A MICROMACHINED POLYURETHANE/STAINLESS-STEEL CAPACITIVE PRESSURE SENSOR WITHOUT CAVITY AND DIAPHRAGM

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ABSTRACT

This paper reports micromachined capacitive pressure sensor intended for applications that require mechanical robustness. The device is constructed with two micromachined metal electrode plates and an intermediate polymer layer that is soft enough to deform in a target pressure range. The plates are formed of micromachined stainless steel with overall dimensions of 4×2.4 mm^2 fabricated by batch-compatible micro-electro-discharge machining. A polyurethane RTV liquid rubber is used as the deformable material. This structure eliminates both the vacuum cavity and the associated lead transfer challenges common to micromachined capacitive pressure sensors. For wireless interrogation of the capacitance, an L-C tank is fabricated by combining the capacitive sensor and a 40-turn coil that are formed by winding a copper wire on the sensor. A preliminary measurement test performed by monitoring frequency shift of a reactance peak of the tank with varying pressure shows its response of 2.6-9.6 Hz/Pa measured over a dynamic range of 350 KPa. Temperature dependence of the tank is also experimentally evaluated.

Keywords: capacitive pressure sensor, stainless steel, polyurethane, micro-electro-discharge machining, resonant tank

I. INTRODUCTION

Capacitive pressure sensors are favored for low-power and telemetric applications since they draw no DC power, and conveniently form passive L-C tank circuits. Micromachined capacitive pressure sensors have typically used an elastic diaphragm with fixed edges and a sealed cavity in between the diaphragm and the substrate below [1, 2]. Since this configuration relies on deflection of a relatively thin diaphragm against a sealed cavity, in some applications there is a concern of robustness of the diaphragm and leaks in the cavity seal. Lead transfer for the sealed electrode has also been a persistent challenge. This has motivated the development of innovative fabrication methods that involve multilayer deposition, planarization, and other remedies, but require relatively high mask counts [3, 4]. Another approach to deal with this has been to move the sense gap outside the cavity [5].

This research explores a capacitive pressure sensor that consists of two micromachined metal plates with an intermediate polymer layer. This configuration aims to eliminate the need of diaphragms and cavities from the sensors. Use of polymeric material soft enough to deform

in a target pressure range allows thickness of the polymer, or capacitance of the parallel plate capacitor, to be dependent on hydraulic pressure that surrounds the device. This capacitive change can be interrogated by either a hard-wired interface or a wireless setup in which the sensor serves as a capacitor of an L-C tank (Fig. 1).

Proper choice of materials compatible with particular environments will offer broader opportunities such as in automobile and biomedical applications that include air pressure monitoring in the tires [6] and bowel pressure detection [7]. The inherent environmental compatibility is a significant advantage because it allows us to circumvent constrains and problems associated with the packaging that in general degrades device performance and cost effectiveness in the device manufacturing.
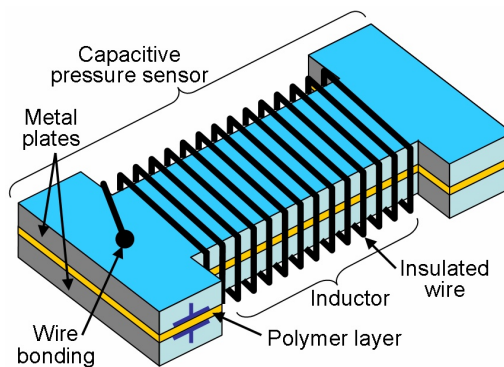

Fig. 1: Concept of the capacitive pressure sensor with an inductor wound on the sensor for constructing an L-C tank.

II. FABRICATION

In this effort, polyurethane rubber was selected to form the polymeric layer. This material offers mechanical robustness such as high tear and abrasive resistances, chemical resistance, and controllability of its softness over a wide range. It has been extensively used in medical implant applications [8] and was also used to fabricate micro/nanostructures for MEMS applications [9, 10, 11].

