Study of Capacitive Tilt Sensor with Metallic Ball

Chang Hwa Lee and Seung Seob Lee

In this paper, a new, simple capacitive tilt sensor with a metallic ball is proposed. The proposed tilt sensor has only two electrodes and a metallic ball, and this design assists in managing the inherent contact problem in measuring tilt angles. Capacitive sensing, compared with other types of tilt sensor, has many advantages such as simplicity, noncontact measurement, long-throw linear displacement, and sub-micron plate spacing. Its design and fabrication process are significantly simpler than previous types of tilt sensors. The dimensions of the prototype tilt sensor are 20 mm × 20 mm, and the diameter of the polystyrene tube is 5 mm with a tube thickness of 0.15 mm. An analytical study of the prototype capacitive tilt sensor was undertaken, and the experimental results demonstrate the relationship between the tilt angles and measured capacitances compared with the analytical study.

Keywords: Tilt sensor, inclinometer, capacitive sensor, noncontact measurement, metallic ball.

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I. Introduction

Tilt is an important parameter in many motion-detection applications, including: transportation vehicles, industrial equipment, cameras, robots, toys, and so on. There are many types of tilt sensors or inclinometers that use various design principles including: electrolyte conductors, gas bubbles in liquid, resistive mercury balls, pendulums, optics inductance, capacitance, and so on [1]–[8]. In comparison with other types of sensors, capacitive sensors are unaffected by temperature, humidity, or mechanical misalignment; they are also noncontact devices capable of high-resolution measurements of a position or change of position. Furthermore, shielding against stray electric fields in capacitive sensors is simple compared with shielding against magnetic disturbances, and the contact problem for the measurement of the tilt angle is a serious problem in resistive tilt sensors [9].

For electrolytic tilt sensors [1]–[2], their measurement range of the tilt angle is 60°, and the measured output voltages are saturated so quickly that the actual effective region is much smaller than 60°. In addition, the sealing of the electrolytic liquid is a tiresome process.

In this paper, a new, simple capacitive tilt sensor using a metallic ball was investigated. Its measurement angle is much wider than other types of tile meter, and its very simple structure, with no contact points from moving parts, makes it easier to fabricate.

The simplified equation for the capacitance of two parallel plates is as follows:

$$C = \varepsilon \frac{S}{d}, \tag{1}$$

where ε is the constant (permittivity) of the dielectric, and S is the area of the conducting plates separated by d, which is the distance between these plates. As shown in this equation, these three parameters are key in determining the capacitance of the configuration. When capacitive sensors are used as motion detectors, the space variation Δd, area variation ΔS, and permittivity variation $\Delta\varepsilon$ can be used as the varying parameters through which the amount of motion can be measured. When the permittivity-variation parameter $\Delta\varepsilon$ is applied to capacitive sensors, the liquid or solid dielectric moves between the electrodes, which are positioned around the dielectric-enabling capacitance variances [9]–[11]. However, a change in dielectric value can also be detected using only capacitance variances [12]. When the area-variation parameter ΔS is applied to capacitive sensors, there is relative motion between the electrodes. The relative motion changes the overlapped area between the electrodes, as in the case of capacitive motion encoders and capacitive limit switches. Using the space-variation parameter (Δd) is the simplest and most effective method for creating capacitive sensors. This method can measure very small spacing changes between electrodes, such as in a capacitive micrometer. The capacitance variation is caused by changing the electrodes' spacing [9]. Among the three parameters in (1), the sensor proposed in this paper uses the space-variation parameter Δd to detect the tilt angle.

In this paper, a new, simple capacitive tilt sensor using a metallic ball is proposed. For this structure, the proposed sensor has only two electrodes and a metallic ball; thus, the proposed sensor has a very easy fabrication process. The proposed sensor has no contact point between the metallic ball and the two electrodes below so as to allow noncontact measurement of the tilt angle. The experimental results demonstrate the relationship between the tilt angles and measured capacitances compared with the analytical solution of the proposed capacitive tilt sensor, which uses a metallic ball.

