Force Balanced Micromachined Pressure Sensors

B. P. Gogoi and C. H. Mastrangelo

I. ABSTRACT

This paper discusses the fabrication and testing of two low-voltage force-balanced pressure sensors. In these devices the force acting on a diaphragm under external pressure and its corresponding deflection are counterbalanced with the force and deflection generated in a parallel plate electrostatic actuator mechanically coupled to the diaphragm. The low balancing voltage is attained using a force multiplication scheme. The first device is implemented using an open gap actuator constructed on top of a vacuum sealed sense diaphragm. The open gap design is exposed to the measurement environment hence susceptible to contamination. The second device eliminates this problem by enclosing the actuator in a hermetically-sealed cavity. Both devices have a full scale range of 1 atmosphere. The open actuator device has a nominal capacitance of 0.34 pF and a full scale range of 70 fF. The sealed actuator device has a nominal capacitance of 2.12 pF and a full scale range of 100 fF. The pressure is balanced by voltages in the range of 12-25 V demonstrating the feasibility of force balanced pressure sensor compatible with low-voltage electronics.

II. INTRODUCTION

Over the last three decades a large variety of micromachined pressure sensors has been developed. The majority of these devices convert pressure induced deflections of a diaphragm to an electrical output through using an electrical element that is sensitive to deflection or associated stress. For example, piezoresistors, capacitors, and resonator elements have been used for this function. In these devices the translation mechanism uses intermediate material properties (i.e. Young modulus, residual stress, doping, etc.) for unit conversion; hence the output is susceptible to variations in material properties, fabrication procedures, and operating conditions [1, 2] which are manifested as fluctuations and drifts in the device response. In practical devices the effect of these variations is minimized through calibration and compensation procedures using special trimming circuits [3–5]. Because the calibration is performed over a wide range of operating conditions, this procedure is quite expensive contributing as much as 30-60% of the total sensor cost.

The influence of material parameters at the sensor output can be removed if the diaphragm deflection is counterbalanced with an actuator. This involves first the detection of a small deflection in the diaphragm producing a large electrical signal at the output. The output signal then drives the actuator in a closed-loop feedback configuration. If the loop gain is sufficiently high, the output of the force balanced pressure sensor is independent of any mechanical properties of the diaphragm or the deflection detection mechanism. In this scheme the output is however dependent on the actuator characteristics; therefore an actuator with transfer function independent of material properties must be used. The parallel plate electrostatic actuator is an example of such.

Electrostatic force balance principles have been successfully applied to accelerometers [6], and microvalves [7]. The voltages used in the accelerometer devices are low hence suitable for conventional MOS driver circuits. However, the high voltages [8] (100-300 V) required for balancing high pressures have rendered the technique impractical for pressure sensors. The basic operating principles for force balanced pressure sensor have however been demonstrated using a pneumatic-electromagnetic driving mechanism [9].

In the devices presented here, the voltages required for force balance are reduced tenfold using a force multiplication scheme [10]. In this scheme, the pressure sensing area and the force balancing actuator area are decoupled. By reducing the area of the sensing diaphragm and increasing the area of the electrostatic actuator, the electrostatic force is multiplied by the square root of their areas. Through appropriate ratio of drive electrode and sensing diaphragm, the required voltage for balancing 1 atm pressure is reduced down to 15-25 V.

This paper describes two different surface micromachined devices that use the scheme with different actuator configurations. In the first device, the electrostatic actuator is constructed directly above the sense diaphragm with the electrode gap exposed to the measurement environment hence susceptible to particulate contamination. In the second device the electrostatic actuator is hermetically sealed permitting a lower gap. A performance improvement is achieved in the drive voltage from 25 to about 12 V compared to the open actuator device when counter balancing a 1 atm pressure. The hermetically sealed device is also fabricated using a reduced, 15 mask, surface micromachining process.

