Sensors & Actuators: A. Physical 357 (2023) 114393

Contents lists available at ScienceDirect

Sensors and Actuators: A. Physical

journal homepage: www.journals.elsevier.com/sensors-and-actuators-a-physical

Liquid dielectric layer-based microfluidic capacitive sensor for wireless pressure monitoring

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ARTICLE INFO

Keywords:
Liquid dielectric layer
Parallel plate capacitor
Wireless pressure sensor
Liquid metal
Microfluidic devices
Human motion monitoring

ABSTRACT

Microfluidic capacitive sensors with enhanced performance and wireless sensing capability present great advantages for various pressure sensor applications. In this work, a liquid dielectric layer (LDL)-based wireless capacitive sensor for high sensitivity and low-pressure detection has been demonstrated. The wireless capacitive sensor was designed based on an LC resonant circuit model and integrated into a microfluidic device by introducing liquid-metal Galinstan into polydimethylsiloxane (PDMS) microchannels. The effect of various dielectric mediums (air, deionized (DI) water, and saline) on the performance of the capacitive sensor was characterized to study the sensitivity and robustness of the devices. Moreover, the high permittivity of liquid dielectric mediums enhances the sensitivity of the pressure sensor. The sensitivities of 0.0043 kPa^{-1}, 0.0111 kPa^{-1}, and 0.0125 kPa^{-1} were achieved for air, DI water, and saline-based dielectric mediums, respectively, for a low-pressure region of 0–10 kPa. Furthermore, we fabricated the wireless pressure sensor in three different form factors to enhance the applicability of the flexible wireless sensor. We also demonstrated the possibility of wirelessly monitoring human motion through real-time pressure detection using capacitive sensors fabricated with a liquid dielectric medium. The proposed LDL-based capacitive sensor, with high sensitivity, could be a potential candidate for low-pressure sensor applications, especially in detecting subtle pressure from the human body.

1. Introduction

Flexible and soft pressure sensors are generating increasing interest in wearable electronics and wireless human-machine interface systems [1–6]. For these applications, wireless pressure sensors capable of measuring pressures ranging from 1 to 100 kPa are highly desired [7]. Over the years, various technologies with capacitive, piezoresistive, and piezoelectric sensing mechanisms have been proposed for wireless pressure sensor applications [8–14]. Among them, capacitive sensing technology enjoys great appeal due to its low-pressure sensing capability, signal repeatability, simple design and construction, and low power consumption [15,16]. The capacitive sensor structure consists of a dielectric layer sandwiched between two parallel plates, where the influence of an external force varies the dielectric layer thickness and causes a change in the capacitance of the sensor. However, the sensitivity potential of the existing parallel-plate capacitors is very low due to the small change in the dielectric layer thickness under an external force [7]. Therefore, various reports have focused on modifying the dielectric layer to increase the sensitivity, including surface modification (micro pillars, nano pyramids, and micro line patterns) of the elastomer layer [17,18], and the creation of micropores within the dielectric layer [19,20]. Although the sensitivity of the sensor could be increased using surface modification and micropore techniques, the presence of a modified elastomer dielectric layer would still result in a low dielectric constant and significant stiffness against the external force acting on the parallel plate capacitor. To achieve high sensitivity, the elastomer dielectric layer between the parallel plate capacitor could be replaced with a liquid dielectric layer (LDL) that reduces the stiffness and increases the dielectric constant of the sensor.

To integrate the parallel plate capacitor with an LDL into wearable

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https://doi.org/10.1016/j.sna.2023.114393
Received 26 January 2023; Received in revised form 14 April 2023; Accepted 24 April 2023
Available online 25 April 2023

