Smooth Contact Capacitive Pressure Sensors in Touch- and Peeling-Mode Operation

Jeahyeong Han and Mark A. Shannon, *Member, IEEE*

***Abstract*—Capacitive (C) pressure sensors typically sense quadratic changes in C as a pressure difference (P) deflects a flexible conducting diaphragm near a rigid ground plane. Touch-mode capacitive pressure (C-P) sensors, where the conducting diaphragm touches a dielectric coated ground plane, often show a more linear response, but with less sensitivity, particularly at low-P. Initial contact of the diaphragm often occurs at a critical P. Until $P_{\rm crit}$ is reached, the sensitivity is typically too low for accurate measurements. In this work, two different types of electrodes with "parabolic" and "donut" cavity-shapes have been designed, fabricated, and tested to achieve high-sensitivity at low-pressures. A flexible conducting diaphragm touches the bottom electrode smoothly, and both cavity shapes permit initial contact at a zero-pressure differential. This type of C-P sensors can have touch-mode and peeling-mode operations. The sensitivities of these sensors in two operation modes were measured, and their resolutions were smaller than 0.1 Pa at a mean pressure of 10^5 Pa. Both sensors in two modes have the resolution over total-pressure less than 10^{-6}, which is difficult to achieve at atmospheric pressure.**

***Index Terms*—Capacitive, peeling and touch-mode, pressure sensor, sensitivity, smooth Contact.**

I. Introduction

CAPACITIVE pressure (C-P) plate sensors measure changes in pressure by the deflection of a conducting diaphragm due to applied pressure. Parallel plate C-P sensors typically have a spacer between the two electrodes, and the deflection in the diaphragm produces a quadratic change in capacitance. C-P sensors made with a diaphragm that touches a dielectric coated ground plane typically have a nonlinear response at lower pressures and a larger, more linear response at higher pressure ranges with respect to the full range of the sensor. An initial pressure is needed to bring the conducting plane in contact with the reference ground plane, and the residual stress in the diaphragm provides a substantial resistance to deformation compared to the driving force created by the applied pressure. This residual stress reduces the sensitivity at low pressures and produces a nonlinear signal.

In previous work, several different types of capacitive pressure sensors have been developed [1]–[12], and a touch-mode pressure sensor has been analyzed using membrane deflection theory [3], [13]–[15]. As pressure is applied to these sensors, the diaphragm deflects towards the electrode, and the capacitance increases. To increase the sensitivity, different materials have been used for the diaphragm, and capacitance changes were studied over a pressure range. The reported sensor sensitivities are 0.0041 pF/kPa for a Kapton diaphragm, 0.0008 pF/kPa for a stainless-steel diaphragm, 0.0014 pF/kPa for a titanium diaphragm [2], 0.02 pF/kPa for a silicon diaphragm [3], and 0.45 pF/kPa for a thinner silicon diaphragm [4]. Additional information of the previous work is summarized in Table I. Many of these sensors are used for high-pressure measurements (larger than kilopascals), and these sensor types show a lower sensitivity in the low-pressure regime (less than a kilopascal). However, a resolution of a Pa or less is needed for many Bio-MEMS applications, such as measuring pressure across epitheal tissue [16], osmotic pressure within cells [17], and pressures in the embryonic chicken heart [18]. In these applications, the pressure changes (sub-Pa) occur on top of much larger mean pressures (order of 10^5 Pa).

To obtain a 10^{-6} resolution in differential pressure to the total mean pressure, smooth contact capacitive pressure sensors with parabolic shape and donut shape cavity are developed that operate in a touch-mode and a peeling-mode. The two device schematics are shown in Fig. 1. The parabolic and donut cavity shapes use a smoothly varying contact to allow for an initial contact at a zero-pressure differential for touch-mode shown in Fig. 2(a), which was previously presented in [7]. By removing any space between the two electrodes and by choosing a flexible polymer material for the conducting diaphragm, the capacitance sensitivity is higher than sensors with gaps and higher modulus materials, in particular, for low-pressure range less than 1 kPa. For the peeling-mode sensor shown in Fig. 2(b), the diaphragm zips into contact with the bottom electrode with an applied electric potential, V, which counters the residual and induced tensile stresses in the diaphragm. The capacitance increases with more contact area. A decrease in capacitance occurs as the diaphragm peels from the bottom electrode when the pressure is applied enough to overcome the interfacial electrostatic pressure shown in Fig. 2(c). These types of pressure sensors can be used for very low differential pressure manipulation, well below 100 Pa, which is a difficult regime to obtain accurate measurements in

Manuscript received March 25, 2008; revised June 17, 2008; accepted July 20, 2008. Current version published February 06, 2009. This is an expanded paper from the Sensors 2007 Conference. This work was supported in part by the National Science Foundation (NSF) Science and Technology Center of Advanced Materials for Purification of Water with Systems (Water CAMPWS; CTS-0120978). Any opinions, findings, conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of NSF. The silicon surface grinding and polishing process for the cavity shape was carried out in part in the Frederick Seitz Materials Research Laboratory Central Facilities, University of Illinois, which are partially supported by the U.S. Department of Energy under Grant DE-FG02-07ER46453 and Grant DE-FG02-07ER46471. The associate editor coordinating the review of this paper and approving it for publication was Prof. Gerald Gerlach.