II. Principle of Capacitive Sensing

Figure 1 shows a conceptual schematic view of the proposed capacitive tilt sensor. Figure 1(a) shows a typical configuration of the series connection between the two capacitors. Because the two blue electrodes are a common node in Fig. 1(a), they can be united as shown in Fig. 1(b). The configuration presented in Fig. 1(b) can be modified into Fig. 1(c), in which the blue electrode moves up and the two yellow electrodes move down. Finally, the upper blue electrode can be substituted for a spherical shape, as seen in Fig. 1(d). Therefore, the configuration in Fig. 1(d) is the same as the series connection of the two capacitors in Fig. 1(a), excluding the parasitic capacitance between the two lower electrodes. There is no contact between the blue electrode and the yellow electrodes. The configuration in Fig. 1(d) is the proposed capacitive tilt sensor with a metallic ball, which is presented in this study.

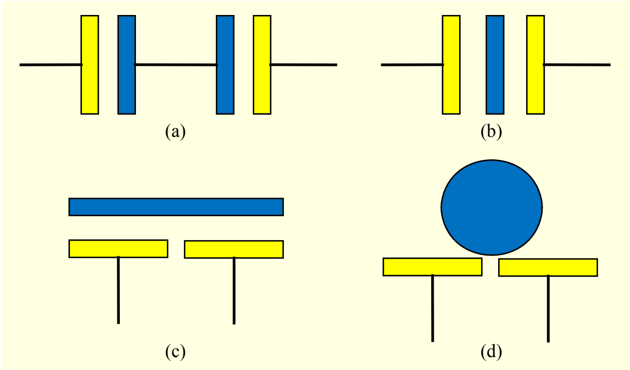

Fig. 1. Concept of capacitive tilt sensor with metallic ball.

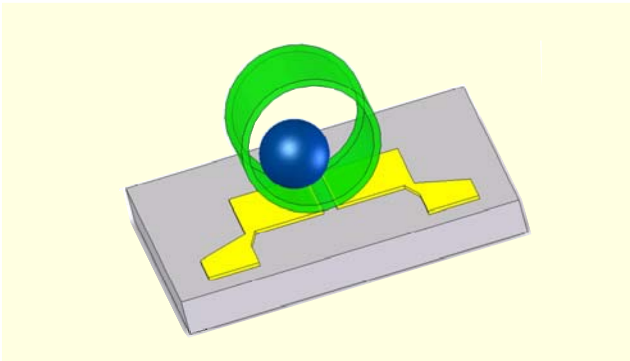

Fig. 2. Schematic view of capacitive tilt sensor with metallic ball.

Figure 2 shows a schematic view of the proposed capacitive tilt sensor using a metallic ball. This is the same configuration as presented in Fig. 1(d). There are two electrodes (identical to the yellow electrodes in Fig. 1(d)) on the glass wafer substrate and a metallic ball (identical to the blue electrode in Fig. 1(d)) in a polystyrene tube. This configuration is the same as the series connection of the two capacitors in Fig. 1(a), excluding the parasitic capacitance between the two lower electrodes. There is no contact between the metallic ball and the electrodes.

Figure 3 shows the schematic views of the operation of the proposed capacitive tilt sensor. The capacitance between the left electrode and metallic ball is C_1, and the capacitance between the right electrode and metallic ball is C_2. Therefore, C_1 and C_2 are connected in a series, as shown in Fig. 1(d). Figure 3(a) shows the tilt sensor at 0°. The metallic ball is in the center of the electrodes, and C_1 and C_2 have the same value. The values of C_1 and C_2 are separated as the sensor is tilted to 90°. The distance between the electrodes and metallic ball increases simultaneously; thus, C_1 and C_2 decrease, resulting in the total capacitance in the series connection being decreased, as shown in Fig. 3(b). The total capacitance can be measured using only the two electrodes; therefore, there is no physical

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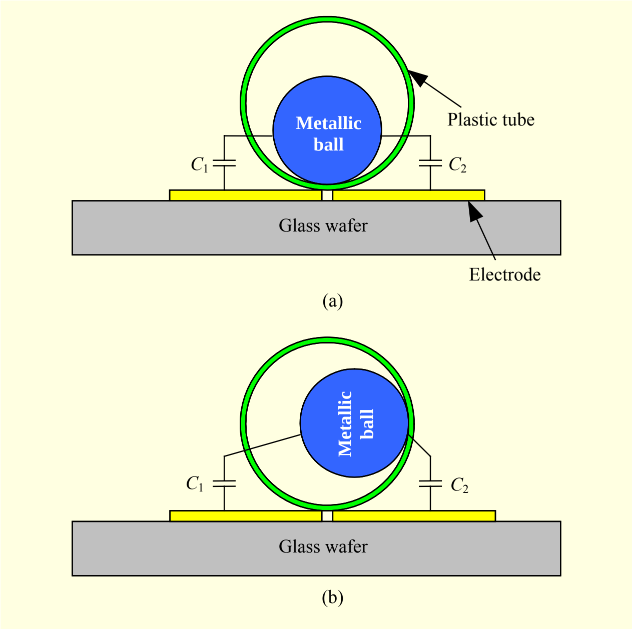