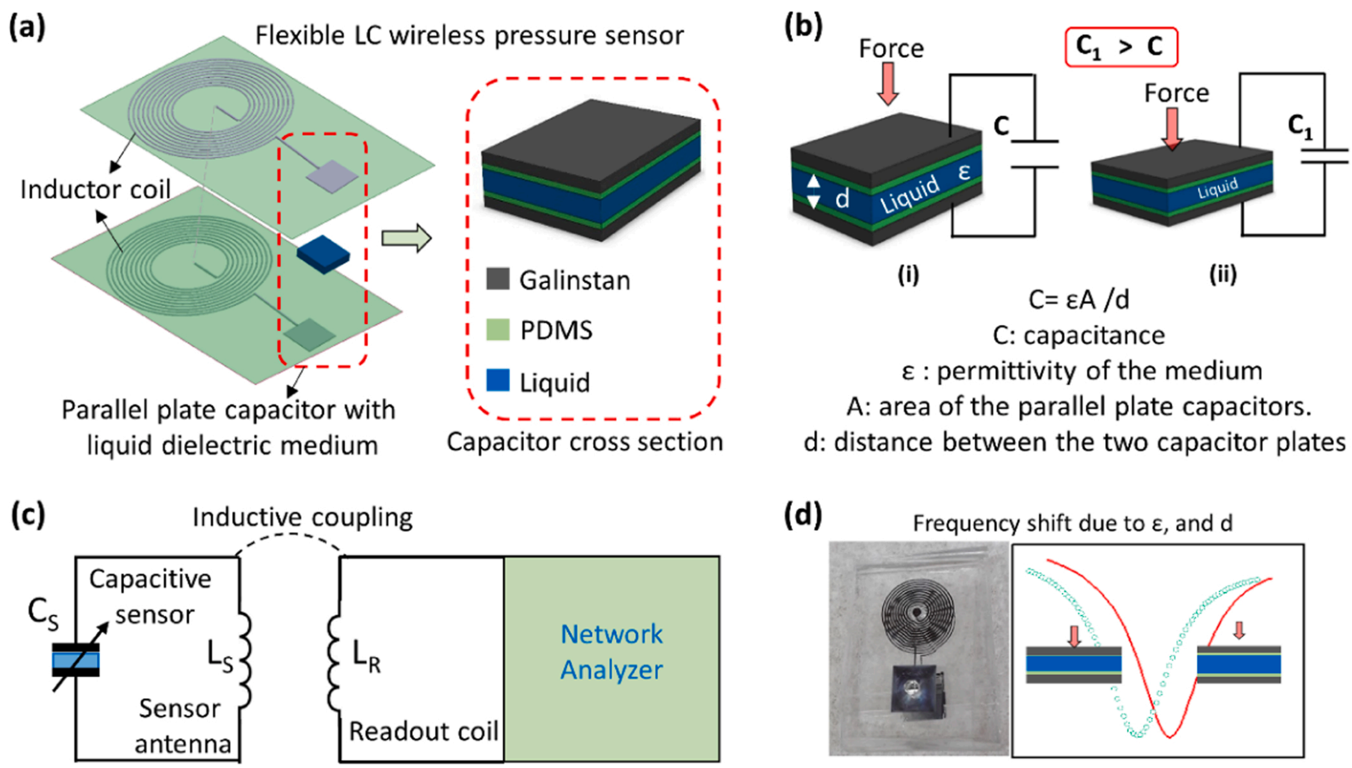

Fig. 1. (a) Schematic of wireless capacitive sensor with LDL. (b) Working mechanism of capacitive sensor. (c) Equivalent circuit for inductively coupled wireless capacitive sensor. (d) Frequency shift due to change in capacitance.

electronics, the sensor must be flexible and have robust electrical connections within the sensor body. Recently, a new concept of "liquid-state electronics" has been proposed to enable flexible and robust wearable electronics by embedding conductive liquid metals into polymer microchannels. These flexible electronics can endure extreme deformations while still retaining the complete circuitry due to the self-healing capability of liquid metal [21,22]. Galinstan, a eutectic composition of gallium-68%, indium-22%, and tin-10%, has been one of the widely considered liquid metal alloys in flexible electronics owing to its electromechanical properties (low viscosity, low toxicity, and high conductivity). In recent years, various fabrication techniques, including liquid metal printing, selective plating, microfluidic approach, direct writing, and spray-deposition, have been used to embed liquid metal Galinstan in polymers. Among these techniques, the microfluidic approach is the most widely employed owing to its attractive advantages (i.e., compact size, rapid processing, and low energy consumption). The current microfluidic approach [23–26] has made effective use of highly elastic polymeric materials, such as polydimethylsiloxane (PDMS), to define Galinstan in the sub-100 µm microchannel [27]. Thus, numerous polymer-based microfluidic devices have been realized for flexible electronics [28–31]. Although several methods have been demonstrated on the capacitive sensor based on microfluidic devices for flexible electronics [32], there are still emerging demands for improving the performance of pressure sensors. Besides, to the best of our knowledge, the LDL-based parallel plate capacitor integrated into a microfluidic device has not been reported for wireless pressure sensor applications.

In this work, we present an LDL-based parallel plate capacitor for high-sensitivity wireless pressure sensor applications. The wireless capacitive sensor consists of a liquid metal inductor and a capacitor plate, with various liquids injected into the capacitor cavity to maximize pressure sensitivity. This configuration allows for achieving a combination of high sensitivity, low-pressure monitoring, and temperature self-compensation. The effect of various dielectric liquids (deionized (DI) water, saline solution, and air) on the electrical and mechanical properties of the wireless capacitive sensor was investigated systematically. Furthermore, we fabricated the wireless pressure sensor in three different form factors to enhance the applicability of the flexible wireless capacitive sensor for a wide range of applications. Finally, we demonstrated the possibility of using a liquid dielectric medium capacitive sensor for wireless human motion monitoring. The proposed wireless microfluidic capacitive sensor, with good electrical and mechanical properties, could be a promising candidate for flexible and wearable electronics in various human-machine interface systems.

2. Design and fabrication of wireless sensors

2.1. Capacitive sensor design and working mechanism

The inherent properties of the LDL embedded between the Galinstan-based parallel plate capacitor help the formation of the inductor-capacitor resonant circuit to achieve a combination of high sensitivity, low-pressure detection limit, high working stability, and favorable flexibility. A wireless capacitive sensor with an LDL as the pressure sensing element and a spiral inductor coil as the sensor antenna for wireless communication is designed, as shown in Fig. S1. It is important to understand the influence of different liquids functioning as dielectric layers on the sensing mechanism of the proposed sensor in mandating the tailoring needs of the end application. Thus, the wireless capacitive sensor explores the effects of DI water, saline solution, and air dielectric layers on pressure sensitivity to understand how their permittivity affects the sensor performance. An interlayer made of PDMS with a cavity for the LDL placed between the capacitor plates acts as a deforming layer to alter the coupling capacitance of the sensor in response to external pressure, as shown in Fig. 1. The variation in capacitance induced by the pressure leads a shift in the resonance frequency (f) of the LC resonator as given by