The authors are with the Department of Mechanical Science and Engineering, University of Illinois at Urbana–Champaign, Urbana, IL 61801 USA (e-mail: jhan3@uiuc.edu; mshannon@uiuc.edu).

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Digital Object Identifier 10.1109/JSEN.2008.2011090

TABLE I
CAPACITIVE PRESSURE SENSORS IN REFERENCE ARE SUMMARIZED AND SHOWN BELOW

Ref	Membrane Material		Pressure Range[kPa]	Sensitivity [pF/kPa]
2	Kapton Polyimide	0.14	0-34	0.0041
	Stainless Steel	0.15	0-178	0.0008
	Titanium	0.25	0-178	0.0014
3	Silicon	4	140-335	0.02
4	Silicon	0.25	0-0.55	0.45
5	Silicon	5.97	80-106	0.2
8	Ceramic	5	0-350	0.0013
9	Silicon	20	100-400	0.049
10	Silicon	10	100-150	0.1
11	Kapton Polyimide	2	±2	5
12	Polyimide	0.13	±100	0.0013
19	Polyimide 2610	0.4	1-100	0.0032

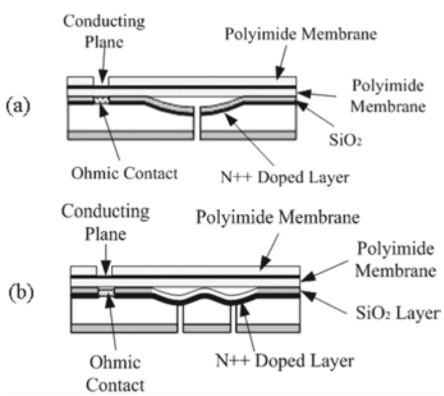

Fig. 1. Two schematics of capacitive pressure sensors are shown here with (a) a parabolic cavity shape and (b) a double parabola "donut" cavity shape. Both start with the conducting diaphragm plane in contact with the N++ doped silicon ground plane.

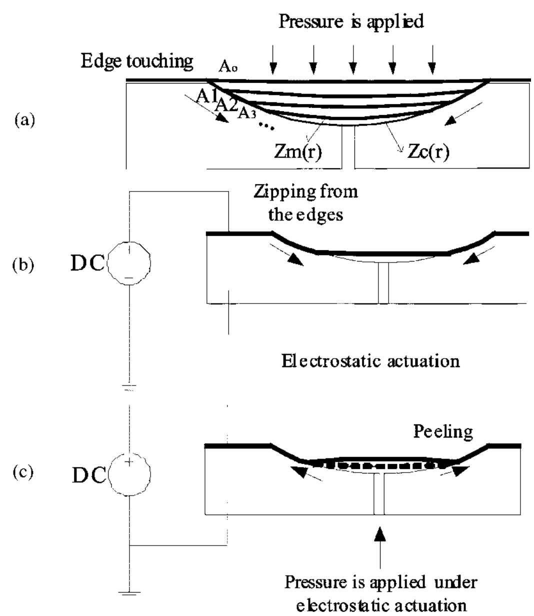

Fig. 2. The description for the two different modes is shown above for (a) touch-mode, (b) peeling-mode operation zipping, and (c) peeling under applied pressure. The capacitance for touch-mode is directly measured from an LCR meter, and the capacitance for the peeling-mode is measured from the bridge circuit under electrostatic actuation.

a high ambient pressure on the order of 10^5 Pa. Pressure sensitive diaphragm materials are selected in order to increase sensitivity at low-pressure [2], [11], [12],[19]–[21]. In this work, the geometric changes of fixed electrodes and the operation mode's effect on the sensitivity are investigated.

Smooth contact-mode C-P sensors have been designed, fabricated, characterized, and tested in two different modes, touch-mode and peeling-mode. The purpose of the current work is to present the experimental results for the smooth contact C-P sensors in touch-mode and peeling-mode in terms of capacitance response, sensitivity at low pressures, and their corresponding resolutions.

II. DEVICE FABRICATION

A. Device Schematics

Each capacitive pressure sensor shown in Fig. 1 consists of a doped silicon bottom die, intermediate electrical insulation layers, and an upper flexible conducting layer. There are two different shapes of the cavities in the bottom doped dies that provide smooth contact to the diaphragm electrode. One is parabolic [Fig. 1(a)], and the other is donut shaped [Fig. 1(b)]. The top of the silicon surfaces are $N++$ doped, and a thermal dry silicon dioxide is thermally grown at 1100 °C in dry oxygen to form a high-strength electrical insulation layer. The flexible conducting layer is a sandwich structure of polyimide film, Cr/Au/Cr layer, and polyimide film on a glass substrate. The intermediate insulation layers are silicon dioxide on the bottom silicon die, air gap, and polyimide on the conduction plane.

