-Mossotti model is used to link the microscopic polarization properties of polymer materials with the macroscopic dielectric change due to CO\(_2\) absorption. Based on the theoretical understanding, experimental tests are conducted to evaluate the CO\(_2\) sensitivity of P(VDF-HFP) in comparison with Teflon polymers as benchmark, which has been applied as CO\(_2\) sensing materials. It is demonstrated that P(VDF-HFP) has significantly improved CO\(_2\) sensitivity compared to Teflon polymers. The cross-sensitivity of P(VDF-HFP) to humidity and temperature has also been evaluated in comparison with Teflon polymers. The possible interaction mechanism between CO\(_2\) and P(VDF-HFP) and Teflon polymers is also explored with Fourier Transform Infra-red spectroscopy (FTIR) method.

II. ANALYSIS ON DIELECTRIC CHANGE DUE TO PHYSICAL ABSORPTION OF CO\(_2\)

The change of dielectric constant in polymer sensing material due to physical absorption of CO\(_2\) can be modeled through the Clausius-Mossotti model [44]. The Clausius–Mossotti model relates the macroscopic dielectric constant \(\varepsilon\) with the molecular polarizibility \(\alpha\) through the following equation,

\[
\frac{\varepsilon - 1}{\varepsilon + 2} = \frac{N\alpha}{3\varepsilon_0}
\]

where \(N\) is the concentration of molecules and \(\varepsilon_0\) is the vacuum dielectric permittivity. From Eq. (1), the dielectric constant \(\varepsilon\) can be rewritten as

\[
\varepsilon = \left(2P_m + 1\right) / \left(1 - P_m\right)
\]

where \(P_m = \frac{N\alpha}{3\varepsilon_0}\).

When a sensing material absorbs CO\(_2\), the dielectric constant of the polymer-CO\(_2\) mixture can be calculated from Eq. (2),

\[
\varepsilon_{s+g} = \left(2P_{m,s} + 2P_{m,g} + 1\right) / \left(1 - P_{m,s} - P_{m,g}\right)
\]

where the subscript \(s\) in Eq. (3) denotes solid polymer and \(g\) denotes gas. Thus, the change of dielectric constant for the polymer due to gas absorption is expressed as,

\[
\Delta\varepsilon = \varepsilon_{s+g} - \varepsilon_s = \frac{3P_{m,g}}{\left(1 - P_{m,s}\right)^2 - P_{m,g}\left(1 - P_{m,s}\right)}
\]

Substituting \(P_{m,s}\) and \(P_{m,g}\) in Eq. (4) with terms of \(\varepsilon_s\) and \(\varepsilon_g\) through the Clausius-Mossotti relation in Eq. (1), the relative change of dielectric constant due to gas absorption can be obtained as,

\[
\Delta\varepsilon = \frac{1}{\varepsilon_s} \left(\frac{C_{\text{sol}}M_g\rho_g}{\varepsilon_g - 1}\left(\varepsilon_g - 1\right)\left(\varepsilon_g + 2\right) - \frac{C_{\text{sol}}M_g}{\rho_g}\left(\varepsilon_g - 1\right)\left(\varepsilon_g + 2\right)\right)
\]

where \(C_{\text{sol}}\) is the solubility of gas in polymer, \(M_g\) is the molecular mass of the gas, and \(\rho_g\) is the density of the gas corresponding to the dielectric constant of gas \(\varepsilon_g\). The term \(C_{\text{sol}}M_g / \rho_g\) is equivalent to the concentration of molecules \(N\) in Eq. (1).

From Eq. (5), the gas solubility in polymer \(C_{\text{sol}}\) and the dielectric constant of the polymer \(\varepsilon_s\) are the controlling factors to account for the change of dielectric constant of the selected sensing polymer.

Figure 1 illustrates the change of dielectric constant with the solubility of CO\(_2\) in sensing polymer material and the dielectric constant of the polymer. It is evident that higher CO\(_2\) solubility and larger dielectric constant of the sensing polymer material will lead to larger dielectric change. For polymer materials with the same CO\(_2\) solubility, polymer with larger dielectric constant has larger dielectric change due to CO\(_2\) absorption.