$$f = \frac{1}{2\pi\left[\sqrt{L_S} \quad C_S\right]}$$

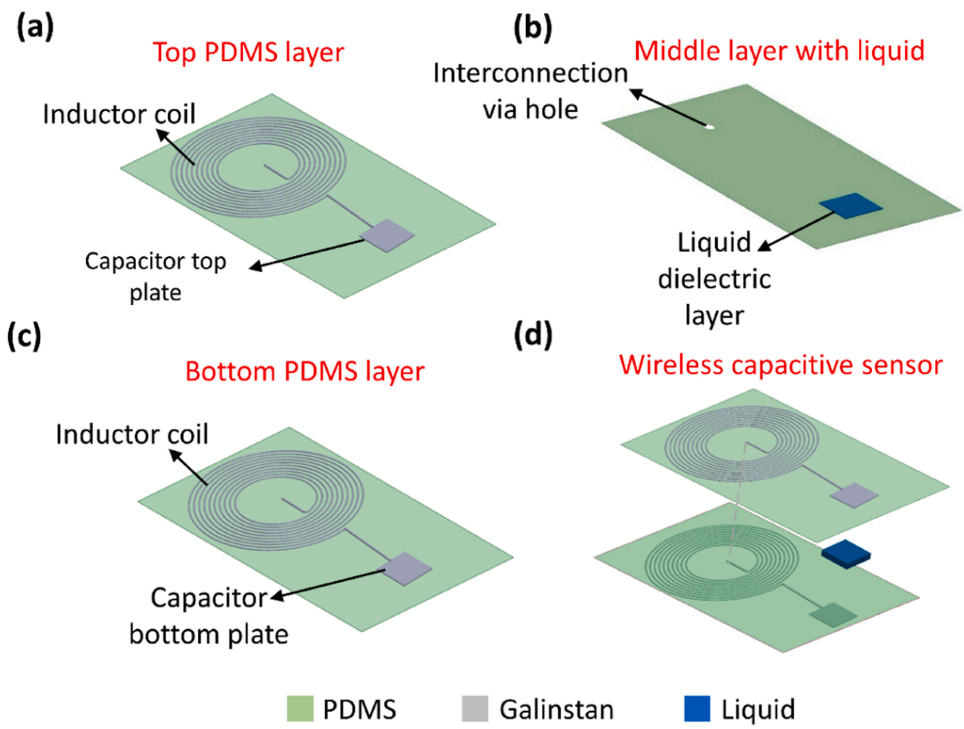

Fig. 2. (a–d) Fabrication schematic of liquid metal-based wireless capacitive sensor with liquid dielectric medium.

where C_s and L_s are the capacitance and inductance of the sensor, respectively. The Impedance Analyzer readout method enables wireless characterization of the signal reflection coefficient (S_{11}) with a dip around f, and thus provides wireless estimation of f. The electrical performance of the wireless capacitive sensor depends on both the permittivity of the medium and the distance between the capacitor plates. We used PDMS because of its unique flexible property with high mechanical deformation under external pressure and no capacitance drift during measurements. The LC circuit made with liquid metal maintains good integrity inside the device even after severe deformation and external pressure.

2.2. Fabrication of the LDL-based wireless capacitive sensor

The LDL-based wireless capacitive sensor is fabricated by defining the PDMS microchannel with Galinstan to form an LC resonant circuit. The proposed wireless capacitive sensor has three PDMS layers, the top and bottom layers with an identical LC structure having a microchannel that is 40 μm thick and 200 μm wide to form an LC resonant circuit. The middle layer, designed with a thickness of 1 mm, has two features: 1) a cavity for the LDL between the capacitor plates and 2) an interconnection hole for the inductor coil. Thus, the LDL is systematically located between the sensing parallel plate capacitor with a 10-turn inductor coil connected to each capacitor plate, resulting in the formation of the wireless capacitive sensor, as shown in Fig. 2.

In the fabrication process, a master mold on the silicon wafer for each layer is developed from SU-8 photoresist by the lithography process, as shown in Fig. S2. The cured PDMS (10:1) mixture is poured directly onto the silicon wafer and cured on a hot plate at 80 °C for 2 h. After careful debonding, the PDMS microchannel is cut into individual devices forming the top, middle, and bottom layers treated with low-pressure oxygen plasma at 100 W power for 60 s and the layers bonded permanently for 1 h at 80 °C to form the wireless capacitive sensor microchannel. Next, Galinstan liquid metal is introduced into the microchannel using a syringe and the inlet and outlet are sealed using cured PDMS. Finally, the liquid is injected between the capacitor plates to form the liquid dielectric-based wireless capacitive sensor.

3. Result and discussion

3.1. Characteristics of the capacitive sensor with different liquid dielectrics

The electrical response of the wireless capacitive sensor was studied using a bench-top experimental setup, as shown in Fig. 3(a), using an impedance analyzer (Agilent 4395A) and a 10-turn external antenna for the wireless readout operation (Fig. S3). External pressure, ranging from 0 to 80 mmHg, was applied to the LDL-based capacitor plate through a 10 mL syringe at 0.5 mL/min. Because the liquid metal-based LC circuit was printed on an elastomer, the device was naturally flexible at the structural level; moreover, sensor sensitivity depends on the separation distance and permittivity of the dielectric medium of the plates under pressure. The influence of external pressure on electrical and mechanical parameters such as resonance frequency, capacitance, permittivity, and deformability was studied systematically.