B. Device Fabrication

The device fabrication procedure is shown in Fig. 3. The bottom electrode die and the upper conducting diaphragm are

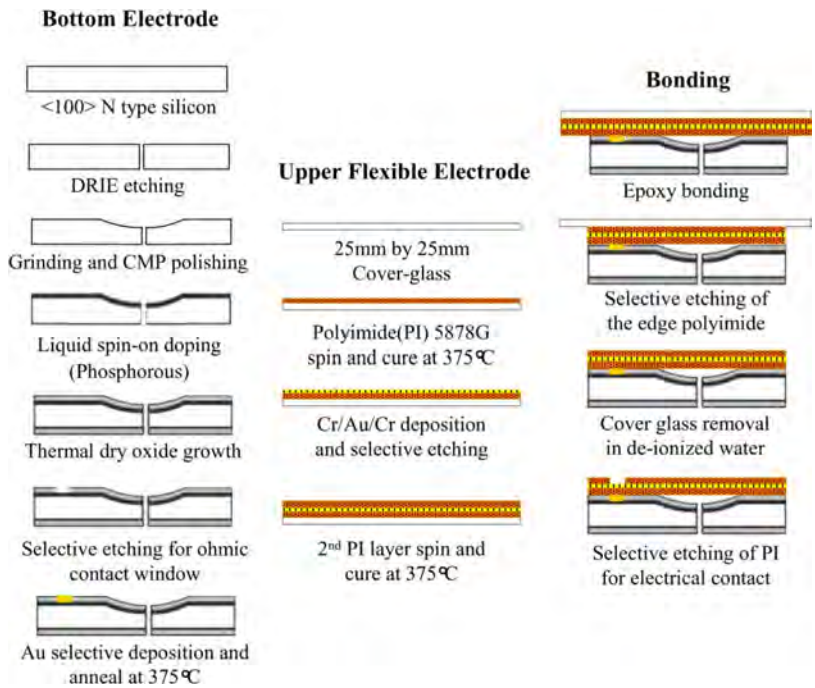

Fig. 3. The smooth contact capacitive pressure sensor fabrication procedure is shown above. Two different cavity shapes are prepared, including parabolic and donut shapes. Bottom electrode and upper flexible electrode are fabricated individually and align-bonded using adhesive at 110 °C and cured at 140 °C.

fabricated and assembled together using an epoxy bonding contact printing method [22].

A 100 mm silicon wafer ($\langle 100 \rangle$ N type, 1–10 Ohm-cm, 500 μm thick, Silicon Quest) is patterned using AZ 4620 photoresist (Clariant). Line trenches separating individual dies and vent holes in each die are etched through in deep reactive ion etching system (Plamsa-Therm SLR 770) using the Bosch process to generate twelve 16 × 18 mm dies. Then, a 1 μm thick SiO_2 film is grown on the dies to protect their surface during the subsequent grinding process. Cavities of two different shapes are ground using a diamond slurry (METADI II, Buehler) in a dimpling machine (Dimpler D500i, VCR Group, Inc.). Subsequently, chemical mechanical polishing (CMP) is implemented in the same dimpler with a CMP liquid (Logitech, Polishing Suspension Type SF1) to remove microscopic protrusions and ensure a smooth surface for mechanically and electrically stable contact. An SC-1 cleaning process and etching of the protective SiO_2 layer is performed to clean the outer surface of the dies. The silicon die is spin-coated with a phosphorous spin-on dopant, which is driven into the Si surface at 1000 °C for 30 min to form the conducting plane on the cavity die surface. After the diffusion process, the silicon die is deglazed in a buffered hydrofluoric acid (HF). A 1000 Å thick SiO_2 film is then thermally grown for electrical insulation at 1100 °C for 50 min. An ohmic contact window is created by using standard photolithography, the underlying SiO_2 layer is etched with BOE, and a 100 Å/1000 Å thick Cr/Au layer is selectively sputtered on the window under an Ar background pressure of 10^{-2} Torr. The sample dies are placed in a tube furnace at 375 °C for 15 min to form Au/Si ohmic contacts.

The fabrication for the diaphragm electrode starts with an SC-1 cleaned cover glass on which a PDMA-ODA polyimide (PI) layer is coated. The PDMA-ODA PI film is cured at 375 °C for 3 h under a nitrogen environment to form a 3 μm cross-linked PI layer. A Cr/Au/Cr (100 Å/1000 Å/100 Å) thick conducting metal layer is deposited on the PI surface and patterned to form the conducting electrode. Another layer of polyimide (3 μm thick) is spin-coated on the conducting plane and cured under the same conditions.

The PI diaphragm electrode and the Si bottom electrode die are epoxy-bonded as described in [22]. A round PDMS (Sylgard 184, Dow Corning) substrate is casted and cured for epoxy transfer. The custom-made epoxy is spin-coated onto a PDMS round carrier substrate, and the adhesive is selectively transferred to the bottom electrode die except the cavity region.

The bottom die is aligned with the upper conducting diaphragm, pressed using a Teflon ball from the top of the diaphragm at 110 °C, and cured at 140 °C for 10 min on a hotplate. After the bonding process is done, the edge of the diaphragm is selectively removed. The bonded sample is inserted into hot water (100 °C) so that the cover glass lifts off from the polyimide diaphragm. Finally, the polyimide is selectively etched using O_2/Ar (2:1 ratio) plasma at 250 watts in the RIE (March Instrument, Jupiter III) for 20 min to open the electrical connection pads on the bottom electrode and on the upper conducting diaphragm.

