Flexibility and Sensitivity Enhancement of a Capacitive Sensor by Encapsulating Liquid as Dielectric

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Flexible and highly-sensitive capacitive sensors that are capable of detecting pressure distribution on curved surfaces are on demand these days. Using solid dielectric material could deteriorate the sensors flexibility, while using air as the dielectric might compromise the sensors sensitivity. We propose a distributed capacitive sensor encapsulated in liquid that has high permittivity constant, namely, DI water and glycerin, as the dielectric. This design can increase the sensitivity while maintaining the flexibility of the sensors. The proposed sensor was micro-fabricated and proven to maintain its flexibility while being deformed. The sensitivity enhancement of the device is to be demonstrated by comparing some characteristics of the devices; between that with and without liquid encapsulated. The experiment results showed that the devices with liquids encapsulated were more sensitive when higher pressure is applied, and amplification ratios of the devices with DI water and glycerin increased ±7 and ±3.5 times respectively, as compared to the device without the liquid encapsulated.

Key Words: Capacitive Sensor, Liquid Encapsulation, High Flexibility

1. Introduction

With the increasing interest in humanoid robots that are equipped with tactile sensor, highly sensitive tactile sensors are on high demand in these recent years. Tactile sensors with high sensitivity are needed to be used as the robot’s skin so that safe interaction between human and robots could be made possible [1]. These tactile sensors are also required to have high flexibility so that they can be applied to non-flat surfaces like robot’s hands and fingers, thus allowing them to have larger application range.

Capacitive sensors are among those of the tactile sensors frequently used [2]. Capacitive sensors are those that when pressure or load is applied to them, would detect their mechanical deformations as a result of variation in the gap between two electrodes. The measurement principle of a capacitive sensor is expressed in Eq. (1), where $C$ is the capacitance, $\varepsilon_0$ and $\varepsilon_r$ is permittivity constant in vacuum and of the dielectric respectively, $S$ is the surface area of an electrode, and $d$ is the distance between 2 electrodes.

$$C = \varepsilon_0\varepsilon_r \frac{S}{d}$$ (1)

We proposed a capacitive sensor made of a flexible polymer material with encapsulated DI water and glycerin as dielectric. As both are liquids that have permittivity values of approximately 80 and 47 times higher than air, using them as dielectric could increase the capacitance thus the sensitivity of the capacitive sensor; without compromising the flexible characteristic of the capacitive sensor device itself.

2. Design

The proposed device consists of 4 layers that are mainly made from polydimethyl siloxane (PDMS), as shown in Fig. 1. The bumps which are 300 $\mu$m in height and 1 mm in diameter are designed to enhance the spatial resolution of the sensor. The 3×3 circular electrodes of 1 mm in diameter each are arrayed with a gap of 500 $\mu$m are patterned and attached to the top and bottom layer of the device, with polyimide film in between to enhance the adhesion between the copper electrodes and the PDMS layers. Since the liquids that have been encapsulated in the spacer chamber are incompressible liquids, an extra space for the liquids to escape when load is applied has to be designed. Therefore, we made a C-shape chamber that surrounds the bottom electrodes at the bottom layer as the escape reservoir for the liquid to escape when pressure is applied on the sensor device. The largely deformable PDMS layer, which could stretch until 6.6 times of its actual size, is fabricated below the spacer layer, so that when pressure is applied on top of the device, the deformation of the largely deformable PDMS made the incompressible liquid escape to the C-shape escape reservoir without flowing out from the spacer chamber, as shown in Fig. 2.

![Fig. 1 Conceptional diagram of the device](image-url)
3. Fabrication Processes

The fabrication processes of the device are shown in Fig. 3. We used adhesives less polyimide copper clad laminate with 25 μm thick of polyimide film and 18 μm thick of copper layer (ESPA#X MC18-25-00RFM, Nippon Steel Chemical Co., Ltd.) as the electrodes. Photolithography processes were used to pattern the electrodes on the polyimide.