In Figure 1, the yellow asterisk point represents the change of dielectric constant due to CO\(_2\) absorption for Teflon AF 2400 polymer. Teflon is a type of fluoropolymer which has been used as the sensing material for capacitive CO\(_2\) sensors [22].Teflon polymers have high CO\(_2\) solubility of 177 \(\mu\text{moles/cm}^3/\text{atm}\) [22], but the dielectric constant is only 1.9. The change of dielectric constant for Teflon AF 2400 is 32 ppm with 1\% CO\(_2\). Other fluoropolymers such as PVDF-based polymers have lower CO\(_2\) solubility but the dielectric constant is much higher than that of Teflon polymer. It is possible that some PVDF-based polymers may have larger dielectric change due to CO\(_2\) absorption than that of Teflon polymer because of larger polymer dielectric constant and moderate CO\(_2\) solubility. As shown by the red asterisk in Figure 1, if the CO\(_2\) solubility in P(VDF-HFP) polymer is the same as that of Teflon AF 2400 polymer, P(VDF-HFP) polymer will have 64 ppm dielectric...
constant change with 1% CO$_2$, which is twice of the sensitivity of Teflon AF 2400 polymer at the same condition. Though the actual CO$_2$ solubility in P(VDF-HFP) polymer may be lower than that of Teflon AF 2400 polymer, it is possible that the CO$_2$ sensitivity of P(VDF-HFP) polymer could be higher than that of Teflon AF 2400 polymer. The experimental work in Section 3 will show the comparison of CO$_2$ sensitivity of Teflon AF 2400 and P(VDF-HFP) polymers for use as capacitive CO$_2$ sensors.

III. SAMPLE FABRICATION AND CHARACTERIZATION

A. Fabrication of P(VDF-HFP) capacitive CO$_2$ sensors

As theoretically analyzed in previous section, P(VDF-HFP) polymer may have larger dielectric constant change compared to Teflon AF 2400 polymer, if the CO$_2$ solubility in P(VDF-HFP) polymer is comparable with that of Teflon AF 2400 polymer. To experimentally evaluate the capacitive sensitivity of P(VDF-HFP) polymer to CO$_2$, P(VDF-HFP) film was deposited to a prior-fabricated capacitance test structure. The capacitance test structure is composed of double meander aluminum lines with width and spacing of around 1 µm and height of 0.8 µm. P(VDF-HFP) (Sigma-Aldrich, Singapore) was dissolved in mixture of dimethylformamide (DMF, Sigma-Aldrich, Singapore) and acetone (Sigma-Aldrich, Singapore) (1:1 in volume) at a concentration of 3.5 wt%. The solution was then sprayed on the capacitance test structure using an air brush. After spraying, the P(VDF-HFP) films were dried at 80 °C and then annealed at 135 °C. As a control group, Teflon AF 2400 polymer was also deposited on the capacitance test structure. Teflon AF 2400 (DuPont, US) was dissolved in perfluorinated solvent (C5-18) at a concentration of 1 wt%. The solution was sprayed on the capacitance test structure using an air brush. After spraying, the Teflon AF 2400 films were dried at 50 °C. The thicknesses of the P(VDF-HFP) and Teflon AF 2400 films are in the range of 8-10 µm, determined by a profilometer and confirmed by cross-sectional inspection by scanning electron microscope.

Figure 2 presents the cross-sectional scanning electron microscopic (SEM) image of P(VDF-HFP) film with thickness of 8 µm deposited on the capacitive structure.

B. Characterization of capacitive CO$_2$ sensors

A gas sensor testing system was built to evaluate the capacitive CO$_2$ gas sensors. Figure 3 shows the schematic diagram of system setup for the characterization of the capacitive CO$_2$ sensors. The characterization system consists mainly of the controlled temperature/humidity chamber, mass flow controller based gas supply, LCR meter (E4980-AL, Keysight), PC-based data acquisition system and various sensors for temperature, humidity and atmosphere monitoring.

CO$_2$ sensitivity was first measured in dry N$_2$ (0 % RH) at room temperature (25 °C) condition, with CO$_2$ concentration at 0 %, 0.05 %, 0.1 %, 0.2 %, 50 % and 100 %, and exposure time of 1-2 hour for each CO$_2$ concentration setting. Temperature sensitivity measurement was measured with in dry N$_2$ (RH at 0 % and CO$_2$ at 0 %) at 25 °C, 30 °C, 35 °C, 40 °C and 45 °C, RH sensitivity measurement was measured with temperature at 25 °C, and in N$_2$ (CO$_2$ at 0 %), with RH at 0 %, 30 %, 45 %, 60 % and 75 %.