To evaluate the performance of the LDL-based capacitive sensor, the wireless LC sensor, with an area of 40 mm^2, was fixed on a customized chamber. The external pressure, ranging from 0–80 mmHg (0–10 kPa) with an interval of 20 mmHg (2.5 kPa), was applied using a syringe pump and a syringe with a diameter of 10 mm. Initially, the pressure sensor was characterized with air as the dielectric medium. The resonant frequency of the pressure sensor in air decreased from 127.5 MHz to 126 MHz as shown in Fig. 3(b). Similarly, the use of DI water and saline solution as dielectric mediums also decreased the resonant frequency of the pressure sensor from 117 MHz to 114 MHz and 115–110 MHz, respectively, for external pressures ranging from 0 to 80 mmHg (0–10 kPa). These results are shown in Fig. 3(c, d). In addition, the changes in the capacitance of the pressure sensor at pressures ranging from 0 mmHg to 80 mmHg were also measured using air, DI water and saline as dielectric mediums. The results are linearly fitted as shown in Fig. 3(e-g). To study the performance of the LDL-based capacitive pressure sensor, parameters such as sensitivity and Limit of Detection (LOD) were obtained theoretically. Initially, the sensitivity of the pressure sensor is

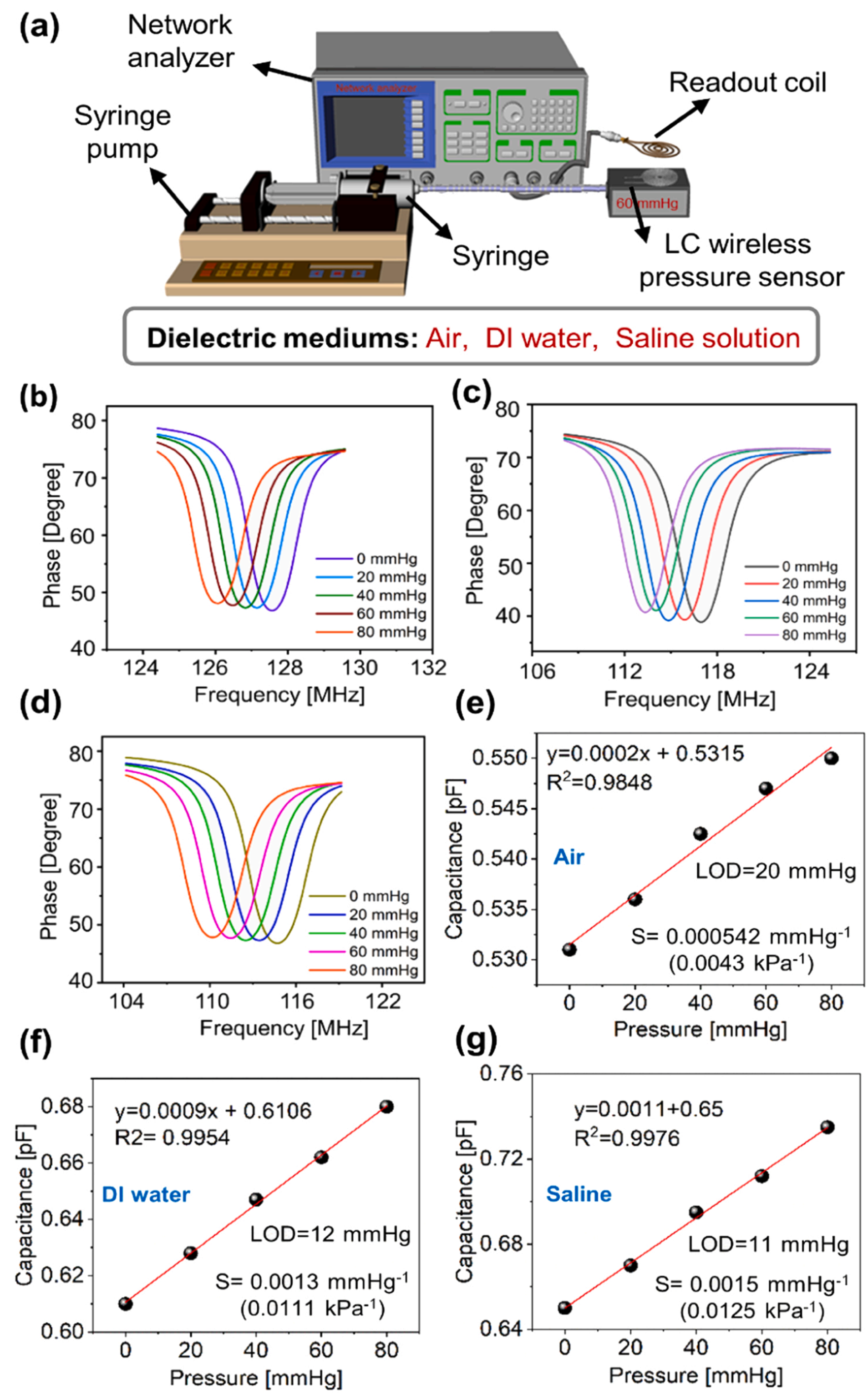

Fig. 3. Characterization of wireless capacitive sensor with different dielectric media under external pressure (0–80 mmHg). (a) Experimental setup used to study the performance of capacitive sensor. Influence of pressure on resonant frequency of the sensor with (b) air, (c) DI water, and (d) saline solutions (e, f, g) capacitance of the pressure sensor with different dielectric mediums.

obtained based on the expression:

$$S = \frac{\left[\frac{\Delta C}{C_0}\right]}{\Delta P}$$

where C_0 is the initial capacitance with no pressure, and ΔC and ΔP are relative changes in capacitance and external pressure, respectively. The results of the sensitivity of the various pressure sensors fabricated are shown in Fig. S4. The sensitivity of the pressure sensor with air, DI water and saline solution as a dielectric medium were also summarized in Tables S1 and S2, and S3, respectively. The pressure sensor with air as a dielectric medium exhibited a sensitivity of 0.00054 $mmHg^{-1}$ (0.0043

Table 1
Comparison of the sensitivities of the capacitive pressure sensor with various pressure ranges.