The PDMS (Silot 184, Dow Corning Toray Co., Ltd.) layers of bumps, top layer, and bottom layer, with a thickness of 300 μm each, were made using photolithographically patterned negative photoresist (SU-8 2075, Nippon Kayaku Co., Ltd.) molds, while the spacer layer that is 500 μm in thickness was made using an acrylic mold. For the largely deformable PDMS layer, the silicon elastomer paste (Dow Corning® 3145 RTV MIL-A-46146 adhesive/sealant, Dow Corning Corp.) that had been mixed with thinner (RTV Thinner, Dow Corning Toray Co., Ltd.) was simply spin-coated on a glass substrate to have the thickness of 130 μm.

The fabricated layers were then bonded together after O₂ plasma treatment by plasma etcher. Finally to encapsulate liquid into the device, a process called Bonding-in-Liquid Technique (BiLit) was used, where UV curable resin (ThreeBond 3164, ThreeBond Co., Ltd.) was used as the glue. The resin was first spin-coated on a glass substrate to get a flat, thin layer of it and then transferred onto the spacer layer. The device layers were then contacted in the liquid and UV rays were exposed to cure the resin. Since the bonding was conducted in liquid, the liquids were successfully encapsulated without any interfusion of air bubbles [3].
4. Experiments and Results

4.1 Experiment Method

The fabricated capacitive sensor is shown in Fig. 4(a). Fig. 4(b) shows that the device is flexible enough to deform without failure. The deformation of the fabricated device was tested in an experiment using an experimental set-up as shown in Fig. 5. Load was applied on the bumps of the device using while the deformation and capacitance were recorded and analyzed. A needle tip with diameter 1.75 mm was placed onto the micro strength evaluation testing machine (Micro Autograph MST-I, Shimadzu Corporation) and pressure was applied by contacting the needle tip to the bump, while the applied loads and displacements were recorded. In the same time, the capacitance values of the device were measured using a capacitance-to-digital converter (AD7746, Analog Devices Ltd.). The results are shown in Fig. 6.

4.2 Experiment Results

From the deformation test result shown in Fig. 6(a), we can conclude that the deformations of the devices with liquid encapsulated were lower than the one without liquid encapsulated. This is due to the repulsion forces from the liquids are higher than that from the air. The device without any liquid encapsulated, or in other words, with compressible fluid inside could freely deform without the influence of the repulsion force from the fluid, while deformations of the devices with liquids, or incompressible fluids inside were influenced by the repulsion force from the liquids.

Fig. 6(b) shows the result of the relationship between capacitance and pressure. From the graph, capacitances of the device with DI water were observed to be the highest, followed by the device with glycerin. The device without liquid had the lowest capacitance values. This result shows that capacitance values depended on the relative permittivity of the dielectrics. From this result, we calculated the amplification ratios of the devices with liquid encapsulated. As shown in Fig. 6(c), the amplification ratios, i.e. the ratios of the increase in the capacitance of the devices with encapsulated liquid to that of the device without liquid, were ±7 for the device with DI water and ±3.5 for that with glycerin.

Next, we measured the sensitivity of the devices with and without liquid. We defined the sensitivity of the sensor as how much the sensor could detect the difference in the intensity of the applied pressure. If the sensor could show a difference in capacitance for different intensity of pressure, the sensor could then be considered sensitive. The result is shown in Fig. 6 (d). Capacitance differences (C-C₀) of the devices with liquids are found to be increased and nearly proportional to the pressure, whereas we observe only a flat change in the capacitance difference of the device without liquid after about 100kPa of pressure applied. From this result, we can conclude that the devices with liquids were more sensitive to a larger pressure, thus they could have larger application range.

Fig. 4 (a) The fabricated device, (b) flexibility of the device

Fig. 5 The experimental set-up with close-up detail of the fabricated sensor device
5. Conclusion

We proposed and designed a flexible capacitive sensor with encapsulated liquid as dielectric. The concept was verified experimentally with the capacitance amplification ratios of ±7 with DI water and ±3.5 with glycerin. The devices with liquid encapsulated were proved to have better sensitivity compared to the device without liquid as dielectric, without compromising their flexibilities.

References