IV. RESULTS AND DISCUSSIONS

Figure 4(a) and 4(b) show the time domain capacitance measurement at 5 kHz for test structure with P(VDF-HFP) and Teflon AF 2400 polymers, respectively with temperature and RH profiles recorded. It is observed that both P(VDF-HFP) and Teflon AF 2400 polymers show no response to the variation of CO$_2$ concentration below 2000 ppm. This may be due to the noise of the measurement, which is around ~0.001 pF corresponding to the detection limit of 1 % CO$_2$. Capacitance changes were observed in P(VDF-HFP) and Teflon AF 2400 polymers when the CO$_2$ concentration increased to 50 % and 100 % respectively. The capacitance result of Teflon sample showed a higher noise level as illustrated in Figure 4(b). This is because the Teflon sample has lower capacitance. The LCR meter used in the measurement has lower accuracy at lower capacitance.

Figure 5 shows the detailed capacitance change at the variation of CO$_2$ concentration. It is observed that the capacitance change follows the profile of CO$_2$ concentration rather than that of the temperature or RH. However, a significant drift of capacitance with temperature can also be observed, which indicates the dielectric permittivity of P(VDF-HFP) polymer is very sensitive to temperature changes. The response time to CO$_2$ concentration for capacitance change is around 0.1 hour, which is around 6 minutes for P(VDF-HFP).

Figure 6 shows the CO$_2$ sensitivity of P(VDF-HFP) polymer and Teflon AF 2400 polymer in the frequency range of 1 kHz to 200 kHz. The CO$_2$ sensitivity is defined here as the ratio of capacitance change to capacitance for interpolated 1% CO$_2$ concentration change. It was observed that P(VDF-HFP) polymer has significant larger CO$_2$ sensitivity than that of Teflon AF 2400 polymer in all frequency range. Both P(VDF-HFP) and Teflon AF 2400 show decreased CO$_2$ sensitivity with frequency. Teflon AF 2400 polymer has relative stable CO$_2$ sensitivity for frequency up to 200 kHz while the sensitivity of P(VDF-HFP) polymer is more frequency dependent. This might be due to the different polarization mechanisms in P(VDF-HFP) and Teflon AF 2400 polymers. P(VDF-HFP) is a nonlinear dielectric polymer. The polarization mechanism of P(VDF-HFP) polymer is mainly from frequency-dependent dipolar polarization and interface/space charge polarization, which have reduced contribution to the polarization of P(VDF-HFP) polymer at higher frequency. However, Teflon is a linear dielectric polymer without substantial dipolar polarization or interface/space charge polarization. The nonlinearity of the dielectric constant of P(VDF-HFP) polymer may lead to the frequency-dependent CO$_2$ sensitivity of the polymer. The CO$_2$ sensitivity is slightly higher at 50% CO$_2$ concentration than that of at 100% CO$_2$ concentration for P(VDF-HFP) up to 200 kHz.
and for Teflon AF 2400 in the frequency range below 50 kHz. At 5 kHz, the CO$_2$ sensitivity for P(VDF-HFP) polymer and Teflon AF 2400 polymer are 38 ppm/1% CO$_2$ and 13 ppm/1% CO$_2$, respectively. The CO$_2$ sensitivity of P(VDF-HFP) polymer is 2.9 times of that of Teflon AF 2400 polymer at 5 kHz. These results demonstrate the significantly high sensitivity of P(VDF-HFP) polymer compared to Teflon AF 2400 polymer for use in capacitive CO$_2$ sensors.

