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One-Side-Electrode-Type Fluid-Based Inclinometer Combined with Complementary Metal Oxide Semiconductor Circuitry

Asrulnizam Bin Abd Manaf*, Kazumasa Nakamura and Yoshinori Matsumoto

Faculty of Science and Technology, Department of Applied Physics and Physico-Informatics, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama, Kanagawa 223-8522, Japan

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In this study, electrical double layer theory is applied to realize a one-side-electrode -type fluid-based inclinometer combined with complementary metal oxide semiconductor (CMOS) circuitry. Substrate penetration lithography was applied in the fabrication of high-aspect-ratio SU-8 container molds, and molds with heights of 0.5 mm and 1.0 mm were fabricated. Polydimethylsiloxane (PDMS) was used as the container material, and electrodes were fabricated on a printed circuit board (PCB). Considering the electrical double layer property, low surface tension, the dielectric constant and the problem of volatilization, methanol and propylene carbonate were tested as electrolytes. A charge-balanced capacitance circuit was designed as a detection circuit for this sensor and it was fabricated using 0.35 μm CMOS technology. To overcome the surface tension of the PDMS surface, silicone oil was injected in the container to cover the entire inner surface so that the movement of solution in the container became smooth. The linearity of the analog output of ±60° inclination for container dimensions of ϕ4.0 mm × 1.0 mm (diameter × thickness) was less than 6%/F.S. The minimum moving angle and response time were 0.4° and 0.9 s, respectively, when propylene carbonate was used as the electrolyte.

1. Introduction

Small and high-performance inclinometers have been in demand for electronic appliances and robotic technology. Inclinometers can be categorized into two types: mechanical and fluid-based systems. In mechanical-system-type tilt sensors, a solid proof mass is attached to a cantilever. Most of these devices are mechanical accelerometers that detect a capacitance change due to the deflection of a proof mass,

*Corresponding author: e-mail: dr064510@hc.cc.keio.ac.jp

and they can be used to measure the angle of inclination by measuring the acceleration due to gravity.(1–3) Some researchers have reported inclination sensors using 3-axis acceleration sensors fabricated by micro-electronic-mechanical-system (MEMS) technologies. However, these sensors are problematic in that it is difficult to obtain a linear output with respect to inclination. Moreover, the other problem of these sensors is the effect of acceleration when the inclination angle is measured. Therefore, software and an additional signal processing circuit have been used to remove the effect of acceleration and to obtain the inclination angle with a linear output.

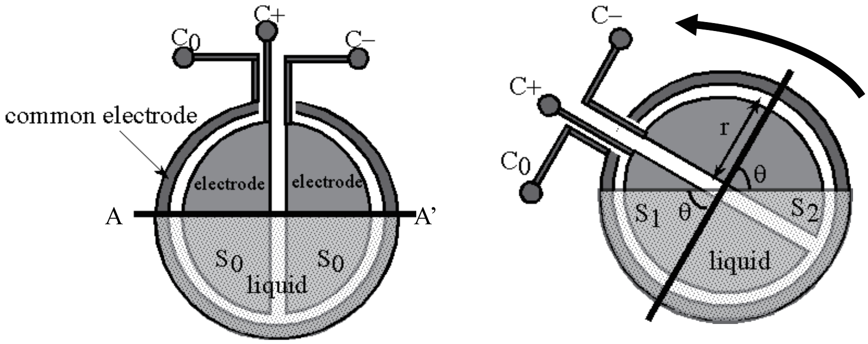
Fluid-based inclinometers measure the angle of inclination by detecting the movement of a fluid or gas inside a container or well. The movement of fluid due to gravity is most commonly detected by measuring resistance or capacitance change. Fluid-based tilt sensors provide capabilities not available in mechanical equivalents, including low power consumption, repeatability and reliability. Furthermore, they can sustain considerable shock and high external pressure. However, the effect of meniscus force becomes large in fabricated miniaturized sensors. Therefore, the problems of the hysteresis and nonlinearity of the output response due to surface tension have been reported.(3–4)

In this study, electrical double layer theory is applied to realize a one-side-electrode -type fluid-based inclinometer combined with CMOS circuitry. In addition, we also attempt to develop an inclination sensor that is not affected by acceleration. The sensor design and substrate penetration lithography method are demonstrated in sensor fabrication, and an experiment to find a suitable fluid for this application is implemented. The miniaturization and integration of low-cost and high-efficiency inclination sensors are particularly required in the automobile, telecommunication and medical fields.

2. Design and Principle

A capacitive inclination sensor has a circular common electrode that opens at the end and two semicircular opposing electrodes to form two capacitors (Fig. 1). These electrodes are fabricated on the surface on one side of the sensor. The sensor cavity is half filled with liquid.

When a voltage is applied to the electrode by the detection circuit, which was designed using CMOS circuit technology, a charge is formed between the surface of the PDMS insulator layer and the electrode. This state is the same as that of a capacitor. Therefore, as shown in Fig. 2, the two detection electrodes can act as two capacitors. A capacitor is also formed on the ring-type common electrode (C_0), as shown in Fig. 2. Therefore, an electrical double layer can be formed on the surface of the PDMS insulator when an electrolyte is used. The behavior of the liquid is similar to that of a conductor. Therefore, a simple parallel-plate capacitor can be realized when an electrolyte is formed on these surfaces. The capacitance depends on the thickness of the PDMS insulator layer and the permittivity of PDMS. On the other hand, when air contact with the surface insulator, the series is connected between this capacitor and the capacitor whose capacitance is determined by the permittivity of the air layer. Therefore, the total capacitance becomes small and can be disregarded.



(a) (b)

Fig. 1. Sensor pattern in level (a) and inclined (b) states.