Fig. 3. Schematic views of operation of capacitive tilt sensor at: (a) 0º and (b) 90º.

contact between the electrode and metallic ball in this sensor.

III. Analytical Study of Capacitive Tilt Sensor

Figure 4 presents an analytical study of the capacitive tilt senor with a metallic ball. The green circle is the polystyrene tube with a radius of b; in this part, it does not have a thickness for convenient calculation. The blue ball is a metallic ball with center point $P(x, y)$.

In accordance with the motion of the blue ball, $P(x, y)$ creates a dotted black circle with radius r (red line), which has equation

$$x^2 + y^2 = r^2 . \tag{2}$$

The two yellow blocks are the sensor electrodes A and B with centers (–a, –b) and (a, –b), respectively. As a result of (2), x and y can be written as follows; with θ being the angle between the x-axis and r:

$$\begin{aligned} x &= r\cos\theta, \\ y &= r\sin\theta. \end{aligned} \tag{3}$$

To understand the capacitive-variance trend and the capacitance order, approximation is applied to calculate the capacitance of this configuration. It is assumed that the configuration of Fig. 4 is the same as the configuration of two parallel plates; thus, the capacitance between the two electrodes can be derived using (1). The capacitance between the left electrode and metallic ball is C_1, and the capacitance between the right electrode and metallic ball is C_2. Furthermore, it is assumed that S is fixed in both C_1 and C_2. The analytical

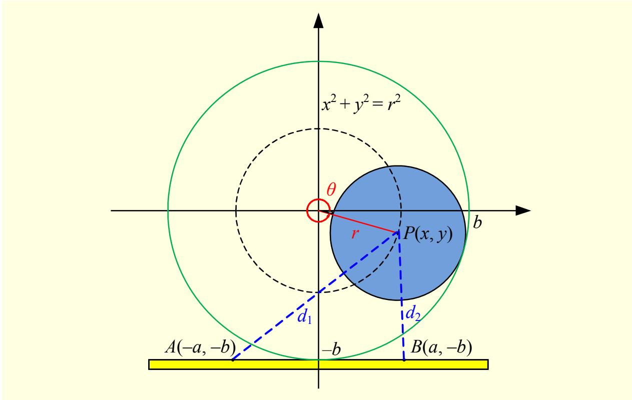

Fig. 4. Analytical study of capacitive tilt sensor.

solution can exhibit the capacitive-variance tendency according to the angle variation. The distance between the left electrode and the metallic ball is d_1, and the distance between the right electrode and the metallic ball is d_2; they are defined as follows:

$$\begin{aligned} d_1 &= \sqrt{(x+a)^2 + (y+b)^2} \\ &= \sqrt{(r\cos\theta + a)^2 + (r\sin\theta + b)^2}, \end{aligned} \tag{4}$$

$$\begin{aligned} d_2 &= \sqrt{(x-a)^2 + (y+b)^2} \\ &= \sqrt{(r\cos\theta - a)^2 + (r\sin\theta + b)^2}. \end{aligned} \tag{5}$$

Because the total capacitance C is connected in series, it is defined as follows:

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} = \frac{C_1 + C_2}{C_1 C_2}, \; C = \frac{C_1 C_2}{C_1 + C_2}. \tag{6}$$

Another approximation is that the areas of C_1 and C_2 are equal; that is, $S_1 = S_2 = S$; thus

$$C = \frac{\varepsilon\frac{S_1}{d_1}\varepsilon\frac{S_2}{d_2}}{\varepsilon\frac{S_1}{d_1} + \varepsilon\frac{S_2}{d_2}} = \frac{\varepsilon\frac{S}{d_1 d_2}}{\frac{1}{d_1} + \frac{1}{d_2}} = \varepsilon\frac{S}{d_1 + d_2}. \tag{7}$$

The distances d_1 and d_2, of (4) and (5), can be substituted into (7) giving the total capacitance as

$$C = \varepsilon\frac{S}{\sqrt{(r\cos\theta + a)^2 + (r\sin\theta + b)^2} + \sqrt{(r\cos\theta - a)^2 + (r\sin\theta + b)^2}}. \tag{8}$$

Using the analytical solution with this approximation, the capacitive-variance trend and order of magnitude can be analyzed with the increase of tilt angle from (8).

