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Characterization of miniaturized one-side-electrode-type fluid-based inclinometer

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Abstract

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 1.0 mm were fabricated. Polydimethylsiloxane (PDMS) was used as the container material, and electrodes were fabricated on a ceramic substrate. 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–voltage (*C*–*V*) conversion circuit was designed as a detection circuit for this sensor and it was fabricated using 0.35 μm CMOS technology. The sensor part and detection circuit were integrated in one ceramic packaging for realize a miniaturization of inclination sensor system. 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 Ø 4.0 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. The change in temperature did not affect the output voltage of the sensor between 0 and 50 °C. The effect of vibration was demonstrated in this paper.

Keywords: Inclinometer; Surface tensioning; Electrical double layer; SU-8; Capacitance sensor

1. Introduction

Recently, the miniaturization and integration of low-cost and high-efficiency inclination sensors are particularly required in the robotic, telecommunication, electronic appliance and medical fields. Moreover, the inclination sensor that suitable for use in the vibration environment without vibration effect is widely demanded in automotive field [1–5]. Some researchers have reported inclination sensors using three-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 that are not available in mechanical equivalents, including low power consumption, repeatability and reliability. Furthermore, they can sustain considerable shock and high external pressure. Although they are commercially available, their electrodes have a much larger size about 24 mm diameter and 1.5 mm thickness. The opposed-electrode-type fluid-based inclinometer with 40 μm in a gap has been reported. 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 [4,5].

In this study, electrical double-layer theory is applied to realize a miniaturized of one-side-electrode-type fluid-based inclinometer combined with CMOS circuitry. Because this

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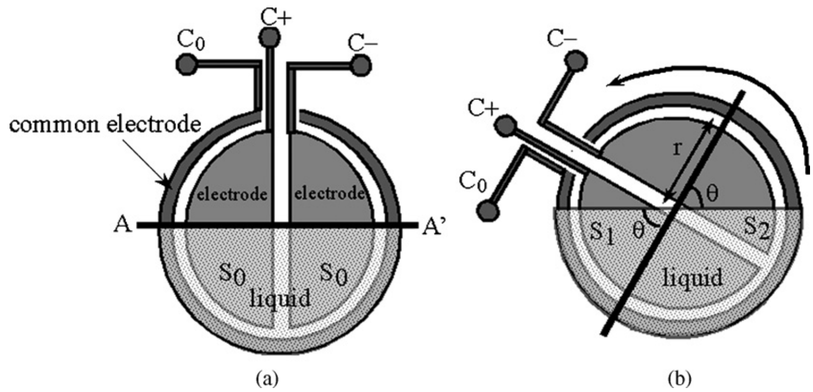

Fig. 1. Sensors pattern in level (a) and inclined (b) states.

sensor is fabricated in one-side-electrode-type, it can fabricate with a low cost. Moreover, by implementing the electrical double-layer theory, the large of capacitance value can be achieved with a small area electrode. In addition, we also attempt to develop an inclination sensor that is not affected by acceleration because electrolyte can provide damping effect. To realize miniaturization of the inclination sensor, the sensor part and detection circuit were integrated in one ceramic packaging.

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

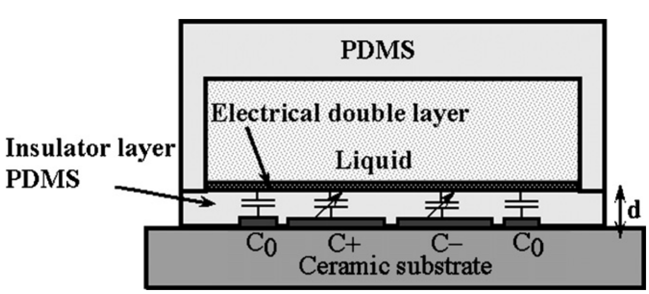

Fig. 2. Cross-sectional structure view A–A′.

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.

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. Eq. (3) expresses the proportional relationship between capacitance change ΔC and inclination angle:

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

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

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

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

CMOS-integrated circuitry exhibits low power consumption and high input impedance, so that it is suitable for the capacitor detection circuit.

To detect the inclination angle of one axis, a charge-balanced capacitance–voltage (C–V) conversion circuit has been developed. The operational amplifier used in the detection circuit is not affected by offset voltage [6]. 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 charge capacitances 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