III. Measurement Setup

A. *Touch-Mode Measurements*

In order to characterize the capacitance output in response to an applied pressure, a precision LCR meter (Agilent 4284A) with 10 fF resolution is employed in the test setup, as shown in Fig. 4(a). For the pressure source, a nitrogen gas (99%) tank is used. A stream of N_2 flow (99% pure) is controlled via a precision pressure regulator (Pressure regulator type 700,

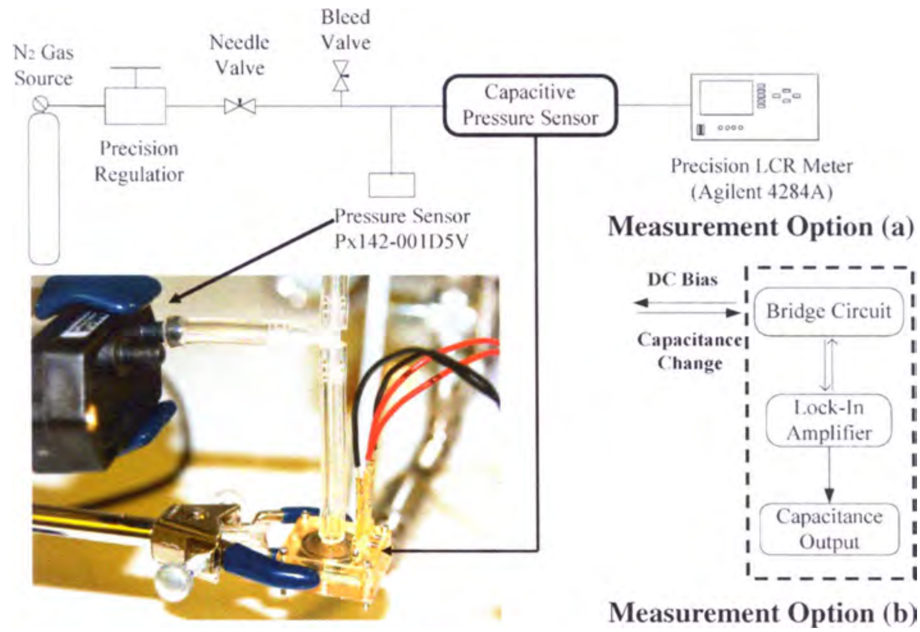

Fig. 4. The test setup schematic for capacitive pressure sensors for touch-mode operation is shown above. The pressure is controlled using a precision regulator, one needle valve, and one bleed valve. The measurements are made by either option (a) Agilent 4284A meter or by option (b) bridge circuit system. The bridge circuit measures the capacitance of the C-P sensor, while providing dc voltage for electrostatic actuation of the sensor.

Control Air, Inc.) and two needle valves. A pressure sensor (PX 142-001D5V, Omega.com) is used to measure the applied pressure at the inlet of the capacitive pressure sensor. The package to accommodate the electrical and fluidic connections into the sensor is made using a stereo lithography (SLA) machine. As the applied pressure from the top increases, the polyimide surface in the diaphragm electrode starts to touch the bottom electrode, resulting in an increase in capacitance.

B. *Peeling-Mode Measurements*

In peeling-mode operation, a dc voltage is applied to the device first. Under electrostatic actuation, the diaphragm starts to zip from the edges to the center, and the capacitance of the device increases. Then, pressure is applied from the bottom hole. As the pressure increases, the polyimide surface starts to peel off, and it reaches the equilibrium position, resulting in a capacitance drop.

For pressure control, a precision regulator, needle valve, and bleed valve are used along with a pressure sensor at the inlet of the capacitive pressure sensor. The test setup schematic is shown in Fig. 4(b), and the capacitance changes are measured versus applied pressures under an electrostatic actuation. In order to apply a constant dc voltage to the sensor and measure the capacitance, the bridge circuit used is shown in Fig. 5, which is a modified circuit originally from the design in [23]. The circuit applies dc bias to the capacitive sensor through both ends, and an ac excitation signal is applied to the circuit. The ac signal output is minimized when the circuit is balanced. A variable capacitor and several fixed capacitors are used to balance the circuit, and the ac signal is monitored using a lock-in amplifier. The bridge circuit is calibrated with known capacitors before the actual measurement.

IV. Results and Discussion

A. *Touch-Mode Results*

The sensitivity of the C-P sensors is defined as the rate of change in the capacitance per unit of applied pressure in pF/KPa, and varies over the pressure ranges of interest. For the parabolic cavity shape, the capacitance response with pressure is shown in Fig. 6(a), with the 95% confidence level uncertainty shown for each point. The parabolic cavity sensor has a square root of pressure response, making it most sensitive at pressures below 1 kPa. The sensitivity in Fig. 6(b) varies from 100 to 2 pF/KPa as pressure changes from 0 to 35 kPa. The average sensitivity for pressures less than 1 kPa is 84 pF/KPa. For the donut cavity shape, the capacitance response is more complex, as shown in Fig. 7(a), with the 95% confidence level uncertainty shown for each point. The donut cavity sensor follows a hyper tangent function of P, making it most sensitive over a narrow range from ~ 3 to 7 kPa. The sensitivity in Fig. 7(b) at pressures less than 1 kPa is about 30 pF/KPa. For a low-pressure measurement requiring a resolution as low as 10 Pa, the sensitivity of the capacitive pressure sensor is important. For one example of a low-pressure measurement in the embryonic chicken heart in [18], the sensitivity needed was about 7.7 pF/KPa. The smooth contact touch-mode sensor is one possible solution for this application because the sensitivity of this sensor is sufficiently large for this application and requires voltages below 9 volts with low-power consumption. The current capacitance measurement technology makes it possible to measure the capacitance as low as 10 fF, i.e., Agilent 4284A LCR meter. The resolution of the pressure sensor can be as low as 0.012 Pa for parabolic shape sensor, and 0.033 Pa for donut shape sensor. A small hysteresis can also occur in the capacitance signal as a function of increasing or decreasing pressure. The capacitance hysteresis can be seen in a representative plot in Fig. 8(a) for the touch-mode sensor, and the maximum hysteresis variation over the full range observed is about