Figure 5 shows the graph of the capacitances of metallic balls of different sizes versus tilt angles that were calculated using (8). When θ is 270° in Fig. 4, the tilt angle in Fig. 5 is 0°. Due to the assembling tolerance between the tube and the substrate, I insert an assembling tolerance of 0.15 mm into my

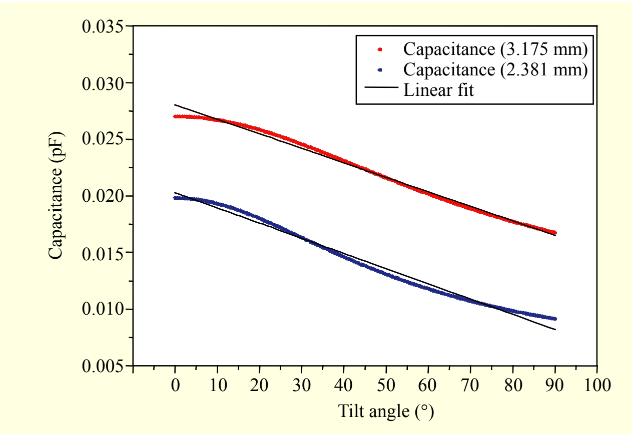

Fig. 5. Calculated capacitance of metallic balls of different sizes vs. tilt angle.

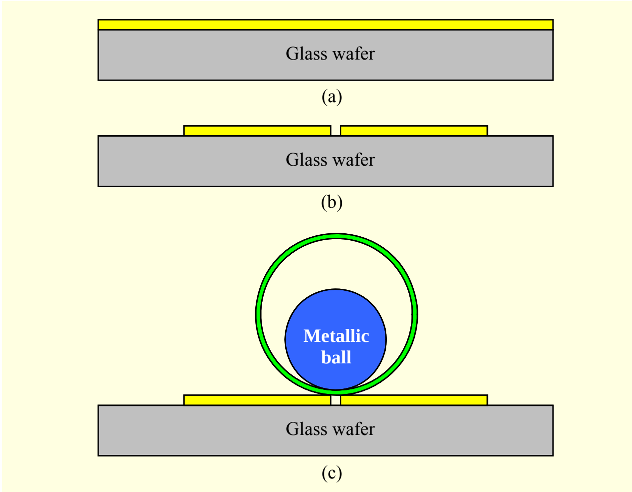

Fig. 6. Fabrication process of capacitive tilt sensor: (a) Cr (300 μm) and Au (2,000 μm) evaporation; (b) patterning electrode; and (c) attaching plastic tube with metallic ball.

calculations. The small red dots represent the capacitances for a ball with diameter of 3.175 mm, and the small blue dots represent the capacitances for a ball with diameter of 2.381 mm. These capacitances demonstrate the monotonic decrease in the capacitance with the increase in the tilt angle; and a device with this characteristic can be used as a sensor. A linear relationship (although not perfectly linear) is observed except in the range of the low tilt angle between approximately 0° and 10°.

IV. Fabrication Process and Experimental Setup

Figure 6 presents the fabrication process of the proposed capacitive tilt sensor using a metallic ball. The structure and fabrication process of this sensor is very simple. A Silicon wafer cannot be used as a substrate in the proposed sensor, because it is doped by p-type (positive) dopant or n-type (negative) dopant. When the substrate is not a perfect insulator it can function as another electrode, or the electrodes on the Si substrate can cause electrical shorts. Therefore, a doped Si wafer can affect the entire capacitance of the capacitive tilt sensor. For this reason, a glass wafer (a perfect insulator) must be used as a substrate of the capacitive tilt sensor.