As shown in Fig. 1(b), when it is inclined, the liquid moves and electrode C_+ is covered with the liquid. Consequently, in the inclined state, the electrostatic capacity between electrodes C_+ and C_- is changed from the level state. Equation (3) expresses the proportional relationship between capacitance change ΔC and inclination angle.

$$C_+ = \frac{\varepsilon S_1}{d} = \frac{\varepsilon S_0}{d} + \frac{1}{2d}\varepsilon r^2 \theta \tag{1}$$

$$C_- = \frac{\varepsilon S_2}{d} = \frac{\varepsilon S_0}{d} - \frac{1}{2d}\varepsilon r^2 \theta \tag{2}$$

$$\therefore \Delta C = C_+ - C_- = \frac{\varepsilon r^2 \theta}{d} \tag{3}$$

Here ε, θ, r, d, S_0, S_1 and S_2 are the permittivity of the PDMS insulator, the inclination angle (rad), the radius, the thickness of the insulator and the surface areas of the electrodes, respectively.

3. Detection Circuit Design

The performance of the detection circuit is important because the capacitance change of the capacitive sensor is small. CMOS integrated circuitry exhibits low power consumption and high input impedance, so that it is suitable for the capacitor detection circuit. Therefore, a switched-capacitor detection circuit that is not affected by stray capacitance was designed using CMOS circuit technology. The stray capacitances are those between electrodes (C_+ and C_-, C_+ and C_0, C_- and C_0), and capacitance between wiring. There is also stray capacitance between the electrode and the remaining liquid when the sensor is inclined.

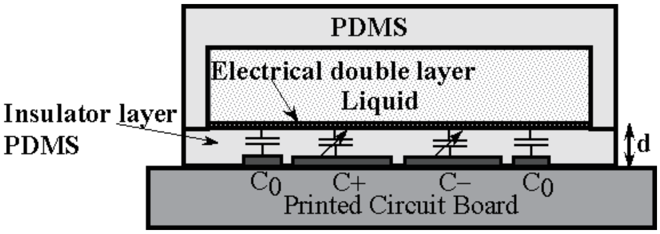


Fig. 2. Cross-sectional structure view A–A'.

To detect the inclination angle of one axis, a charge-balanced capacitance-voltage conversion circuit (C-V converter) has been developed. The operational amplifier used in the detection circuit is not affected by offset voltage.(5) The circuit was fabricated using 0.35 µm CMOS circuit technology and the consumption current is 250 µA at V_{DD} = 3.3 V. The overall chip size is 1.0 mm × 0.5 mm. A schematic of the circuit and a photograph of the chip are shown in Figs. 3 and 4, respectively. In the operation of the circuit, three states of circuit operation exist. The first state is when switch S_1 is set to on and S_2 is set to off. The circuit takes in a capacitance signal in this stage. This state is called the initial state. In the following state, switch S_2 is turned on and S_1 is turned off. This state is called the amplification mode. In the third state, S_1 and S_2 are turned off. The circuit is said to be in the output mode during this stage. Finally, the output of the circuit can take on an equilibrium steady-state value depending on the input by repeating the operations. Equations (4) and (5) express the proportional relationship between output voltage V_m and inclination angle. As shown in Fig. 1, the difference in the area that is covered with the liquid between electrodes C_+ and C_- depends on the angle gradient. Therefore, the output voltage V_m can be proportional to the inclination angle.

$$V_m = \frac{C_+}{C_+ + C_-} V_{dd} = \frac{1}{2} V_{dd} + \frac{r^2 \theta}{4 S_0} V_{dd} \tag{4}$$

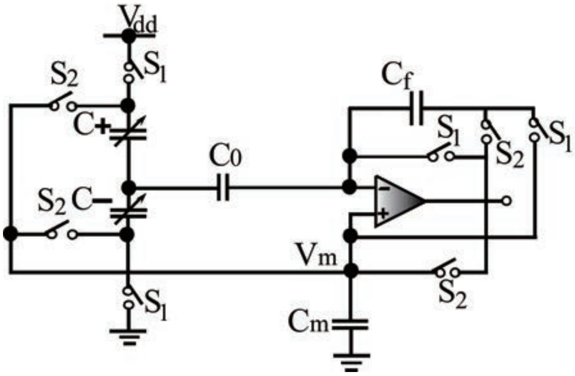
Then $S_0 = \frac{1}{2}\pi r^2$ is substituted into eq. (4).

$$\therefore\ V_m = \frac{1}{2} V_{dd} + \frac{\theta}{2\pi} V_{dd} \tag{5}$$

The advantage of this sensor, as shown in eq. (5), is that its output V_m does not depend on sensor structure parameters such as radius (r) and thickness of insulator (d).

4. Optimization of Fluid

The properties of fluids, particularly the electrical double layer and low surface tension, are important for realizing a functional sensor. The theory of these properties is described as follows.



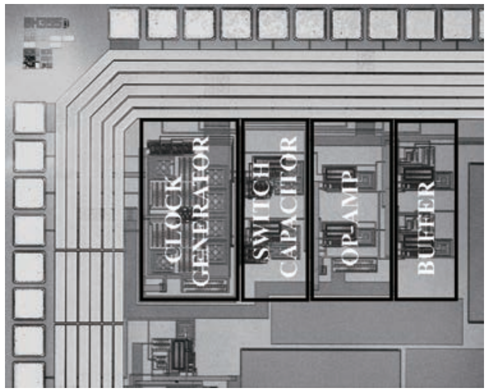


Fig. 3 (left). Schematic of charge-balanced capacitance detection circuit.
Fig. 4 (right). Photograph of detection circuit fabricated using 0.35 μm CMOS technology.

4.1 *Electrical double layer (EDL)*

Recently, the electrical double layer (EDL) principle has been applied in capacitors. The resulting device is called the electrical double layer capacitor (EDLC). The earliest model of the electrical double layer has been familiar to electrochemists since the late 1800s when Helmholtz discovered charge storage at the boundary between a conductor and an electrolyte. The Helmholtz-Perrin model developed at the same time in fact describes the double layer as a simple parallel-plate capacitor.

When the electrode and electrolyte come in contact with each other, the positive and negative poles are distributed relative to each other over an extremely short distance. The distance of approach is assumed to be limited to the radius of the ions and a single sphere of solvation around each ion. The overall result is two layers of charge (the double layer) and a potential drop, that is confined to only this region (termed the outer Helmholtz plane, OHP) in the solution. The result is analogous to an electrical capacitor, which has two plates of charge separated by some distance (d) (on the order 10^{-10} m).