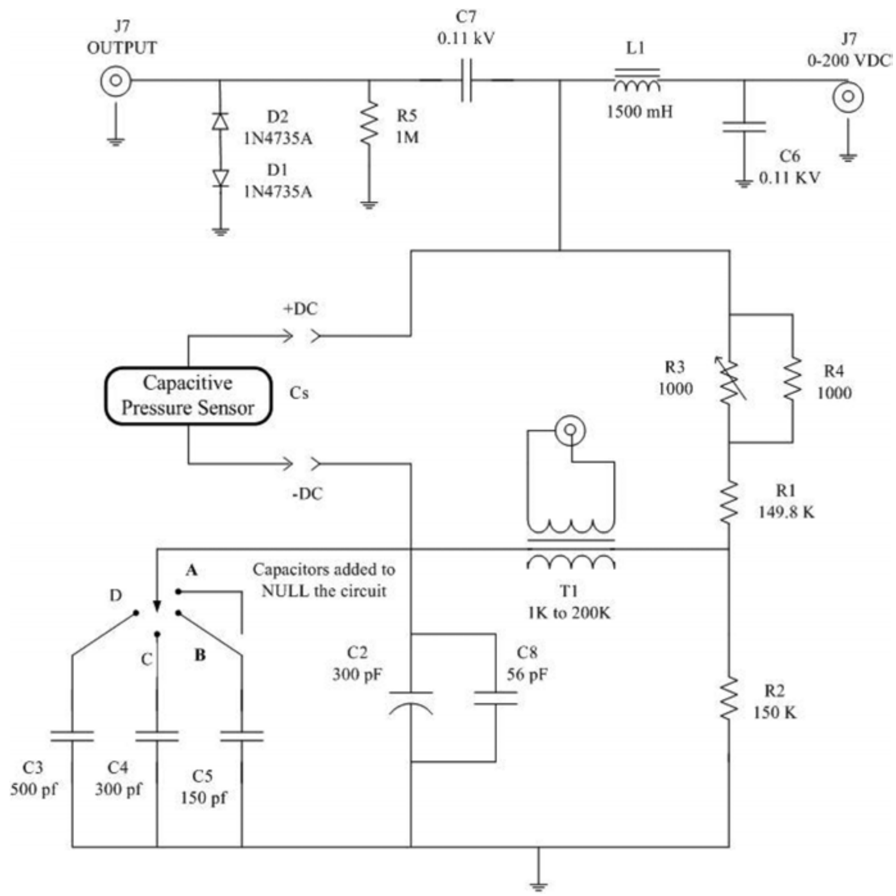

Fig. 5. This bridge circuit is used for the measurement of the C-P sensor capacitance, while applying a dc voltage for electrostatic actuation to the sensor.

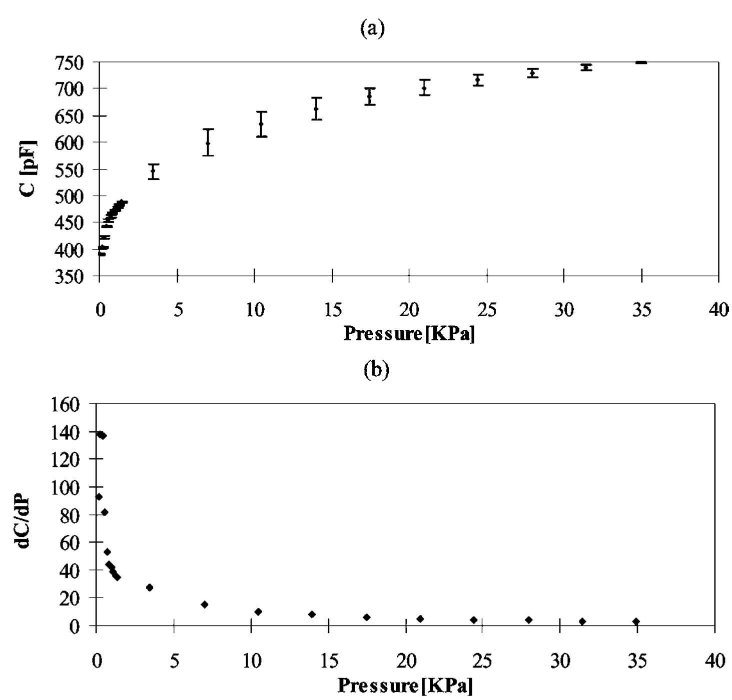

Fig. 6. The capacitance C response in pF of the touch-mode parabolic cavity sensor versus pressure P is shown in (a). The sensitivity given by dC/dP in pF/kPa is shown in (b) as a function of an applied pressure in kPa.