The fabrication process is illustrated in Fig. 2. Two plates were patterned in stainless steel sheets with micro-electro-discharge machining (µEDM) technique [12] (Fig. 4). The base and top plates with the layout shown in Fig. 3 were cut from stainless steel sheets with thickness of 200 µm and 50 µm respectively. Since these plates potentially have burrs at the edges, the top plate was designed to be slightly smaller than the base plate (50 µm off from all sides of the base plate) as seen in Fig. 3 to minimize

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probability of physical/electrical contact between the two plates at the edges. The base plate was still connected to the original sheet through two tethers after the machining as shown in Fig. 4. This effort used a two-part polyurethane RTV liquid rubber (Poly 74-20, part A: polyurethane pre-polymer, part B: polyol, Polytek Development Co., PA, USA) with the softener (part C: plasticizer), which is vulcanized to very soft (<20 Shore A) and robust rubber. The softness of the rubber can be adjusted by changing the proportion of the softener to be mixed. This effort used a formulation of part A:B:C=1:1:1. After applying the mixed solution to the upper surface of the base plate, the top plate was placed on it. In this step, the top plate is self-aligned to the base due to surface tension of the solution as shown in Fig. 5a. After curing, the device was released by mechanically breaking the tethers (Fig. 5b). An L-C tank was formed by winding an enamel-coated copper wire (~ϕ127 μm, 40 turns) on the sensor (Fig. 6) and bonding

the terminals on separate stainless steel plates with conductive adhesive. Although this effort used serial micro-EDM with single electrodes and manual assembly of the plates, the process can potentially be performed in a batch manner by a combinational use of batch-mode μEDM [13] for cutting the plates and screen printing or splay coating for the liquid rubber layer formation.

Fig. 4: Base (lower) and top (upper) plates for the pressure sensor fabricated by μEDM (step 1 in Fig. 2).
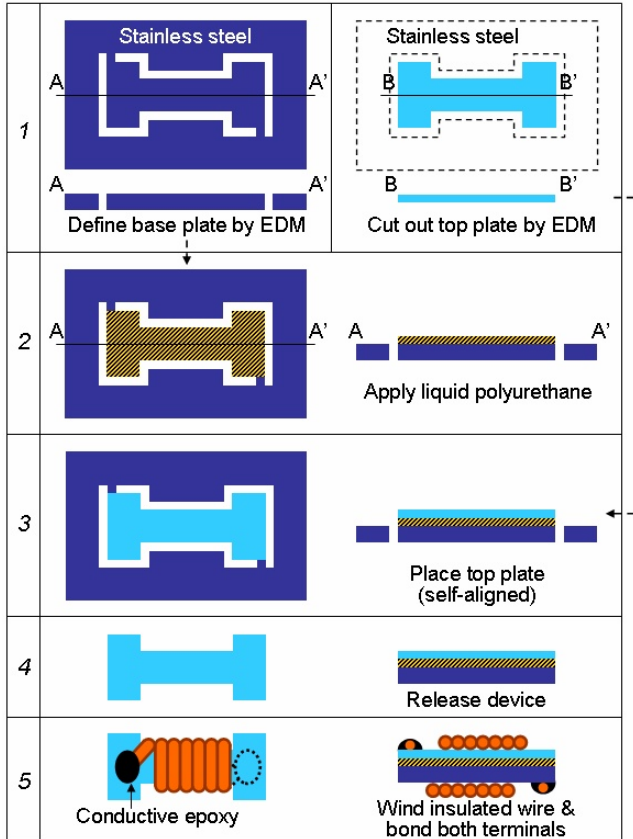

Fig. 2: Fabrication process flow to fabricate the pressure sensor (step 1-4) and the L-C tank (step 5).

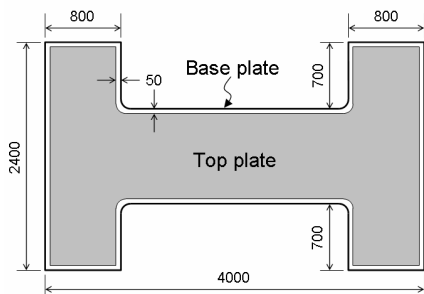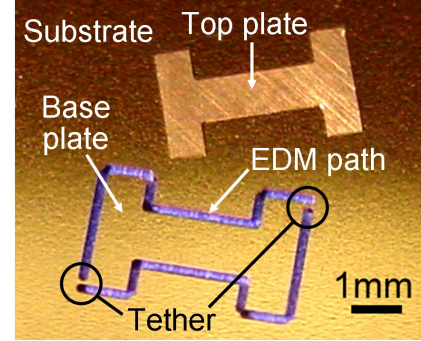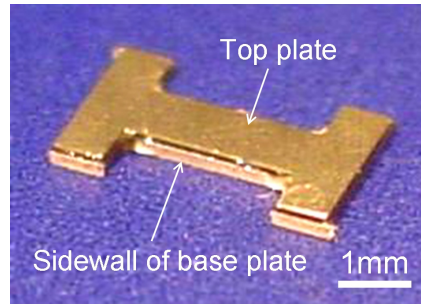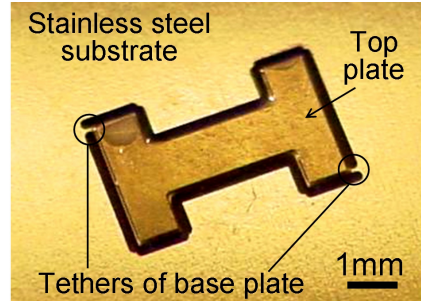Fig. 3: Dimensions of the top and base plates