To realize the electrical double layer mechanism, solution polarity must be selected. In general, it will be easy to ionize the solution if the polarity is high. Then, only a high-polarity solution can generate an electrical double layer. In the conventional EDLC, organic solvents such as poly(urethane), propylene carbonate and lithium perchlorate are used as electrolytes.[6,7]

4.2 *Surface tension*

The next characteristic is the movement of the fluid in the container. The fluid can move easily owing to the force of gravity. The movement of fluid depends on kinematic viscosity, the surface tension of the liquid, and the solid it is in contact with. Surface tension between interfaces must also be reduced, since surface tension at this scale can prevent the fluid's movement, increase the response time, and create rounded interfaces. If the surface tension is not reduced in this sensor, the fluid will not move and hysteresis will occur.

Surface tension is caused by differences between the affinity the fluid has for itself and the affinity it has for the material it is in contact with. In order to overcome surface tension and enable the smooth movement of fluid in the container, a lower-surface-tension liquid should be used as electrolyte and a hydrophobic material should be used for the container. However, a fluid with lower surface tension such as silicone oil has a lower dielectric constant, which reduces the magnitude of the capacitance change of the sensor and thus the resolution. Furthermore, to eliminate the hysteresis problem, differences between the advancement angle (θ_A) and retreat angle (θ_R) of the liquid should be small when it is moving in the container. Therefore, to find an optimized fluid for our sensor, four parameters were considered. They were kinematic viscocity, dielectric constant, surface tension and differences between the advancement and retreat angles of the liquid when it is flowing.

As described above, PDMS is selected as the container material because it has hydrophobic characteristics and low surface tension and can be fabricated in a batch process at low cost using a lithography process. Then, water, ethanol, methanol and propylene carbonate were tested as the electrolyte for this sensor.

5. Fabrication Technology

5.1 *Fabrication method*

The container part was fabricated by substrate penetration lithography, as shown in Fig. 5, and electrodes were fabricated on a printed circuit board (PCB). Then the container and PCB were sealed.

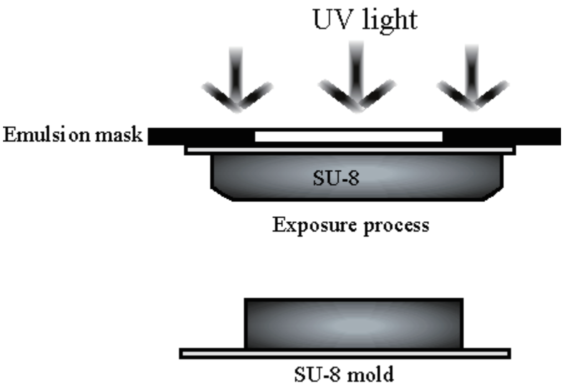
5.2 *Container fabrication*

5.2.1 *Fabrication of three-dimensional SU-8 mold container*

Mask patterns were designed using drawing software. Then, the patterns were printed out on transparency film and photoreduced at a rate of 1/5 onto emulsion glass masks.

Then substrate penetration lithography was applied in the lithography process to fabricate a mold. The advantage of this technique is that the cumbersome optimization of the resist-coating process can be shortened since the surface of the final structure does not depend on the precoated resist surface. Negative resist SU-8 10 was used to form three-dimensional high-aspect-ratio molds. We applied 0.5-mm-thick and 1.0-mm-thick SU-8 resist to a thin glass substrate (t = 0.17 mm) and prebaking was performed for 4 and 6 h at 100°C. Then lithography was performed to fabricate an SU-8 three-dimensional container mold. As a trial test, a height of 0.5 mm was obtained with a 45 s exposure time. Then, by increasing the exposure time to 180 s, the height was successfully increased from 0.5 to 1.0 mm.

The fabrication method is shown in Fig. 5. A SEM image of SU-8 mold is shown in Fig. 6. Photographs of the SU-8 mold are shown in Figs. 7 and 8.



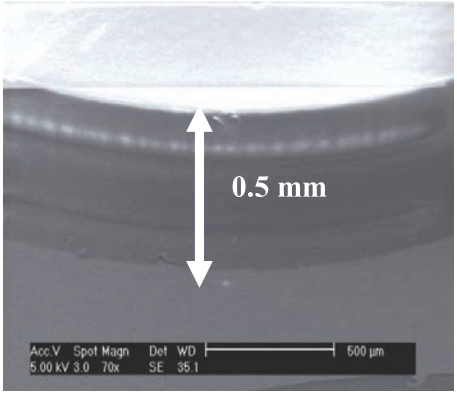
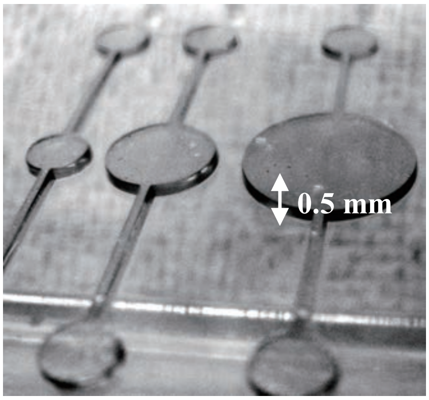


Fig. 5 (left). Method of fabricating SU-8 mold by substrate penetration lithography.
Fig. 6 (right). SEM image of SU-8 mold for exposure time 45 s.