No	Electrode	Dielectric medium	Pressure range (kPa)	Sensitivity (kPa^{-1})	Ref.
1	Liquid metal	Air	0–10	0.0043	This work
2		DI water		0.0111	
3		Saline solution		0.0125	
4	AG NWs	Solid PDMS	0–50	0.00004	[35]
5	Liquid metal	Solid PDMS	0–20	0.000633	[32]
6	PEDOT:PSS	Solid PDMS	0–22	0.00354	[34]

kPa^{-1}) for ΔP ranging from 0 to 80 mmHg. However, the pressure sensor with DI water and saline solution as a dielectric medium exhibited sensitivities of 0.0013 $mmHg^{-1}$ (0.0111 kPa^{-1}) and 0.0015 $mmHg^{-1}$ (0.0125 kPa^{-1}), respectively, for the pressure ranging from 0 to 80 mmHg (0–10 kPa). The sensitivity of liquid dielectric medium-based pressure sensors is significantly enhanced by two key factors: 1) high permittivity of the liquid dielectric, and 2) liquid property of the dielectric. Specifically, air can produce more deformation as compared to that of a solid dielectric layer and produce a significant change in capacitance. However, the air dielectric medium, with a permittivity of 1, replaced by DI water (permittivity=84 F/m at 20 °C) and saline (permittivity=80 F/m at 20 °C) [33], contributes further enhancement in the capacitance change due to the effective permittivity of the medium. Furthermore, the sensitivity of the liquid dielectric medium-based pressure sensor is high because their high permittivity increases the electric field concentration, which in turn increases the sensor's capacitance. The sensitivities of capacitive pressure sensors for different dielectric mediums, in different ranges, are compared in Table 1. The LDL-based capacitive sensor offers high sensitivity to the low-pressure range due to the high permittivity and liquid property of the dielectric mediums. Finally, the LOD obtained from the expression (Fig. S5) shows that the LDL-based capacitive pressure sensor with air, DI water and saline solution as the dielectric medium.