The cross-sensitivity to relative humidity (RH) and temperature (T) of P(VDF-HFP) and Teflon AF 2400 polymer are evaluated as it is important for practical CO$_2$ gas sensor application. The RH is defined as the ratio of the partial pressure of water vapour in a gaseous mixture to the saturated vapour pressure of water at given temperature [45]. The test structure for the cross-sensitivity experiments has larger capacitance than the test structure used for experiments of CO$_2$ sensitivity with different electrode dimensions. Please note that the change of test structure dimension does not affect the testing results for CO$_2$. RH or temperature sensitivities of the P(VDF-HFP) polymers, which are based on the relative changes. Figure 7(a) and Figure 7(b) show the changes of capacitance with respect to relative humidity and temperature respectively for P(VDF-HFP) polymer. It is observed that P(VDF-HFP) polymer shows significant capacitance changes at the variation of RH and temperature as indicated in Figure 7. The cross sensitivity to relative humidity is defined as the change of capacitance in ppm with the change of 1% relative humidity and the cross-sensitivity to temperature is defined as the change of capacitance in ppm with the change of 0.1 °C. Table I listed the cross-sensitivity of Teflon AF 2400 and P(VDF-HFP) polymers to relative humidity and temperature. It is found that both Teflon AF 2400 polymer and P(VDF-HFP) polymer have higher cross-sensitivity to RH than CO$_2$. However, by comparing the RH sensitivity to CO$_2$ sensitivity, it should be noted that the RH sensitivity of P(VDF-HFP) polymer is 4.1 times of that of CO$_2$ sensitivity, which is much lower than that of Teflon AF 2400 polymer which is 6.4 times. This indicates that P(VDF-HFP) polymer has lower cross-sensitivity to humidity in comparison with Teflon AF 2400 polymer. For the temperature sensitivity, Teflon AF 2400 has much better temperature sensitivity of 19 ppm/0.1°C in comparison with 364 ppm/0.1°C for P(VDF-HFP) polymer. The negative drift of capacitance in Figure 7(a) may be related to possible temperature drift in the chamber. When both temperature and RH are monitored as shown in Figure 4(a), this becomes clear.

Figures 8(a) and 8(b) illustrated the impacts of temperature and RH on the CO$_2$ sensitivity measured at 5 kHz of P(VDF-HFP) polymer. It is observed in Figures 8(a) and 8(b) that the CO$_2$ sensitivity of P(VDF-HFP) polymer decreases with the elevation of temperature but increases with the increase of RH.

These results on cross-sensitivity indicate that accurate data compensation is needed to minimize the impact of cross-sensitivity to RH and temperature for both Teflon AF 2400 and P(VDF-HFP) polymers. Since accurate temperature data can be obtained much more conveniently than RH, it may be practically more feasible to compensate the temperature effect for P(VDF-HFP) polymer than to overcome the more significant RH cross-sensitivity issue for Teflon polymer.

Burker Vertex 70 FTIR spectrometer in transmission mode was used to probe the interactions between the CO$_2$ and the Teflon AF 2400 and P(VDF-HFP) polymers. FTIR results were collected for the polymer films of P(VDF-HFP) and Teflon AF 2400 on silicon wafer. The sample was loaded in a gas cell, and exposed to the flow of controlled CO$_2$ or N$_2$ gas introduced at 10 psi for five minutes prior to the measurement. Each measurement was scanned for 100 times with the resolution of 4 cm$^{-1}$. The outlet of the gas cell was then opened to allow the CO$_2$ to escape and release from the gas cell and the samples were then re-measured in air flow in the gas cell. A blank silicon wafer without polymer film was used as the control. Figure 9(a) and 9(b) shows the FTIR results of P(VDF-HFP) and Teflon AF 2400 polymers on silicon wafer after the release of CO$_2$ gas from the gas cell and in N$_2$ ambient respectively.

Kazarian et al [46] reported that polymer possessing electron donating functional groups like C=O, C-F, exhibit specific interaction with CO$_2$, likely of Lewis acid-base nature. An evidence of this specific interaction is the observation of the splitting of the band in the bending mode (ν$_2$) of CO$_2$. Thus the ν$_2$ mode (in the range of 670 to 650 cm$^{-1}$) of CO$_2$ is analyzed here to track the possible interactions. The peak at 669 cm$^{-1}$ in Figure 9(a) correlates to the free and unassociated CO$_2$ surrounding the polymer film in the gas cell. For P(VDF-HFP), the spectra show the formation of splitting of the band within the ν$_2$ mode with peak position at 658 and 650 cm$^{-1}$ as shown in Figure 9(a). The splitting can be regarded as an indication of the polymer-CO$_2$ interaction, likely caused by the interaction of C-F dipole with the carbon atom of CO$_2$ molecule as postulated by Kazarian [46]. This phenomenon was not as obvious for Teflon AF 2400 polymer in transmission mode, thus might be indicative of a weaker interaction with CO$_2$ for Teflon than P(VDF-HFP). The reason may be that P(VDF-HFP) possesses -CF$_3$ in the molecular structure of (CH$_2$CF)$_{2-n}$(CF$_2$CF(CF$_3$)$_n$, which is more electrostatically interactive with CO$_2$, likely of Lewis acid-base nature, in contrast to all -CF$_3$ in Teflon’s molecular structure of (CF$_2$)$_n$. This process is reversible as demonstrated in Figure 9(b) when samples are flushed and re-measured in the nitrogen ambient.