1.9% for a parabolic shaped sensor and 2.5% for a donut shaped sensor. The cause of the hysteresis includes the viscoelastic material property of polyimide, the surface contact adhesion, and pressure control uncertainty.

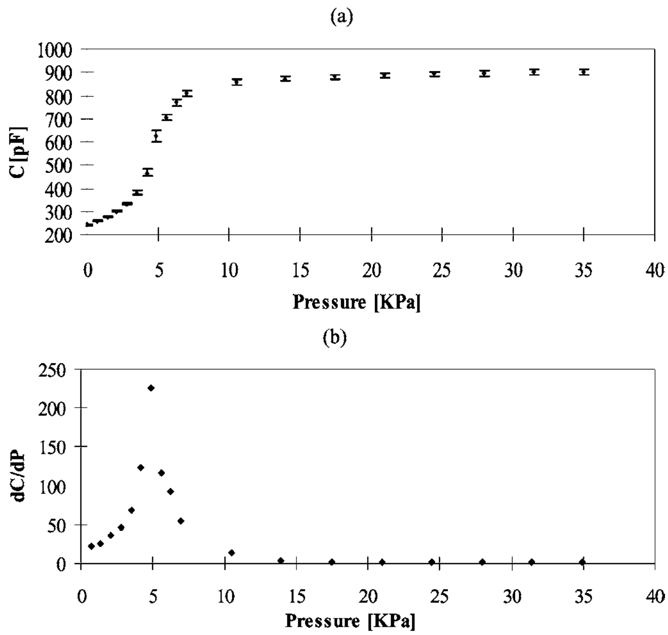

Fig. 7. The capacitance C response in pF of the touch-mode donut cavity sensor versus pressure P is shown in (a). The sensitivity given by dC/dP in pF/kPa is shown in (b) as a function of an applied pressure in kPa.

B. Peeling-Mode Results

When a dc voltage is applied to the device, the diaphragm starts to zip from the edges to the center, and the capacitance of the device increases, primarily due to the capacitance across the SiO_2 and polyimide dielectric layers. The contribution across the air gap is several orders of magnitude smaller. Therefore, the change in capacitance is primarily due to a change in contact area, which varies nearly linearly with applied pressure, which is applied through holes in the bottom wafer. As the pressure increases, the polyimide surface starts to peel off, and it reaches the equilibrium position, resulting in a decrease in capacitance.

The response of the peeling-mode sensor changes as a function of applied dc bias. For the parabolic cavity shape, the dc bias is increased from 0 to 40 volts, and the capacitance is measured versus the applied pressure up to 130 Pa, which is shown in Fig. 9. As the dc bias increases, the initial capacitance output of the sensor is higher, and the capacitance decreases when the applied pressure increases. When the pressure reaches a critical pressure, and the system becomes unstable, the diaphragm pops up, resulting in a capacitance drop. With applied voltages of 20, 30, and 40, the sensitivities are approximately 1.35, 1.42, and 1.53 pF/Pa, respectively. For the donut cavity shape, as the dc bias increases from 0 to 90 volts, and the capacitance that is measured versus the applied pressure up to 1.2 kilopascals is shown in Fig. 10. With applied voltages of 50, 70, 90, and 110 V, the sensitivities are 0.209, 0.131, 0.375, and 0.397 pF/Pa, respectively. The resolution of the pressure sensor can be as low as 0.0007 Pa for the parabolic shape sensor, and 0.003 Pa for the donut shape sensor. The maximum variation in capacitance due to hysteresis over the full range is about 2.3 % for the parabolic shape sensor, shown in a representative plot in Fig. 8(b) and 2.7% for the donut shape sensor.

C. Discussions

In touch-mode operation, the capacitance response of the sensors is proportional to the applied pressure. The pressure and capacitance relationship involves membrane deflection and surface to surface contact. The capacitance output of the two modes is based on the contact area between the diaphragm and the fixed electrode. The deflection of the diaphragm is proportional to applied pressure. Applied pressure increases the touching area from the sides and decreases the distance between the two electrodes, thus increasing the capacitance response, shown in Fig. 2(a). The capacitance is related to the contact area and noncontact area of the membrane (1). As the contact area increases, the free standing diaphragm area decrease, thus increasing the stiffness of the diaphragm. Thus, the capacitance response monotonically converges with smaller area increment per unit pressure increase, such that

$$\begin{aligned} C &= C_{\text{contact}} + C_{\text{noncontact}} \\ &\approx \varepsilon_0\varepsilon \frac{\varepsilon_0\varepsilon}{t_1+t_2}\int_{R_1^R} 2\pi r\sqrt{1+z_c'^2}dr \\ &\quad + \varepsilon_0\varepsilon\int_{R_1}^{R}\frac{1}{z_m-z_c}2\pi r\sqrt{1+z_m'^2}dr \end{aligned} \tag{1}$$

where ε_0 is permittivity constant, ε is a dielectric constant, t_1 is polyimide layer thickness, t_2 is silicon dioxide thickness, g is the gap between two dielectric layers, R is the radius of the cavity, R_1 is the radius where the diaphragm touches the bottom electrode, z_c is a bottom electrode shape function, and z_m is the flexible upper electrode layer shape function.