displays a minimum detectable pressure of 20 mmHg, 12 mmHg,

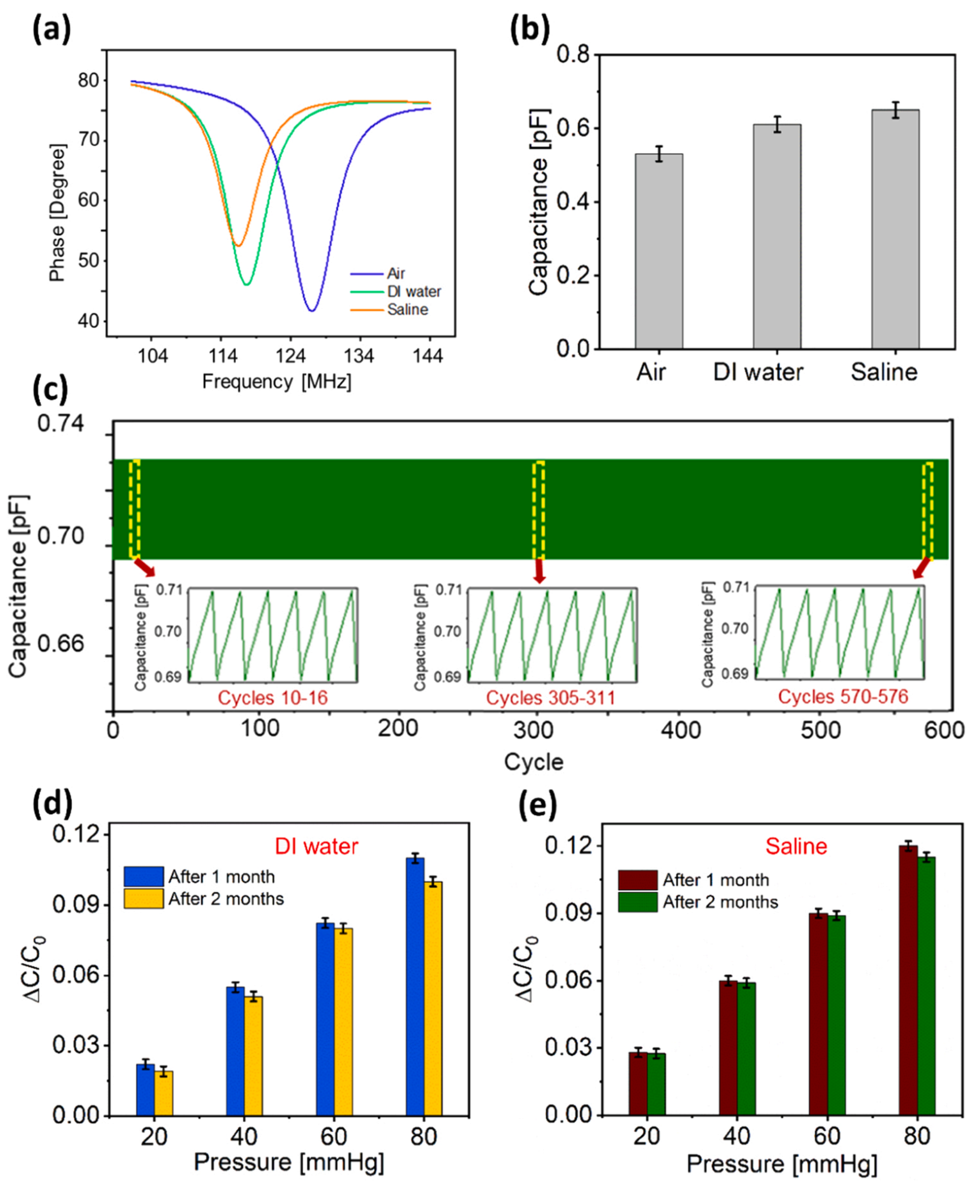

Fig. 4. Comparison of capacitive sensor performance with different dielectric media: (a, b) air, DI water, and saline solution. Durability and robustness study of wireless capacitive sensor, for (c) loading and unloading of 600 cycles, (d) two months with DI water as dielectric layer and (e) two months with saline as dielectric layer.

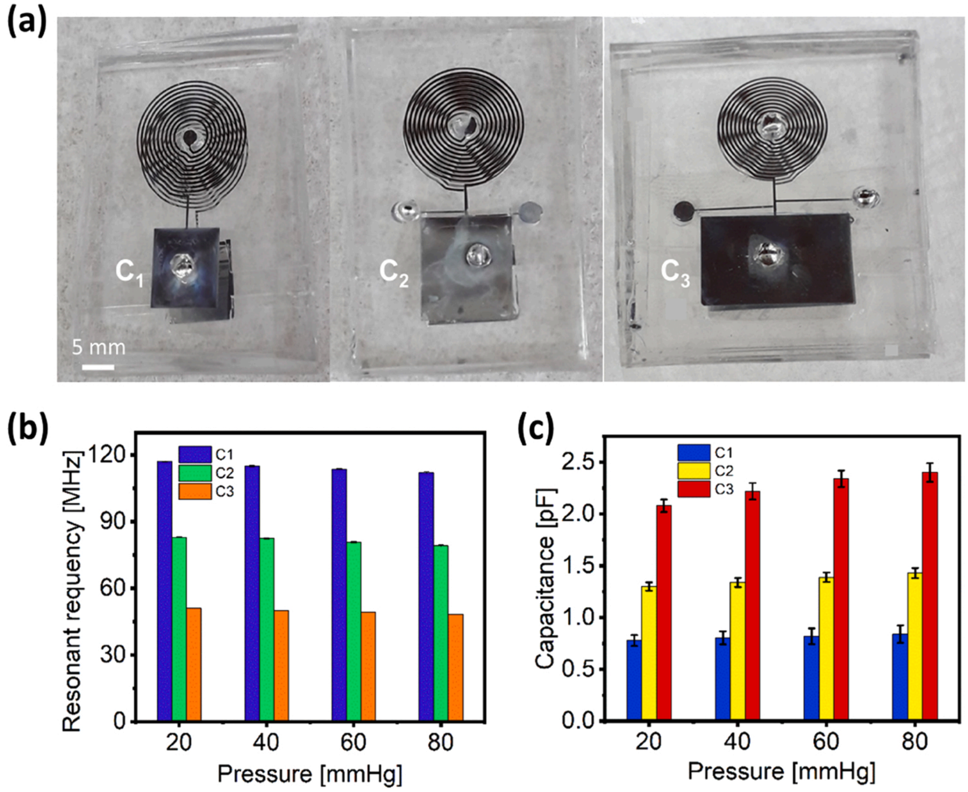

Fig. 5. Characterization of wireless capacitive sensor with different form factors. (a) Images of LC sensor fabricated with different sizes (40, 80, and 125 mm^2). (b, c) Performance comparison of capacitive sensor with different sizes using saline dielectric medium.

and 11 mmHg, respectively. This indicates that the use of a liquid dielectric medium is also an effective way to improve the sensitivity of the capacitive pressure sensor, especially in low-pressure sensor applications, including the detection of subtle pressure from the human body.

One of the important demonstrations for the LDL-based capacitive sensor is to study the influence of the dielectric medium on durability, robustness, and reproducibility.

during repeated deformation. Initially, the effect of dielectric mediums (air, DI water, and saline) on the sensor performance was studied with no external pressure. Fig. 4(a, b) show the influence of the permittivity of the dielectric medium on the performance of the capacitive sensor. The resonant frequency of the sensor decreased from 127 MHz to 112 MHz, while the capacitance increased from 0.53 pF to 0.65 pF, owing to the high permittivity of water-based solutions. It can be observed that the saline solution offers more capacitance, due to its high permittivity, compared to DI water and air. In general, the high permittivity increased the electric field concentration in the liquid medium, which effectively increased the equivalent capacitance and decreased the resulting phase-dip frequency. Thus, the liquid dielectric media improves the performance compared to the air medium and thereby increases the sensitivity of the capacitive pressure sensor. The durability and robustness of the liquid metal-based wireless capacitive sensor were tested using liquids as the dielectric layer. The capacitive sensor with saline as a dielectric layer was tested under 600 loading (0–80 mmHg) and unloading (80–0 mmHg) of pressure cycles as shown Fig. 4(c). The change in capacitance shows nearly linear behavior during loading and unloading process indicating the cyclic stability of the pressure sensor. Further, the LDL-based capacitive sensor shows good repeating and reproducing ability for all loading and unloading cycles at the pressure range of 0 mmHg and 80 mmHg, respectively. The inset in Fig. 4(c) shows the enlarged view of different pressure cycles. The liquid-metal-based capacitive sensor exhibits good mechanical and electrical properties during repeated deformation, especially on soft substrates such as PDMS. Moreover, although the dimensions of the capacitor may change under high external pressure, the liquid metal-based capacitor plates remain well connected without significant electrical changes even in large deformation. At the same time, conventional solid metal materials may generate cracks under high external pressure and tensile strength. Similarly, the capacitive sensor with DI water as a dielectric layer reproduces its performance even after two months with a negligible difference as shown in Fig. 4(d). Equally, the saline solution was also able to maintain its electrical performance after two months as shown Fig. 4(e). From these results, it is clear that the capacitive sensor contained with liquid dielectric mediums displays good durability for continuous and long-term performance. Thus, the characterization of an LDL-based capacitive sensor with a liquid dielectric medium, under loading and unloading pressure cycles, elaborates the cycle stability, an essential parameter of the pressure sensor. Further, the response after two months strengthens the long-term durability of the pressure sensor.