Chrome (Cr) and gold (Au) were deposited on the glass wafer as electrodes using an e-beam evaporator, as shown in Fig. 6(a); their thicknesses were 300 μm and 2,000 μm, respectively. Cr functions as an adhesive layer between the glass wafer and Au. Then, the electrodes were patterned via photolithography, as shown in Fig. 6(b).

Next, a polystyrene tube with a metallic ball was attached using adhesive, as shown in Fig. 6(c). Tilt sensors, with metallic balls of different sizes, were fabricated for the test: the diameters of these metallic balls were 3.175 mm and 2.381 mm. The substrate dimensions were 20 mm × 20 mm; the polystyrene tube diameter was 5 mm; and the polystyrene tube thickness was 0.15 mm.

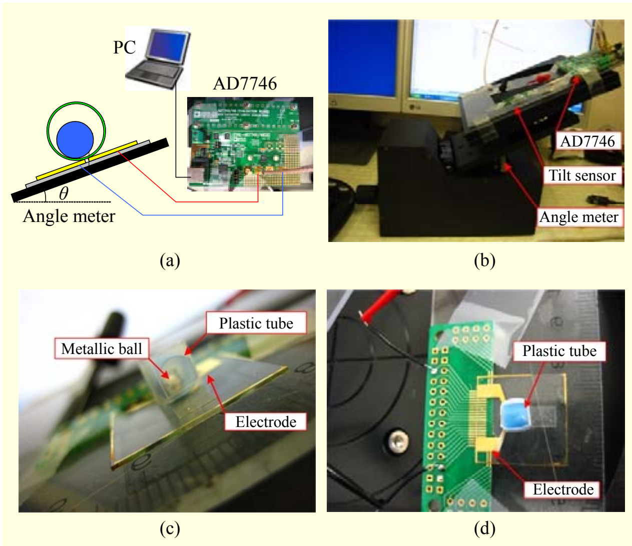

Fig. 7. (a) Schematic experimental setup of capacitive tilt sensor for measuring tilt angle, (b) actual experimental picture of measuring tilt angle and fabricated capacitive tilt sensor, (c) side view, and (d) top view.

Figure 7(a) presents a schematic experimental setup of the capacitive tilt sensor used to measure the tilt angle. An angle meter was used for the tilting angle of the tilt sensor, and an AD7746 evaluation board (Analog Devices, Inc.) was used to measure the capacitance of the tilt sensor. Figure 7(b) is the actual experimental setup to measure the tilt angle. For accurate measurements, the AD7746 evaluation board was mounted on the angle meter with wires, as shown in Fig. 7(b), to prevent the wires from bending. The measured capacitance was affected by the wires bending. Figures 7(c) and 7(d) show the side and top views, respectively, of the fabricated capacitive tilt

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sensor using a metallic ball on the angle meter. To prevent the metallic ball escaping, the polystyrene tube was surrounded by a plastic cage.

V. Results and Discussion

Figure 8 shows the experimental results in a graph with the measured capacitances versus tilt angles of the tilt sensor. The tilt-sensor capacitances were measured with metallic balls of different diameters, at angles ranging from 0° to 90°.

As shown in Fig. 5, there was a monotonic decrease in the measured capacitances with increases in the tilt angle; and capacitances increased as the size of the metallic ball increased. The red line indicates the capacitance for a metallic ball with diameter 3.175 mm, and the blue line indicates the capacitance for a metallic ball with diameter 2.381 mm.

The capacitances in Fig. 8 are much larger than those in Fig. 5. Furthermore, there are other parasitic capacitances in the tilt senor connected in parallel. To measure the parasitic capacitances, the capacitances should be measured without the metallic ball in the tilt sensor. The capacitances indicated by the green line are as such. The capacitances without the parasitic capacitances can be derived by subtracting the parasitic capacitances (green) from the measured capacitances (red and blue).