Fig. 5: (a: upper) Two plates are self-aligned together through a polyurethane liquid layer (step 3 in Fig. 2), and (b: lower) the device released from the original sheet of the base plate (step 4 in Fig. 2).
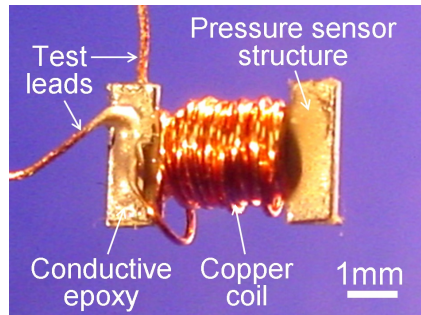

Fig. 6: Fabricated L-C tank (step 5 in Fig. 2).

III. MEASUREMENT RESULTS

Young's Modulus of Polyurethane Rubber

To characterize Young's modulus of the polyurethane rubber with the formulation mentioned above, a loading test was performed with a 3-mm-cubic sample of the rubber. The measurement was performed with a force gauge (DPS-1, Imada Inc., IL, USA) that provided 1-mN resolution. Figure 7 plots measured pressure with varying strain up to 0.33 in the test, showing the modulus of 67-267 KPa, which is 15-59 % of the modulus reported in [9].
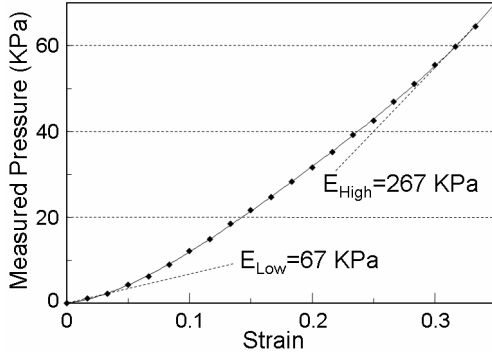

Fig. 7: Pressure vs. strain measured with a polyurethane rubber sample for Young's modulus estimation.

Pressure Measurement with the L-C tank

The fabricated L-C tank shown in Fig. 6 was measured to have nominal capacitance of 6.3 pF and inductance of 640 nH. Measured resonant frequency and quality factor of the tank, which were probed via test leads shown in Fig. 6, were 106 MHz and 1.9 respectively. The tank was placed in a pressurized chamber. The variation of its reactance peak with applied pressure was monitored by a spectrum analyzer (HP4195) using the test leads transferred through the chamber wall. Figure 8 shows measured shifts of these reactance peaks due to gauge pressure change in 69 KPa steps up to 345 KPa. This reactance is an output from DSP based on a series capacitor-resistor model of the analyzer and exhibited the most distinct shift in this set-up. The result is plotted in Fig. 9, indicating the response of 2.6-9.6 Hz/Pa and sensitivity of 10.5-39.0 ppm/KPa in this pressure range.

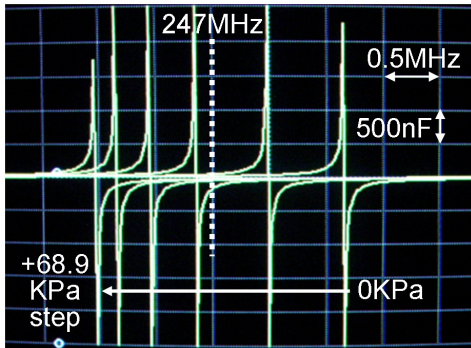The measured resonant frequency of the tank is close

Fig. 8: Measured frequency response of the L-C tank with DSP due to gauge pressure change from zero to 345 KPa in 68.9 KPa steps.
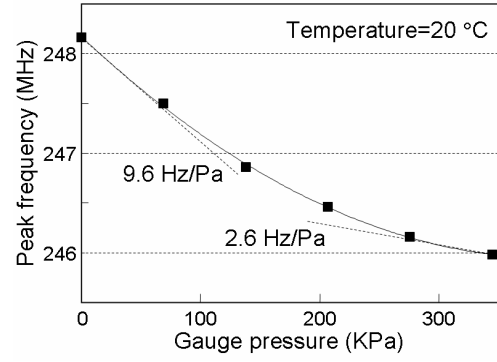