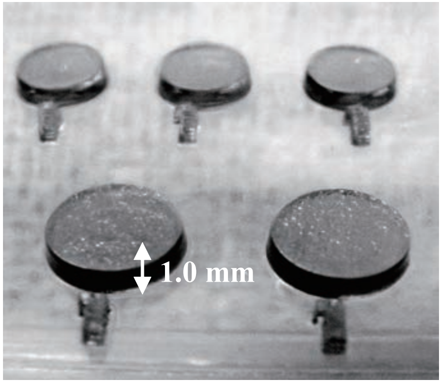


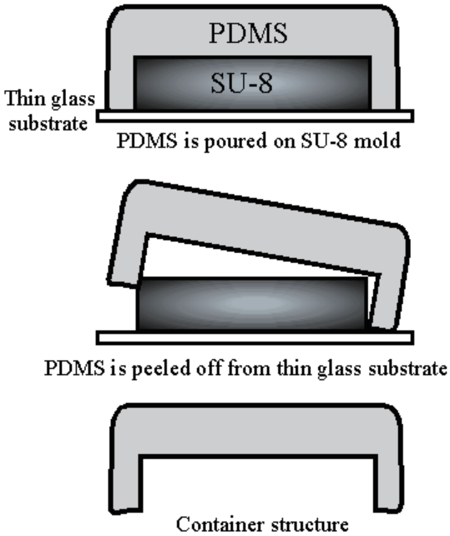
Fig. 7 (left). Photograph of SU-8 mold for exposure time of 45 s.
Fig. 8 (right). Photograph of SU-8 mold for exposure time of 180 s.

5.2.2 *Fabrication of PDMS container*

The SU-8 mold was placed in a petri dish onto which PDMS (Dow Corning Sylgard 184) was poured. PDMS was mixed with the catalyst at a rate of PDMS:catalyst = 10:1. Then PDMS was defoamed in a vacuum desiccator for 1 day. After that, PDMS was peeled off from the glass plate. The fabrication method is shown in Fig. 9. A SEM image of the PDMS container is shown in Fig. 10. Photographs of the container are shown in Figs. 11 and 12.

5.3 *Electrode fabrication*

An electrode was fabricated on a PCB. The electrode pattern was designed using drawing software. Then, the designed pattern was printed on transparency film.



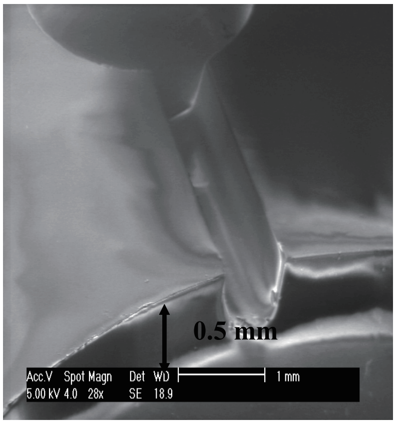
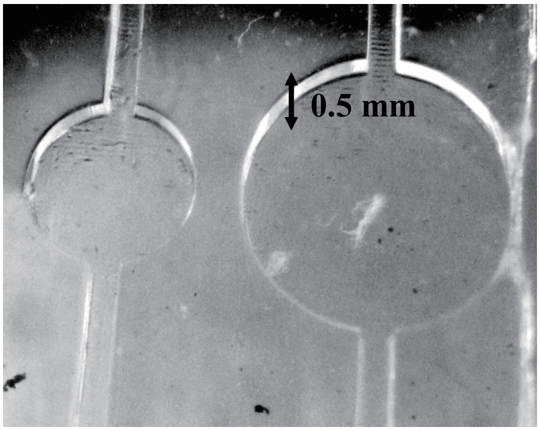


Fig. 9 (left). Fabrication method for PDMS container.
Fig.10 (right). SEM image of PDMS container with thickness of 0.5 mm.



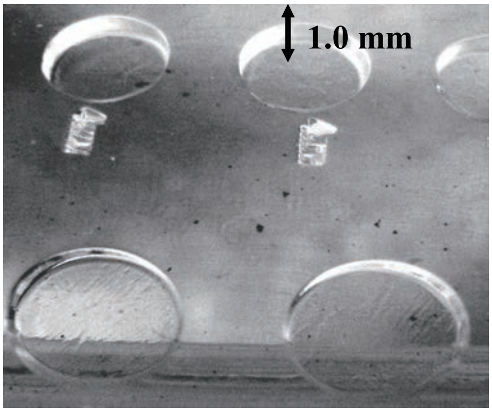
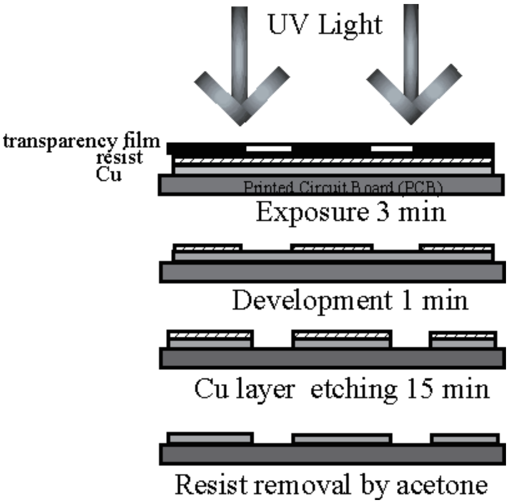


Fig. 11 (left). Photograph of PDMS container structure with thickness of 0.5 mm.
Fig.12 (right). Photograph of PDMS container structure with thickness of 1.0 mm.

A photo resist-type PCB was used and was exposed for 3 min. After development for 1 min, Cu was etched using PCB etching solution ($FeCl_3$) for 15 min. Then, the resist was removed using acetone. The thickness of Cu was measured to be 24 µm. The fabrication method and a photograph of the electrode are shown in Figs. 13 and 14, respectively.



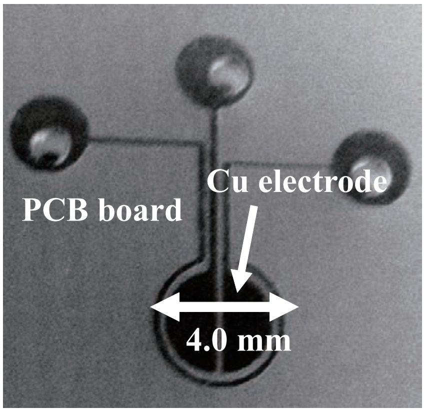


Fig. 13 (left). Fabrication of electrode on PCB.
Fig. 14 (right). Photograph of electrode on PCB (top view).