Figure 9 shows the capacitances without the parasitic capacitances and the calculated capacitances (small dots) with the measured capacitances. The red line (with red rectangular dots and small red dots) indicates the capacitances for the metallic ball with diameter 3.175 mm, and the blue line (with blue round dots and small blue dots) indicates the capacitances for the metallic ball with diameter 2.381 mm. The measured capacitance decreases dramatically in the range of 10° to 40° and for larger tilt angles of more than 40°; the measured results follow the calculated data trend. This is caused by the approximation $S_1 = S_2 = S$ in (7). In the 10° to 40° range, the symmetry of configuration of these two capacitors is broken, and the effective area for capacitance S_1 is decreased rapidly compared to S_2. Consequently, C_1 is decreased rapidly compared to C_2. The total capacitance C is always smaller than C_1 or C_2, and this explains the dramatic decrease of capacitance in the range of 10° to 40°. Beyond 40°, the effective area for capacitance S_1 becomes equals to S_2, and so the measured results follow the calculated data trend. The measured capacitance for metallic ball with diameter 2.381 mm shows more hysteresis-like characteristics of the sensor performance than the measured capacitance for metallic ball with diameter 3.175 mm. If the width of the plastic tube is wider than the diameter of the metallic ball, the moving path of the ball cannot be reproducible. For a tilt senor with a smaller metallic ball, a guideline is necessary.

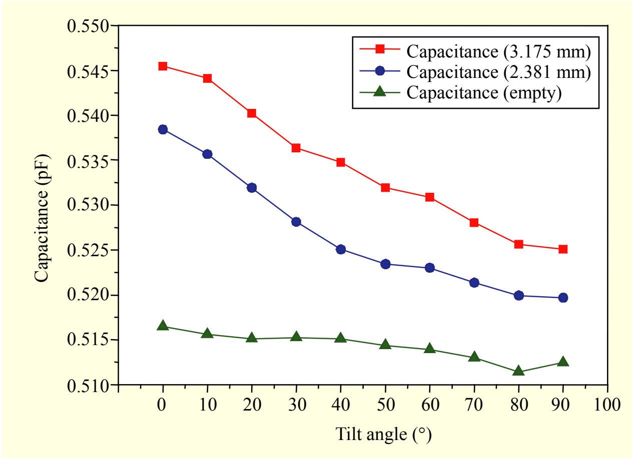

Fig. 8. Measured capacitance of metallic balls of different sizes vs. tilt angle.

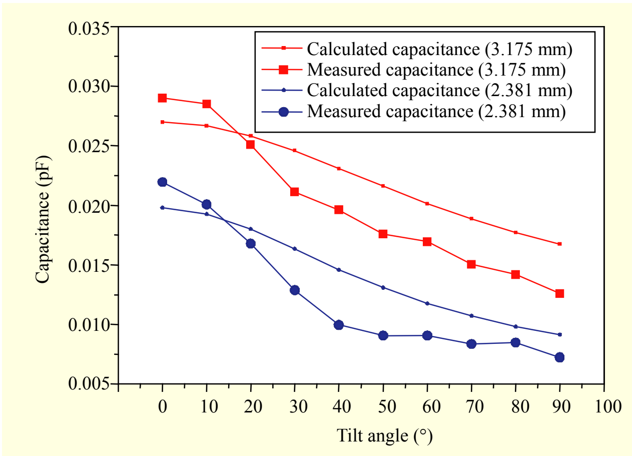

Fig. 9. Comparison of calculated capacitances and measured capacitance without parasitic capacitance.

Overall, this demonstrates that the measured capacitance and calculated capacitance are almost matched in the capacitive-variance tendency and order of capacitance.

VI. Conclusions

A new, simple capacitive tilt sensor using a metallic ball was fabricated and investigated. The structure of this sensor is very simple, and the fabrication process is much easier than other types of tilt sensor. Using the space-variation approximation Δd, an analytical study was undertaken through changes in the metallic ball sizes, and these results were then compared with the experimental results. The results demonstrate that these capacitances are almost matched in the capacitive-variance tendency and order of capacitance. Furthermore, these results demonstrate a monotonic decrease with an increase in the tilt angle, which is one of the essential characteristics of tilt sensors.

However, the suggested tilt sensor cannot distinguish the difference between positive and negative inclination. To distinguish between these differences, the two electrodes in the suggested tilt sensor should be replaced with four electrodes. The measurement for inclination could then be done by connecting these two electrodes respectively. This would make the four small electrodes into two large electrodes, as before. After that, another measurement for the sign of the inclination must be done after disconnecting these two small electrodes respectively. The capacitance of the small electrodes closer to the metallic ball would show a larger value than that of the other side electrodes. The different capacitances of each side could show the sign of inclination.

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