For a peeling-mode sensor, the area in contact from the sides increases as the applied voltage increases by diaphragm zipping. The pressure is applied, peeling the zipped surface and reducing the capacitance. The capacitance output of peeling-mode sensor is inversely proportional to the pressure applied. The pull-in voltage can be calculated from the energy balance [24] or force balance [25], such that

with

$$\sum_n F = F_{\text{electric}} - F_{\text{structure}} - F_{\text{pressure}} = 0$$

with

$$\begin{aligned} F_{\text{electric}} &= \frac{V_p^2}{2}\frac{\varepsilon_o A}{\left(\frac{t_1}{\varepsilon_1}+g+\frac{t_2}{\varepsilon_2}\right)^2} \\ F_{\text{structure}} &= KA\Delta z, \text{ and} \\ F_{\text{pressure}} &= pA \end{aligned} \tag{2}$$

where V_p is the applied pull-in voltage, K is a structural stiffness of the diaphragm [25], Δz is the center deflection of the diaphragm, A is the diaphragm surface area, and p is the applied pressure to the sensor. For $V_p^2 = V_{\text{dc}}^2(1+V_{\text{ac}}/V_{\text{dc}})^2$, and where $V_{\text{ac}}/V_{\text{dc}} \ll 1$ as in our experiments, the affect of the ac component on the pull-in and capacitance change due to the deflection is negligible and can be safely neglected. Therefore, the measurement voltage applied should not affect the pressure measured.

At the pull-in voltage, a stability of the equilibrium breaks, and the system reaches another state of equilibrium. As the voltage is applied to the sensor, a zipping action occurs and the freestanding diaphragm area decreases. As a result, the stiffness

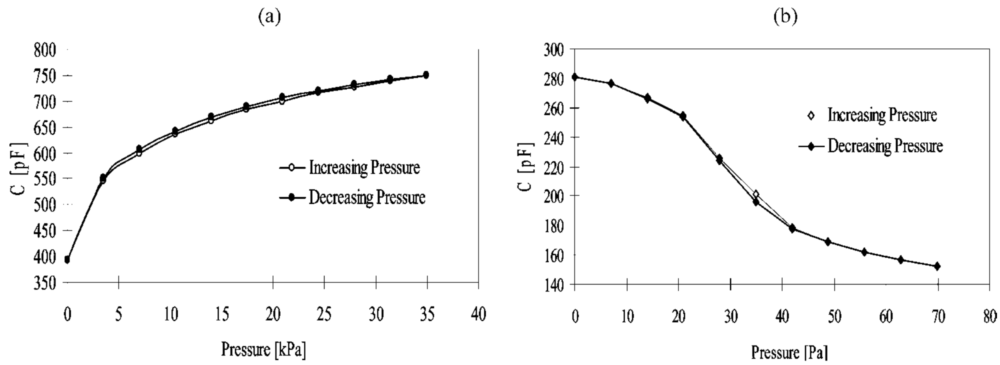

Fig. 8. Representative capacitance responses as a function of increasing and decreasing pressure is shown for parabloic shaped sensors operating in (a) touch-mode and (b) the peeling-mode at $V = 30$. A small $(< 3\%)$ hysteresis in the capacitance value at the same pressure can for both sensor types.

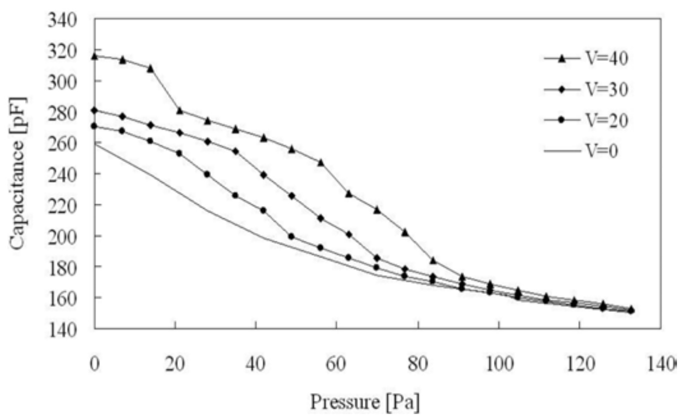

Fig. 9. The peeling-mode capacitance response to applied pressure is presented here for the parabolic cavity sensor. Actuation voltage is applied up to 40 volts, and each voltage shows a different sensitivity.

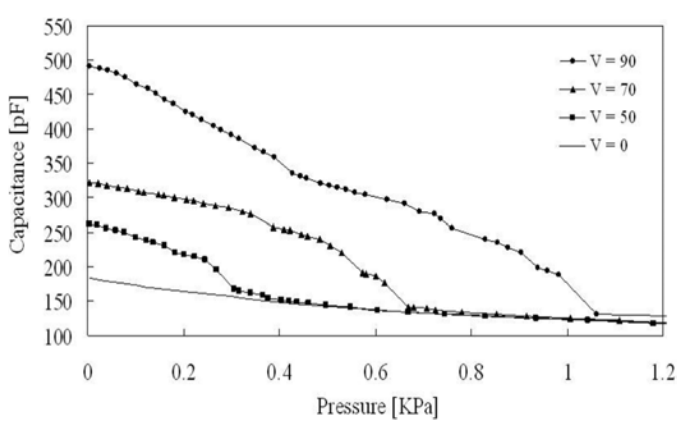

Fig. 10. The peeling-mode capacitance response to applied pressure is presented here for the double cavity sensor. Actuation voltage is applied up to 90 volts, and each voltage shows different sensitivity.

of the circular diaphragm gradually increases, and further increases in contact area require a higher voltage. As the contact area increases, the capacitance increases. When a pressure differential is applied to the sensor, the force equilibrium changes due to the pressure force term, and the contact area changes with a corresponding reduction in capacitance. The sensor can operate in a peeling-mode at a given voltage as long as the equilibrium of forces holds. When the applied pressure increases and the instability point is reached, the diaphragm will pull off the bottom electrode.