III. ERRORS IN OPEN AND CLOSED LOOP SENSORS

In conventional pressure sensors such as diaphragm-based transducers, without loss of generality, we can assume a linear relation between pressure \( u_m \) and electrical output \( u_e \)

\[
u_e = \alpha u_m + \varepsilon \tag{1}
\]

where \( \alpha \) is the slope of the sensor output characteristic and \( \varepsilon \) its offset. Both \( \alpha \) and \( \varepsilon \) are subject to material property variations; hence they are only known within a given tolerance range, \( \alpha_m \leq \alpha \leq \alpha_{m_{\text{in}}} \) and \( |\varepsilon| < \varepsilon_{\theta} \). Therefore the relationship between \( u_e \) and \( u_m \) can only be determined within the uncertainty band shown in Figure 1(b)
Since there is no point in this curve where the error band becomes zero, the actual values of $\alpha$ and $\epsilon$ must be first determined for each device using calibration procedures, and compensation and trim circuits are added to provide a uniform output versus pressure characteristic under a wide range of operating conditions (pressures and temperatures).

In a force balanced system, the electrical output of the transducer $u_e$ is amplified with gain $A$ producing a larger signal $y_e$. This signal drives an actuator producing a pressure output on the diaphragm

$$y_m = \beta y_e$$

which opposes the external pressure in the closed-loop configuration of Figure 2.

IV. PRESSURE SENSING USING FORCE BALANCE

The basic electrostatic force balancing device configuration for pressure sensors is shown in Fig. 4. A typical device consists of an elastically-supported rigid plate and one or two fixed electrodes. The elastic plate is normally displaced downward by an external pressure $P_o$. The position of the middle plate and the balance of the forces is determined from the capacitance $C_{sens}$ between the middle and bottom plates. The displacement signal drives a charge pump circuit that injects charge onto the top electrode. The top and middle plate form a parallel plate capacitor servomechanism which implements a charge-pressure relationship and restores the position of the midplate to its original position. When this condition is met, the electrostatic pressure $P_E$ of the actuator is exactly equal to the external pressure $P_o$. Hence, the drive electrode voltage is

$$V_{drive} = \sqrt{\frac{2P_E}{\varepsilon_o} h_o}$$

where $h_o$ is the equilibrium gap between the top and middle plate. For example, in order to balance a pressure of 1 atm ($10^6$ Pa) with a 1 $\mu$m gap actuator, a voltage of 150 V is needed. This voltage is too high to be handled by low-voltage electronic circuits.

In the modified force-balancing scheme shown in Fig. 5, the area of the drive electrode generating the restoring force is made...
much larger than the displacement generating diaphragm. This results in a much lower voltage needed to restore the middle plate to its original position.

In this scheme, the condition for force balance demands

$$P_o A_s = P_E A_d$$  \tag{5}$$

where $P_E$ is the electrostatic pressure of the drive electrode, $A_d$ is the area of the drive electrode, $A_s$ is the area subjected to the external pressure $P_o$ being sensed. Hence, $P_o = (A_d/A_s) P_E$ and the drive electrode voltage is

$$V_{drive} = \sqrt{\frac{2P_o A_s}{\epsilon_0 A_d}} V_0$$  \tag{6}$$

The voltage needed for force balance is proportional to $\sqrt{A_s/A_d} \ll 1$. By properly scaling the areas, the force multiplication scheme can reduce the drive voltage substantially. For an area ratio of $A_d/A_s = 100$ and electrode gap of 1 $\mu$m, the drive voltage is reduced from 150 to 15 V, thus compatible with conventional low-voltage MOS circuits. In practice, the area ratio cannot be arbitrarily large, with an upper limit determined by the drive electrode and sensing diaphragm thicknesses. A very small sensing diaphragm may require thicknesses that are too thin for practical processing. Similarly, an electrode that is overly large may be too flexible to provide efficient force transmission to the sensing diaphragm as well as cause stability problems [11].

V. OPEN ACTUATOR DEVICE

The practical micromachined implementation of the force balanced pressure sensor is shown in Fig. 6. The device consists of a 0.26-$\mu$m thick, 20×20 $\mu$m$^2$ SiN/poly-Si diaphragm built on top of a vacuum-sealed cavity etched into the substrate. The intermediate electrode consist of a large, 200×200 $\mu$m$^2$, 1.1 $\mu$m thick polysilicon plate attached to the center of the sensing diaphragm through a 36 $\mu$m$^2$ central boss support. In some of the devices, the intermediate plate is supported at the edges either by periodically spaced feet or four 80×8 $\mu$m$^2$ suspension beams. These additional supports stiffen the plate and provide an electrical connection. A stationary, 3.2-$\mu$m thick polysilicon drive electrode is constructed 1.0 $\mu$m above the intermediate plate. This electrode is supported by a periodic array of anchors connected to the substrate through holes etched in the midplate.