5.4 *Sealing process*

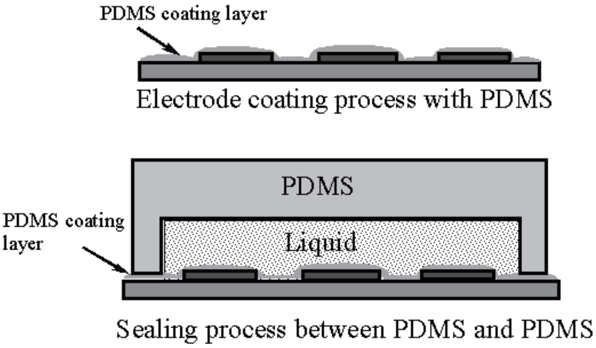
The electrode was spin-coated with PDMS as an insulator layer. After that, the container (PDMS) and electrode were sealed immediately while the coating layer was still wet. Then, they were baked on a hot plate for 20 min at 70°C to strengthen the sealing process. The sealing process and a photograph of the sensor are shown in Figs. 15 and 16, respectively.

6. Experimental Results

We evaluated the output characteristic of the fabricated inclination sensors. Sensors with sizes of ϕ10.0 mm × 0.5 mm, ϕ7.5 mm × 0.5 mm and ϕ5.0 mm × 0.5 mm were evaluated. Considering the requirement for low-surface-tension properties of fluids, we tested water, ethanol, methanol and propylene carbonate as electrolytes. The results of the movement of fluid are shown in Table 1. From Table 1, only methanol could move in the container with the dimensions mentioned above. Therefore, for the first time, methanol was selected as the electrolyte for our inclinometer.

6.1 *Methanol electrolyte*

A methanol electrolyte was tested in sensors with sizes of ϕ7.5 mm × 0.5 mm and ϕ5.0 mm × 0.5 mm. As shown in Fig. 17, the meniscus force becomes large when the sensor is miniaturized. However, we successfully obtained a linear output in the inclination angle range from –60 to +60° (Fig. 18) when methanol was injected in the container. From the result, methanol enables the formation of a double layer and allows



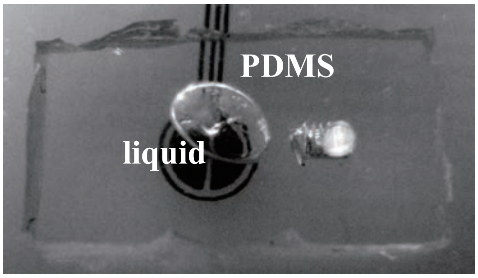


Fig. 15 (left). Method of sealing PDMS insulator with PDMS.
Fig.16 (right). Photograph of inclination sensor (top view).

Table 1
Results of movement of fluid in container.

	Water	Ethanol	Methanol	Propylene carbonate
γ Surface tension (mN/m)	72	23	22.6	41.1
μ Kinematic viscocity (mm^2/s)	0.89	1.37	0.70	1.67
Dielectric constant	80.0	24.3	32.6	65.0
Boiling point (°C)	100.00	78.3	64.7	241.7
Movement of fluid in container	NG	NG	OK	NG

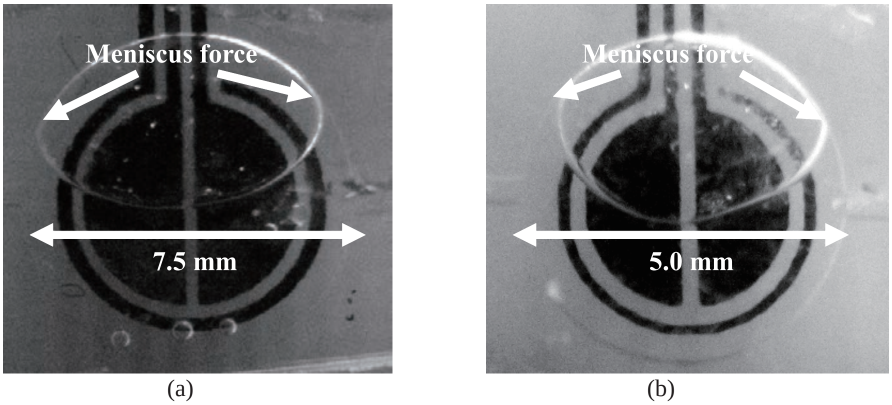


Fig. 17. Meniscus force condition for ϕ7.5 mm × 0.5 mm (a) and ϕ5.0 mm × 0.5 mm (b).

the realization of a parallel-plate capacitor function, as explained in §2. However, the hysteresis width for the 5.0-mm-sized container is 40° and is larger than that for the 7.5-mm-sized container (Fig. 18).

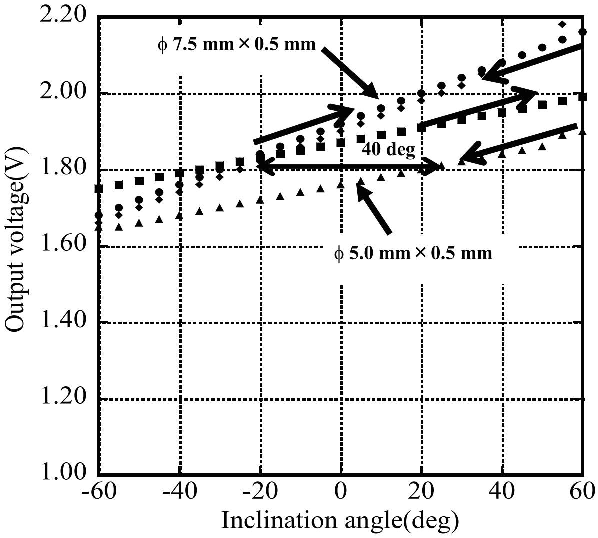


Fig. 18. Relationship between inclination angle and output voltage when methanol is used as electrolyte in container whose inner surface is not modified using silicone oil.

As shown in Table 2, the minimum moving angle and response time are 4.0° and 2.0 s, respectively, for a dimension of 5.0 mm. The movement of methanol is not smooth and the difference between advancement angle and retreat angle is too large. Furthermore, the volatility is too high and hysteresis occurs in the response characteristic of the sensor.