If there is any substantial local temperature change due to an enthalpy change originating from the interaction between the polymer and the CO$_2$, which results in capacitance change, this will contribute to the explanation of the CO$_2$ sensing mechanism. However, this is different from the effect of ambient temperature.

V. CONCLUSIONS

P(VDF-HFP) polymer is investigated as a sensing material for capacitive CO$_2$ sensor applications. Theoretical analysis based on the Clausius-Mossotti model shows that larger CO$_2$ solubility and larger dielectric constant contribute to high CO$_2$
capacitive sensitivity. Both the theoretical analysis and subsequent experimental testing show that P(VDF-HFP) polymer has significantly higher CO$_2$ sensitivity compared to Teflon AF 2400 when they have comparable CO$_2$ solubility. While both P(VDF-HFP) and Teflon AF 2400 polymers exhibit significant cross-sensitivity to RH and temperature, the relatively smaller RH cross-sensitivity for P(VDF-HFP) could be another advantage for practical application, although more accurate temperature compensation is required. FTIR analysis further reveals that the electrostatic interaction of P(VDF-HFP) with CO$_2$ is stronger than Teflon. The theoretical analyses and experimental demonstration indicate that P(VDF-HFP) is a promising sensing material to be applied for capacitive CO$_2$ sensors at room temperature.

REFERENCES


Lei Zhang is currently a research scientist at the Institute of Materials Research and Engineering (IMRE), A*STAR, Singapore. He received his bachelor’s degree in engineering from Shanghai Jiao Tong University, China, in 2002 and his Ph.D. degree from Nanyang Technological University (NTU), Singapore, in 2008. Prior to joining IMRE in January 2010, he had worked at NTU from 2007 until now, he works as a scientist at the Institute of Materials Research and Engineering, on the applications of piezoelectric materials for sensors and energy harvesting.

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<table>
<thead>
<tr>
<th>Materials</th>
<th>CO₂ sensitivity (ΔCp ppm /%CO₂)</th>
<th>RH sensitivity (ΔCp ppm /%RH)</th>
<th>T sensitivity (ΔCp ppm/0.1 °C)</th>
<th>RH sensitivity/ CO₂ sensitivity ((ΔCp ppm/ %RH)/ (ΔCp ppm/%CO₂))</th>
<th>T sensitivity/ CO₂ sensitivity ((ΔCp ppm/0.1 °C)/ (ΔCp ppm/%CO₂))</th>
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</thead>
<tbody>
<tr>
<td>Teflon AF 2400</td>
<td>13</td>
<td>82</td>
<td>19</td>
<td>6.4:1</td>
<td>1.5:1</td>
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<tr>
<td>P(VDF-HFP)</td>
<td>38</td>
<td>157</td>
<td>364</td>
<td>4.1:1</td>
<td>9.6:1</td>
</tr>
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*Experimental data were obtained at 5 kHz.

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Figure 7 Change of capacitance measured at 5 kHz with respect to (a) relative humidity and (b) temperature for P(VDF-HFP) polymer.

Figure 8 Impacts of (a) temperature (RH=0%) and (b) RH (T=25 °C) on CO₂ sensitivity of P(VDF-HFP) polymer (measured at 5 kHz)
Figure 9 FTIR spectra for P(VDF-HFP) and Teflon AF 2400 on silicon wafer, (a) after the release of CO₂ gas from the gas cell and (b) in N₂ ambient. Silicon wafer with polymer film is used as the control.