The center load deflection of the bossed sensing diaphragm under a pressure of 1 atm is [12] approximately $y_o \approx 0.2 \mu$m corresponding to a change in the drive capacitance of about 100 fF.

A. Fabrication Process

Fig. 7 shows the simplified 20 mask fabrication sequence. The process starts with a (100) p-type silicon wafer with a boron concentration of $10^{15}$ cm$^{-3}$. An alignment key is first patterned in the front of the wafer, and the silicon is etched about 1 $\mu$m deep using an SF$_6$ plasma. The diffused sensing electrode areas are lithographically defined and a 5×10$^3$ cm$^{-2}$ dose of Arsenic at 100 KeV is implanted. The next step of forming the diaphragm follows the technique described in [13]. A 0.24$\mu$m thick layer of low-stress nitride [14] is first deposited in a LPCVD furnace at 835 °C with a 4:1 dichlorosilane/ammonia ratio. A 0.5$\mu$m thick layer of LPCVD oxide is used as the etch mask of the SiN. The oxide is then photolithographically defined and then etched in 5:1 BHF. The resist is then stripped and the wafer is placed in a bath of H$_3$PO$_4$ at 160 °C to etch the nitride until the substrate is exposed. The masking oxide is then removed by 5:1 BHF. This step defines the dimension of the diaphragm. Next, an undoped polysilicon interlayer 0.12 $\mu$m is deposited in a LPCVD reactor with SiH$_4$ flow rate of 80 sccm at 160 mT and 590 °C. The polysilicon interlayer is patterned to form the etch channels as shown in Fig. 4(a) and then wet etched in a mixture of 64 : 33 : 3HNO$_3$ : H$_2$O : NH$_4$F. A 0.14$\mu$m thick layer of low stress nitride is next deposited in a LPCVD reactor to define the diaphragm thickness with a 0.5$\mu$m thick layer of LPCVD oxide to act as a mask for the SiN. After defining etch holes to the polysilicon interlayer with the masking oxide, the nitride is etched in H$_3$PO$_4$ until the polysilicon interlayer is exposed. The polysilicon interlayer as well as the silicon substrate under the diaphragm is then etched by KOH-isopropyl alcohol
forming the reference chamber (Fig. 4(b)). After removing the oxide, the etch holes are sealed by 0.12 μm of undoped LPCVD low stress polysilicon at 160 mT; thus, this device can measure absolute pressure.

A 1.5 μm thick sacrificial layer of LPCVD oxide is next deposited at 900 °C and 350 mT. The central support of the middle plate over the center of the diaphragm as well as the anchors are patterned using a combination of dry and wet etch (Fig. 4(d)). About 1.1 μm of oxide is first etched in a plasma reactor using 1:1 CF₄ : CHF₃. The remaining oxide is then etched by 5:1 BHF. The combination of dry and wet etch is used because of insufficient etch selectivity of the plasma etch when stopping over the thin diaphragm. The middle plate is next formed by depositing a 1.1 μm thick layer of low stress polysilicon in a LPCVD reactor. The polysilicon is then implanted with phosphorus at a dose of 1 × 10¹⁶ cm⁻² at 100 KeV. The middle plate is then lithographically defined and wet etched using a mixture of 64:33:3 HNO₃ : H₂O : NH₄F. Holes are also etched in the middle plate to allow for formation of support feet for the top plate.