Fig. 9: Frequency shift plotted from the measurement result in Fig. 8.

the theoretical frequency of about 80 MHz that is obtained from the measured capacitance and inductance of the tank. The saturation of the frequency response observed in Fig. 9 is consistent with the variation of the Young's modulus of the polyurethane rubber, i.e., the layer becomes stiffer as it is squeezed by increased pressure, resulting in the reduced response. The fabrication method used for bonding between the stainless steel plates and copper leads of the tank did not offer sufficient electrical contact between them, resulting in the low quality factor. This significantly limited wireless capability of the device. Achieving good electrical contacts in the tank promises wireless measurement with the sensor.

Temperature Dependence

The variation of the peak frequency with varying temperature, from 20 to 60 °C, was evaluated outside of the chamber at atmosphere pressure (Fig. 10). Temperature was controlled by changing the distance between the device and a source of heat. Temperature of the device was measured by an infrared thermometer (Fisher Scientific International Inc., NH, USA). As seen in Fig. 10, the variation shows a linear dependence on temperature within the tested range. Measured temperature dependence of the peak frequency and its coefficient are 392.5 KHz/°C and 1629 ppm/°C, respectively. Figure 11 shows the response of the peak frequency shift with varying pressure at increased temperature of 40°C. Although the frequency initially dropped as the pressure was increased, as shown in Fig. 11, it started to increase once the pressure exceeded about 80 KPa.
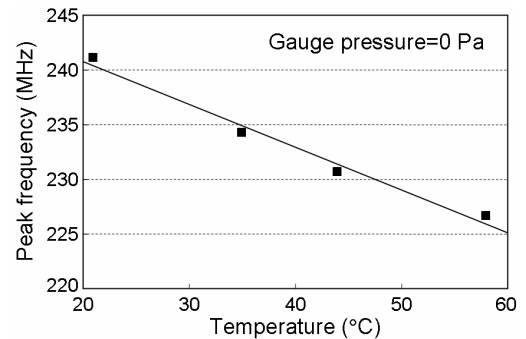

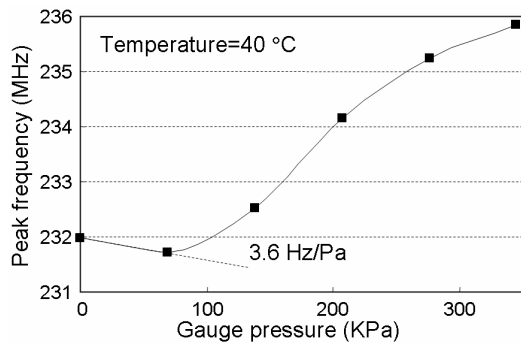Fig. 10: Peak frequency of the tank vs. temperature.

Fig. 11: Frequency shift due to pressure change at increased temperature.

The high temperature coefficient of this device may limit its applications. However, this may be addressed by tailoring the choice of the polymeric filler. Although temperature dependence of material properties of the rubber heavily depends on particular formulations, the following two events can occur at increased temperature: (1) Increase of volume of the rubber layer, and (2) softening of the layer. The dielectric constant of polyurethane elastomer was reported to be stable at the temperature range used in this experiment [14]. Since the sensor of the tank was tightly wrapped with a copper wire, (3) the parallel plates may be not only immovable outward but also pushed inward by the wound wire. With the situations (1)-(3), the following two circumstances may occur at increased temperature: (A) a combination of (1) and (3) generates pressure applied from the rubber layer to the inner surfaces of the parallel plates, and (B) a combination of (2) and (3) thins the layer. Either makes the rubber layer stiffer. This hypothesis is consistent with the reduced response of 3.6 Hz/Pa at the increased temperature in Fig. 11 compared to that of 9.6 Hz/Pa at room temperature for their early pressurizing stages. In addition, since the top plate is relatively thin, and only the center part is physically constrained by the coil but other parts are free to move, the plates may deform at increased temperature. Such structural factor may have partially caused the reversed response in Fig. 11.