As our first objective, we aimed at a minimum moving angle and response time of 0.5° and less than 1.0 s, respectively. To resolve the above problem and to achieve our aim, an improvement in the type of liquid and a modification of the inner surface and dimension size of the container would be necessary.

6.2 *Modification of inner surface of PDMS container*

Modifying the surface using a hydrophobic material will improve the movement of liquid. We had tried to cover the inner surface with Cytop. However, it was difficult to seal the PCB (already coated with PDMS) and the container that was coated with Cytop because both have hydrophobic surfaces.[8]

Silicone oil is known to be an excellent water-repellent solution. A contact angle greater than 90° is shown by KF-96 silicone oil. It is used for the hydrophobic processing of glass, ceramics and fibers. Moreover, it is also useful for fluid improvement and solidification prevention.

Therefore, silicone oil was used to reduce the surface tension of the inner surface of the PDMS container. We injected silicone oil in the container after the sealing process. Then, the container was rotated many times to ensure that silicone oil flowed and adhered to the entire sidewall of the container. Then, the silicone oil was drawn out of the container. After that, the electrolyte was injected. Propylene carbonate and methanol

Table 2
Comparison of minimum moving angle and response time for various dimensions and types of liquid.

Dimentions	ϕ7.5 mm × 0.5 mm			ϕ5.0 mm × 0.5 mm		
Type of liquid	A type	B type	C type	A type	B type	C type
Minimum moving angle	2.5°	1.6°	2.0°	4.5°	4.0°	4.0°
Response time	2.00 s	1.30 s	1.30 s	2.70 s	2.00 s	2.00 s

A type: Methanol electrolyte is injected in the PDMS container whose inner surface is not modified using silicone oil.
B type: Methanol electrolyte is injected in the PDMS container whose inner surface is modified using silicone oil.
C type: Propylene carbonate electrolyte is injected in the PDMS container whose inner surface is modified using silicone oil.

were used as electrolytes. Using this method, we can overcome the problem of sealing the PCB mentioned above because silicone oil is injected after the sealing process.

6.3 *Methanol and propylene carbonate*

As described in §6.1, the volatility of methanol is too high and it affects the output of the sensor. As shown in Table 1, propylene carbonate's boiling point is 4 times higher than that of methanol. In the experiments, propylene carbonate could not flow in the container whose inner surface was not modified using silicone oil.

Therefore, using the modification method mentioned in §6.2, devices with dimensions of ϕ7.5 mm × 0.5 mm and ϕ5.0 mm × 0.5 mm were also evaluated using methanol and propylene carbonate electrolytes. The results of comparisons between 5.0 mm and 7.5 mm devices after inner surface modification are shown in Figs. 19 and 20. From the results, by implementing this method, propylene carbonate could flow in the container and the analog output of the sensor exhibited no hysteresis. Thus, propylene carbonate is a suitable electrolyte because it has a high boiling point and a high dielectric constant.

Actually, the electrolyte glides along the silicone oil that adheres the inner surface of the container. From our observation, liquid (electrolyte) comes in contact with liquid (silicone oil) while it is flowing in the container. Thus, the resistance to the movement of the fluid is decreased and the fluid flows smoothly.

Furthermore, by injecting silicone oil in the container, the difference between the advancement angle (θ_A) and retreat angle (θ_R) of the liquid is small, as shown in Fig. 21. The hysteresis problem was eliminated for the sensor with a dimension of 5.0 mm. Linearities for the 5.0 mm-dimension sensor of less than 12%/F.S and 13%/F.S were obtained for methanol and propylene carbonate, respectively. As shown in Table 2, minimum moving angle and response time were improved. However, propylene carbonate and methanol could not flow when the diameter of the container was reduced to 4.0 mm. Thus, to overcome this problem, the height of the container was increased to 1.0 mm.

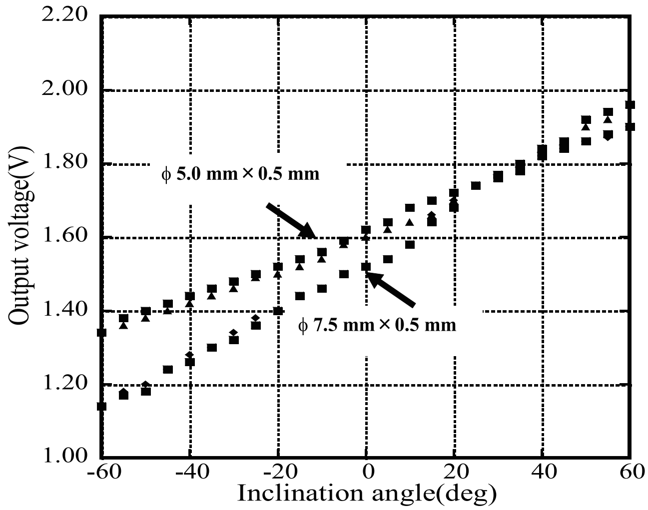


Fig. 19. Relationship between inclination angle and output voltage when methanol is used as electrolyte in container whose inner surface is modified using silicone oil.

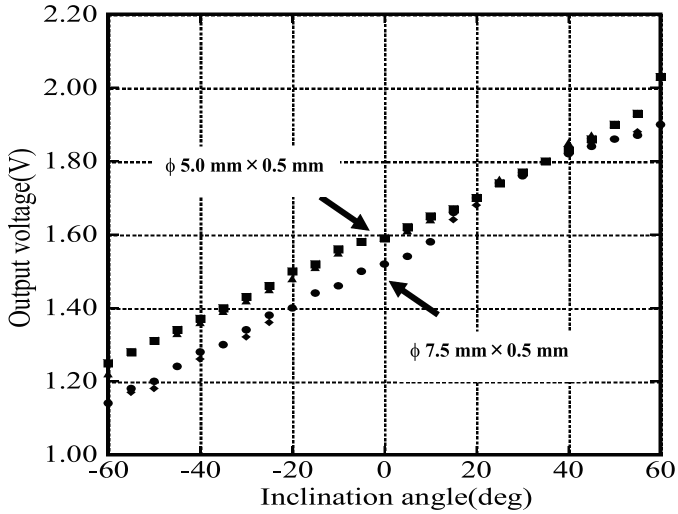
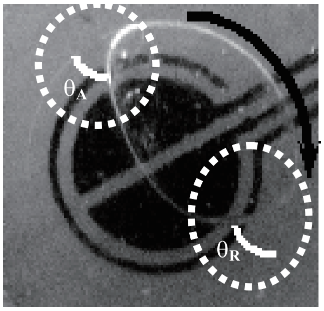


Fig. 20. Relationship between inclination angle and output voltage when propylene carbonate is used as electrolyte in container whose inner surface is modified using silicone oil.