3.2. *Demonstration of microfluidic capacitive sensor and wireless human motion monitoring applications*

The electromechanical behavior of the Galinstan-based wireless capacitive sensor with different form factors was studied to enhance the applicability of the sensor for various applications. Since, different applications may require sensors over different pressure ranges, so the LDL-based capacitive senor sensors with three different form factors: 40, 80, and 125 mm^2 diameters were designed and fabricated, as shown in Fig. 5(a). All three devices were fabricated with saline solution as the dielectric layer due to its high permittivity. The effect of dimension on the sensitivity of all the devices were tested for the same external pressure, ranging from 0 m to 80 mmHg. Fig. 5(b, c) show the influence of external pressure on the resonant frequency and capacitance of the three different-sized capacitive sensors. The largest size sensor shows the largest capacitance change from 2 pF to 2.4 pF when the pressure

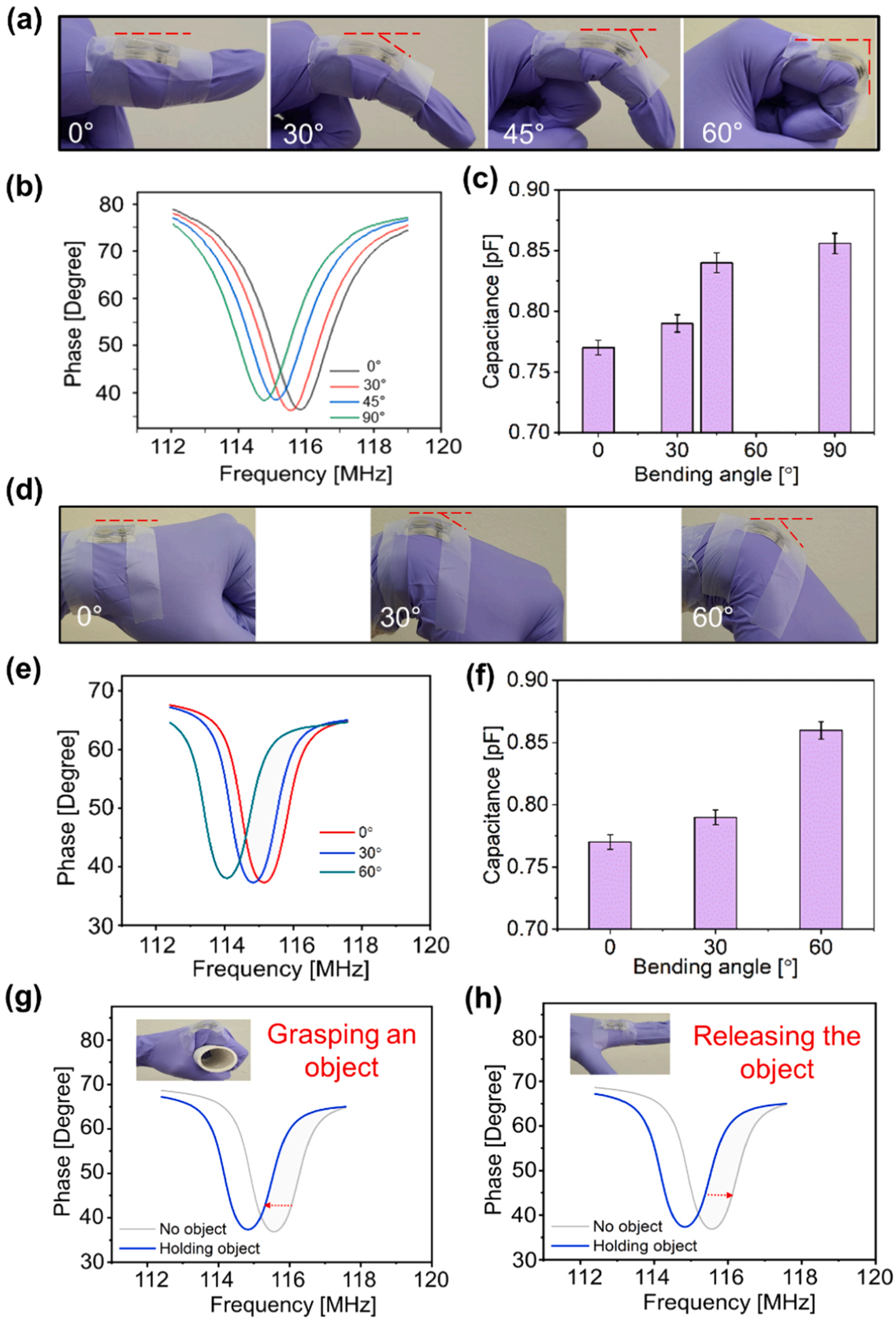

Fig. 6. LDL-based capacitive sensor for human motion monitoring. (a) Images of the fabricated sensor (40 mm^2) attached to the index finger at various bending angles (0–90°), with corresponding changes in (b) frequency and (c) capacitance. (d) Images of the fabricated sensor (40 mm^2) fixed on the wrist at various bending angles (0–60°), with corresponding changes in (e) frequency and (f) capacitance. (g, h) Shift in the frequency of the capacitive sensor when holding an object.