IV. CONCLUSION

This research has explored a micromachined capacitive pressure sensor that eliminated both a diaphragm and a cavity from its construction. The sensor consists of two metal plates and an intermediate polymer, which potentially offers mechanical robustness and high reliability. The device was constructed with micromachined stainless steel plates fabricated by batch-compatible μEDM technique and polyurethane liquid rubber as the polymer layer that permitted self-aligning of the micromachined plates in the assembly process. This material combination can offer good corrosion resistance or biocompatibility. An L-C tank was formed with the sensor of size 4×2.4 mm^2 and a 40-turn copper coil to demonstrate the capability of pressure measurement by resonant frequency readout. The measured sensitivity was 10-40

ppm/KPa for gauge pressure ranging from 0-340 KPa. The temperature dependence of this L-C tank was relatively high, but may be reduced by an appropriate choice of materials and further structural optimization.

The main concept demonstrated in this effort may be extrapolated for use in other contexts. Of course, the use of an L-C tank permits wireless monitoring, as demonstrated by other researchers in the past. The idea of using a bulk metal electrode and a soft material instead of a cavity for the capacitive sensor may be useful in miniaturizing the packaging and housing of certain industrial and automotive pressure sensor assemblies. It may be extended further to other applications in which the sensor must be mechanically robust, such as tactile sensors or load cells.

REFERENCES

[1] H. Chau, K.D. Wise, "An Ultraminiature Solid-State Pressure Sensor for a Cardiovascular Catheter," *IEEE Trans. Electron Devices*, 35(12), pp. 2355-2362, 1988
[2] W.H. Ko, Q. Wang, "Touch Mode Capacitive Pressure Sensors for Industrial Applications," *Proc. IEEE MEMS*, pp. 284-289, 1997
[3] A.V. Chavan, K.D. Wise, "A Batch-Processed Vacuum-Sealed Capacitive Pressure Sensor," *Proc. IEEE Transducers*, pp. 1449-1451, 1997
[4] B. Gogoi, C.H. Mastrangelo, "A Low voltage Force-Balanced Pressure Sensor with Hermetically Sealed Servomechanism," *Proc. IEEE MEMS*, pp. 493-498, 1999
[5] J.S. Park, Y.B. Gianchandani, "A Serve-Controlled Capacitive Pressure Sensor Using a Capped-Cylinder Structure Microfabricated by a Three-Mask Process," *IEEE/ASME J. MEMS*, pp.209-220, 2003
[6] S. Yamamoto, O. Nakao, H. Nishimura, T Suzuki, T. Takizawa, R.S. Pollack, " Touch Mode Capacitive Pressure Sensor for Passive Tire Monitoring System," *Proc. IEEE Sensors*, vol. 2, pp. 1582-1586, 2002
[7] R. Magjarevic, B. Ferek-Petric, K. Lopandic, "Biofeedback in Rehabilitation of Anal Sphincter Muscles," *Proc. IEEE EMBS*, pp. 423-426, 2000
[8] N. Lamba, K. Woodhouse, and S. L. Cooper, *Polyurethanes in Biomedical Applications*, CRC Press, Boca Raton, 1998.
[9] J.M. Engel, J. Chen, D. Bullen, C. Liu, "Polyurethane Rubber as a MEMS Material: Characterization and Demonstration of an All-Polymer Two-Axis Artificial Hair Cell Flow Sensor," *Proc. IEEE MEMS*, pp.279-282, 2005
[10] F. Arias, S.R.J. Oliver, B. Xu, R.E. Holmlin, G.M. Whitesides, "Fabrication of Metallic Heat Exchangers Using Sacrificial Polymer Mandrils," *IEEE/ASME J. MEMS*, 10(1), pp. 107-112, 2001
[11] D. Campolo, S. Jones, R.S. Fearing, "Fabrication of Gecko Foot-Hair Like Nano Structures and Adhesion to Random Rough Surfaces," *Proc. IEEE Nanotechnology*, vol. 2, pp. 856-859, 2003
[12] T. Masaki, K. Kawata, T. Masuzawa, "Micro Electro-Discharge Machining and Its Applications," *Proc. IEEE MEMS*, pp. 21-26, 1990
[13] K. Takahata, Y.B. Gianchandani, "Batch Mode Micro-Electro-Discharge Machining" *IEEE/ASME J. MEMS*, 11(2), pp.102-110, 2002
[14] J. Su, Q.M. Zhang, C.H. Kim, R.Y. Ting, R. Capps, "Effects of Transitional Phenomena on the Electric Field Induced Strain-Electrostrictive Response of a Segmented Polyurethane Elastomer," *J. Appl. Poly. Sci.*, 65(7), pp. 1363-1370, 1997