The sensitivity of the peeling-mode sensor is larger than the touch-mode sensor by an order of magnitude. In peeling-mode, the pressure needs to be just high enough to overcome the electrostatic “pressure” to peel the diaphragm off the surface. The peeling-mode sensitivity depends on the geometry of the bottom electrode as well as the applied voltage between the diaphragm and silicon. The sensitivity and linear sensor range increases as the applied voltage increases. However, the peeling-mode needs a higher dc voltage for the desired electrostatic actuation to determine the pressure range, and the measurement range is also smaller than that for touch-mode actuation. There are other sensors utilizing flexible materials to increase their sensitivity. Their sensitivities are 0.0041 pF/kPa for a Kapton (polyimide) diaphragm [2], 0.5 pF/kPa for a polyimide diaphragm [11], 0.0014 pF/kPa for another with a polyimide diaphragm [12], and 0.0032 pF/kPa for a polyimide diaphragm [19]. The sensitivities of the touch- and peeling-mode sensors with polyimide diaphragm reported here are larger than 30 pF/kPa, which is 60 to 1000 times higher. This higher sensitivity permits accurate pressure measurements less than 1 kPa but at the expense of a smaller range of applicability due to the nonlinearity of the response.

The nonlinear capacitance response sensor is affected by the shape of the bottom electrode cavity, the variable stiffness of the diaphragm, and the contact area. For both types of sensors, the greater the contact area, the more linear the response, but at the expense of sensitivity, which drops down to values close to the other sensors reported. The diaphragm stiffness is a function of its thickness and modulus, the applied voltage and pressure, and the electrode shape. The shape of the bottom electrode can be designed in order to increase the linear response, which will be explored in future work.

V. Conclusion

Smooth contact-mode capacitive pressure sensors have been developed to measure small pressure rises $(< 1000\ \mathrm{Pa})$ at high mean pressures, i.e., atmospheric pressure of $10^5\ \mathrm{Pa}$. These capacitive pressure sensors consist of one conducting diaphragm and one bottom n^{++} doped silicon die with a parabolic cavity shape or a donut cavity shape. These sensors can be operated in touch- or peeling-mode. The sensitivities of peeling-mode are higher than touch-mode sensitivities for each cavity shape sensor by an order of magnitude. Different from touch-mode capacitive sensors, the peeling- mode capacitive sensor needs a dc voltage to actuate, and the capacitance response shows a limited but linear response in the low-pressure regime less than 1000 Pa. However, touch-mode sensors need an excitation voltage less than 9 V with lower power consumption, and the resolution level is well below 0.1 Pa, which gives a resolution/total pressure ratio at atmospheric pressure of less than 10^{-6}. Both cavity sensor types in two different mode operations achieved 10^{-6} resolution/total pressure goal. Therefore, for measuring with high accuracy and low differential pressures $(< 1\ \mathrm{kPa})$ at a high mean pressure, smooth, contact-mode designs provide a potential option for capacitive pressure sensors.

Acknowledgment

J. Han thanks D. Sievers for his technical assistance.

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Jeahyeong Han was born in Korea in 1974. He received the B.S. degree from the Department of Mechanical Engineering, Kyung Hee University, Seoul, Korea, in 2000 and the M.S. degree from the Department of Aerospace Engineering, Georgia Institute of Technology, Atlanta, in 2002. He is currently working towards the Ph.D. degree in mechanical science engineering at the University of Illinois at Urbana–Champaign, Urbana.

He currently works as a Research Assistant at the University of Illinois at Urbana–Champaign. His research interests are capacitive pressure sensors, solid-solid surface interactions in micro/nanoscale, microvalves, and electrostatic micropumps.

Mark A. Shannon (M’99) received the B.S., M.S., and Ph.D. degrees in mechanical engineering from the University of California, Berkeley, in 1989, 1991, and 1993, respectively.

He is currently the James W. Bayne Professor of Mechanical Science and Engineering with the Department of Mechanical Science and Engineering, University of Illinois at Urbana–Champaign, Urbana, and is also currently the Director of a National Science Foundation Science and Technology Center, the WaterCAMPWS, which is a multiple university and government laboratory center for advancing the science and engineering of materials and systems for revolutionary improvements in water purification for human use. He is also currently the Director of the Micro-Nano-Mechanical Systems (MNMS) Laboratory. His current research includes fabrication of micro and nanoelectromechanical systems, microscale fuel cells and gas sensors, microchemical reactors and microcombustors, and micronanofluidic sensors for biological fluids, and he is heavily involved in studying micro-nanoscale transport and systems for sensing and purification of water.

Dr. Shannon is a member of the American Society of Mechanical Engineers.