changes from 20 mmHg to 80 mmHg. Furthermore, when the same pressure range is applied to the other two sensors, the change in capacitance can be detected even though the initial capacitance is lower. The results also suggest that the scalability of the capacitive sensor based on microfluidic devices shows good agreement with the electrical and mechanical characteristics under external pressure. Despite having three different dimensions, a pressure sensor with a 40 mm^2 capacitor plate was considered for basic characterization due to the following reasons: 1) as the capacitor dimensions are small, the pressure required for its deformation will be less, and hence the sensor can detect low pressure, 2) as the volume of liquid required for the dielectric medium will be less, it is more convenient to use in wearable applications, especially for human motion monitoring at various bending angles. Thus, the wireless capacitive sensor can be fabricated in different sizes for a wide range of pressure-sensing applications.

Finally, the applicability of the wireless capacitive sensor based on a liquid dielectric medium for wireless monitoring of human motion was demonstrated by fixing the sensor on a human hand (index finger and wrist). The LDL-based capacitive sensor mounted on the index finger caused various deformations at a bending angle of 0–90°, as shown in

Fig. 6(a). The deformation of the capacitor according to the motion of the index finger reduced the distance between the capacitor plates, causing movement in the dielectric medium (saline solution). As a result, the resonant frequency of the sensor changed from 115.8 MHz (0°) to 114.5 MHz (90°), while the capacitance increased from 0.77 pF to 0.85 pF. These results are shown in Fig. 6(b, c). This indicates that the finger force acting on the capacitor plate is not equal at all bending angles and therefore the resonant frequency of the sensor shifts nonlinearly. Similarly, the LDL-based capacitive sensor mounted on the wrist caused various deformation at bending angles from 0° to 60° at 30° intervals, as shown in Fig. 6(d). The LDL-based capacitive sensor showed similar responses to the index finger at various bending angles. Fig. 6(e, f) shows that the resonant frequency of the sensor decreases during deformation while the capacitance of the sensor is increased. Changes in resonant frequency and capacitance show the effect of human motion on the performance of the capacitive sensor. Overall, capacitance sensors can monitor a variety of human motion wirelessly, even though capacitance changes are nonlinear. The minimum bending angle that the sensor can detect is 25°, calculated from the formula Fig. S5. In addition, the LDL-based capacitive sensor can respond dynamically to hand motion. For example, real-time response recorded from a human action shows that grasping an object reduces the resonant frequency of the sensor, as shown in Fig. 6(g). However, the resonant frequency returns to its initial value after release (Fig. 6(h)), demonstrating the reliability of the LDL-based capacitive sensor. Since the liquid dielectrics can provide more flexibility and greater deformation without fracture, the LDL-based capacitive sensor can be more advantageous than other sensor for monitoring human motion. Examples of the use of these capacitive sensors to recognize human motion can be used to provide tactile feedback for potential applications, including squeezing, lifting, moving, and touching objects.

4. Conclusions

We present an LDL-based wireless capacitive sensor for high sensitivity and low-pressure monitoring. The wireless capacitive sensor was designed based on an LC resonant circuit model and was fabricated using a PDMS microchannel and Galinstan. The effect of various liquids as dielectric layers (air, DI water, and saline solution) on the electrical and mechanical properties of the sensor has been characterized to analyze the sensitivity, and robustness of the device. The use of liquid dielectric mediums produces substantial deformation, compared to that of solid dielectric layers, and enhances the sensitivity of the pressure sensor. The sensitivities of 0.0043 kPa^{-1}, 0.0111 $kPa^{-1,}$ and 0.0125 kPa^{-1} were achieved for air, DI water, and saline-based dielectric mediums, respectively, for a low-pressure region of 0–10 kPa. Furthermore, we fabricated the wireless capacitive sensor in three different form factors to enhance the applicability of the wireless capacitive sensor for various applications. Finally, we demonstrated the possibility of using the liquid dielectric medium capacitive sensor for wireless human motion monitoring applications by fixing the sensor on a human hand. The proposed wireless capacitive sensor results, with good electrical properties under various dielectric layers, provide an alternative approach to improve the sensitivity and low-pressure detection limit of the existing capacitive sensors. Thus, the dielectric layer-based capacitive sensor built on microfluidic devices could be widely employed as a flexible pressure sensor for various human-machine interface systems.

CRediT authorship contribution statement

Karthikeyan Munirathinam: Conceptualization, Investigation, Validation, Formal analysis, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Kyeongha Kwon**: Conceptualization, Investigation, Validation, Data curation. **Jongsung Park:** Methodology, Formal analysis. **Dong-Weon Lee:** Supervision, Funding acquisition, Methodology, Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgements

This study was supported through a National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No. 2020R1A5A8018367).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.sna.2023.114393.

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