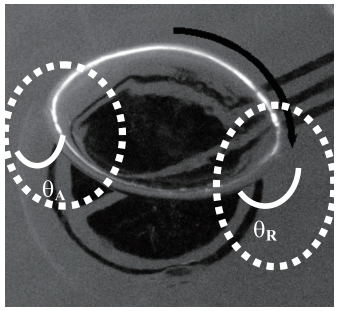
6.4 *Increasing height of container*

First, we tested methanol as the electrolyte in containers with dimensions of ϕ5.0 mm × 1.0 mm and ϕ4.0 mm × 1.0 mm that were not modified using silicone oil.

The hysteresis width could be reduced to 10° for the 5.0-mm-dimension container. However, the large hysteresis width could not be eliminated for the 4.0- mm-dimension container, even though the height of the container was increased to 1.0 mm. The result is shown in Fig. 22.



(a) ϕ 5.0 mm × 0.5 mm dimensions without modification using silicone oil at angle of 60 deg.



(b) ϕ 5.0 mm × 0.5 mm dimensions after modification using silicone oil at angle of 60 deg.

Fig. 21. Comparison of advancement angle (θ_A) and retreat angle (θ_R) when methanol is used as electrolyte in unmodified container (a) and modified container (b).

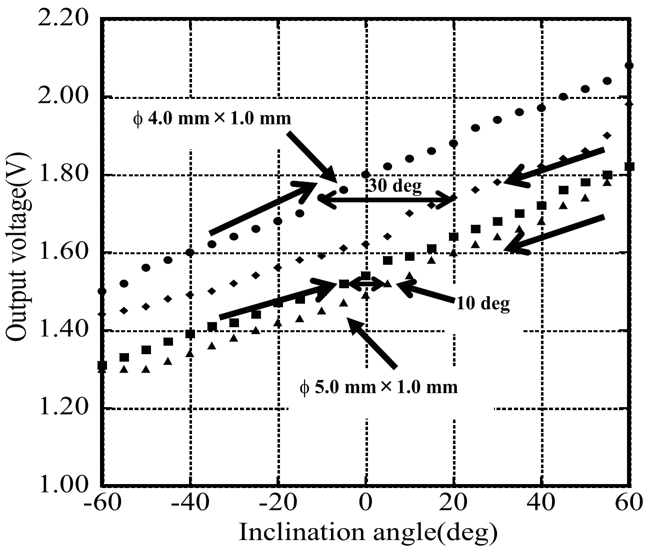


Fig. 22. Relationship between inclination angle and output voltage when methanol is used as electrolyte in container whose inner surface is not modified using silicone oil.

Then, propylene carbonate with the container modified using silicone oil was tested. Figure 23 shows the difference between advancement angle and retreat angle could also be reduced for the 4.0-mm-dimension container. Thus, as shown at Fig. 24, the output was obtained from –60 to +60° for dimensions of ϕ4.0 mm × 1.0 mm without hysteresis, and the linearity was less than 6%/F.S.

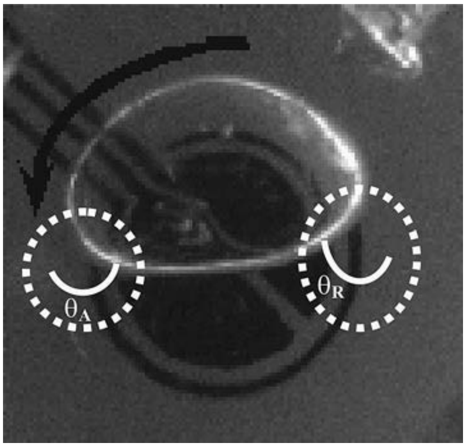


Fig. 23. Comparison of advancement angle (θ_A) and retreat angle (θ_R) when propylene carbonate is used as electrolyte in container that is modified using silicone oil.

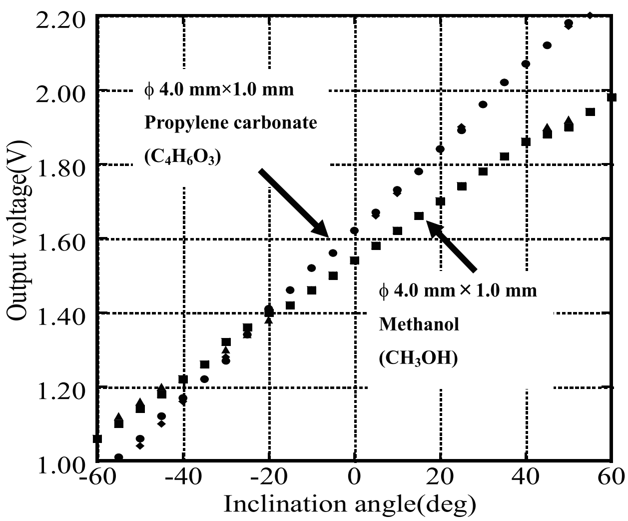


Fig. 24. Relationship between inclination angle and output voltage when methanol and propylene carbonate are used as electrolyte in container whose inner surface is modified using silicone oil for dimensions of ϕ4.0 mm × 1.0 mm.

As shown in Table 1, the dielectric constant of propylene is higher than that of methanol. Therefore, as shown at Fig. 24, the analog output of the sensor when propylene carbonate is injected as the electrolyte is higher than that in the case of the methanol electrolyte. The minimum moving angle and response time can also be improved by increasing the height of the container and modifying the container using silicone oil (Table 3).

Table 3
Comparison of minimum moving angle and response time for various dimensions and types of liquid.

Dimention	ϕ5.0 mm × 1.0 mm			ϕ4.0 mm × 1.0 mm		
Type of liquid	A type	B type	C type	A type	B type	C type
Minimum moving angle	0.8°	0.2°	0.3°	1.0°	0.3°	0.4°
Response time	1.90 s	1.20 s	0.80 s	2.30 s	1.30 s	0.90 s

A type: Methanol electrolyte is injected in the PDMS container whose inner surface is not modified using silicone oil.
B type: Methanol electrolyte is injected in the PDMS container whose inner surface is modified using silicone oil.
C type: Propylene carbonate electrolyte is injected in the PDMS container whose inner surface is modified using silicone oil.

6.5 *Temperature characteristic and reproducibility*

The temperature characteristic was measured for a sensor with dimensions ϕ4.0 mm × 1.0 mm whose inner surface was modified using silicone oil. Propylene carbonate was used as the electrolyte. The temperature characteristic was measured between 0 to 50°C, as shown in Fig. 25. The change in temperature did not affect the output voltage of the sensor between 0 and 50°C. This result shows that the operational amplifier used in the detection circuit (Fig. 3) was not affected by offset voltage.

In a reproducibility experiment, an accurate output voltage of the sensor could be obtained 2 weeks after measurement was carried out using the same sensor when propylene carbonate was used as the electrolyte. However, the electrolyte easily evaporated when methanol was implemented in the sensor. Therefore, by implementing propylene carbonate as the electrolyte, the problem of the evaporation of liquid could be solved and an accurate and reproducible of output voltage was obtained.

6.6 *Vibration characteristic*

The vibration was measured for a sensor size of ϕ4.0 mm × 1.0 mm whose inner surface was modified using silicone oil. Propylene carbonate was used as the electrolyte. In this experiment, a vibrator (EMIC 513-AH: Shin Nippon Co, Ltd.) was used and a 3-axis acceleration sensor (MVP-RFA3-c: Microstone Co, Ltd.) was fixed on the sensor. As shown in Fig. 26, acceleration was demonstrated in the horizontal direction of the sensor. The acceleration was fixed at ±20 m/s^2 (±2 G) while changing the frequency from 5 to 50 Hz. As a result, the vibration was not affected when the frequency was 25 Hz or more at acceleration ±2 G. The result shows that the effect of vibration could be decreased because the electrolyte provided a damping effect and that the sensor could sustain considerable shock.

7. Conclusions

A one-side-electrode-type fluid-based inclinometer has been fabricated for the first time by implementing an electrical double layer principle combined with CMOS

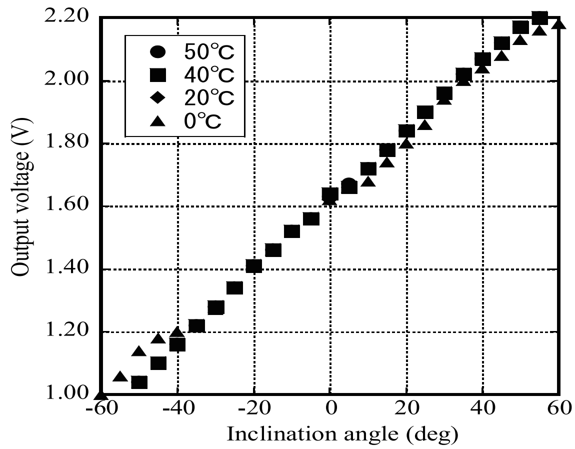


Fig. 25. Temperature characteristic for sensor size ϕ4.0 mm × 1.0 mm.

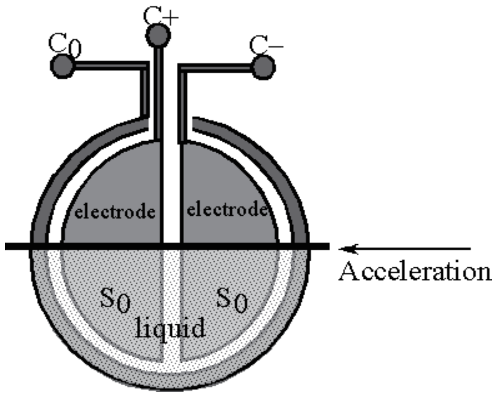


Fig. 26. Direction of acceleration that was demonstrated by the sensor.

circuitry. Substrate penetration lithography is applied in the fabrication of the container. Using a negative resist SU-8, it was possible to increase container height from 0.5 to 1.0 mm.

Methanol and propylene carbonate were tested as electrolytes. An electrical double layer (EDL) was formed and the functionity of a parallel-plate capacitor was observed for both electrolytes.

In order to eliminate hysteresis and to reduce the surface tension of the container, silicone oil was injected in the container and the height of the container was increased from 0.5 to 1.0 mm. Therefore, we successfully obtained a linear output in the inclination angle range from –60 to +60° for dimensions of ϕ4.0 mm × 1.0 mm with a linearity of less than 6%/F.S when propylene carbonate was used as the electrolyte. The minimum moving angle and response time were 0.4° and 0.9 s, respectively.

However, the range of output voltage between ±60° was low. Possible causes for this include the following: the amount of capacitive change in relation to inclination was small because of the low permittivity of the dielectric silicone oil and electrolyte, the nonuniform deposition of the coating layer, and the effect of the parasitic capacitance of wiring during measurement.

As further work, a new container material such as glass or plastic will also be used in the next sensor. The additional of an amplifier stage also has been considered to increase the output voltage. Then, to overcome the problem of parasitic capacitance, the sensor and detection circuit will be combined in one ceramic package. We plan to continue optimizing the size of the sensor with high efficiency to satisfy the demand in the automotive, industrial, medical, entertainment and electrical appliance fields.

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