A second 1.0 μm thick sacrificial layer of LPCVD oxide is then deposited to define the gap between the force balancing plate and the top restoring plate (Fig. 4(f)). The two sacrificial layers are etched to form the anchors of the top plate by a combination of dry/wet etching. To ensure electrical isolation between the middle plate and the top plate, a 0.32 μm thick layer of low stress nitride is deposited and etched in a hot H₂PO₄ bath to form isolation islands using a wet-etched 0.5 μm polysilicon mask. The 3.2 μm thick stationary top drive electrode plate is formed by first depositing a 1.6 μm layer of low stress polysilicon, implanting it with phosphorus at a dose of 2 × 10¹⁶ cm⁻² at 100 KeV and then depositing another 1.6 μm polysilicon layer. This polysilicon layer is then defined and patterned to form the top plate (Fig. 4(g)) by using a SF₆ : O₂ plasma. Etch holes for the subsequent sacrificial etch are also defined on the top plate by wet etching. The wafers are next annealed in nitrogen at 1100 °C for 1 hour to reduce the residual stress. Contact holes are opened to the middle plate as well to the diffused electrodes in the substrate. Contacts are metallized by 50/400 nm Cr/Au evaporation. The wafers are then diced and released by 49 % HF for 2 hours followed by supercritical CO₂ drying in a commercial system (Tousimis 780A). Fig. 8 shows an SEM of a 200 × 200 μm² device supported by four elastic beams. Fig. 9 shows a close up of the gap between the drive and the beamsupported force-balancing electrodes. Fig. 10 shows the pressure sensing diaphragm that lies below the intermediate plate. The broken area corresponds to the central support.

B. Experiments

The devices were tested as follows. First, the response of the unbiased device to pressure was measured using a vacuum probe station (MMR) by monitoring the zero bias drive capacitance as a function of the pressure. Capacitance measurements were recorded at 1 MHz using a high-precision HP4284A LCR meter with a resolution of 0.01fF. At a low pressure of 160 mT, the diaphragm is flat and with a drive capacitance of 0.342 pF. As the pressure is increased slowly to atmosphere, the drive capacitance decreases as the diaphragm is deflected downwards. Fig. 11(a) shows the C-P characteristic of a beam-supported device. The minimum capacitance at atmospheric pressure was 0.272 pF yielding a total capacitance change of 70 fF. The strong nonlinearity is probably originated by the large deflection behavior of the bossed diaphragm [12].

Next, a device was placed at 1 atm and a DC bias voltage was applied between the force balancing and drive electrodes so as to provide a restoring force to the diaphragm. The restoring voltage was increased slowly and the drive capacitance was recorded. Fig. 11(b) shows the C-V characteristic for a device with beam supports. The plot indicates that voltage induced capacitive changes comparable to those induced by external pressure are achieved at about 25 V. The restoring voltage needed to balance the deflection at different pressures was next measured. The zero deflection capacitance of the device was first recorded at 160 mT. Next, the pressure was gradually increased and the drive voltage was adjusted until the deflection was balanced yielding the zero deflection capacitance. Fig. 12 shows a plot of the balancing voltage as a function of the pressure. The plot shows an approximate square root dependence with pressure as predicted by Eq. (6). The measurements indicate that a voltage of 25 V is sufficient to balance the deflection induced by
Fig. 8. SEM photograph of a 200 × 200 μm² device supported by four elastic beams.

Fig. 9. Close-up of the gap between drive and force balancing electrodes.

Fig. 10. SEM photograph of pressure sensing diaphragm.

one atmosphere of pressure.

VI. HERMETICALLY SEALED DEVICE

A significant drawback of the exposed actuator device is its susceptibility to particulate contamination that could be easily trapped in the small actuator gap. The device reported in this section overcomes this problem by enclosing the actuator in a hermetically sealed cavity that permits a lower gap. This is the result of folding the open-actuator device on itself. This device topology not only solves the contamination problem but also resulted in a significantly simpler process with fewer masks. The main difficulty associated with this device arise during the sacrificial etching of the actuator since the actuator plate must be prevented from adhering to the walls of the corresponding enclosing vacuum cavity. The new device is fabricated using a reduced, 15 mask, surface micromachining process.

The electrostatic force balancing scheme used in our device is shown in the basic schematic of Figure 13. The device has three plates and two output terminals. The external pressure \( P_o \) deflects downwards a small area compliant sensing diaphragm of area \( A_s \). The sensing diaphragm is connected to a larger, electrically conductive force balancing plate of area \( A_d \) below it through a dielectric rigid joint. This joint also forms a stiff bossed region at the center of the thin sensing diaphragm. The sensing diaphragm is also attached to a much larger, stiffer restoring plate that in conjunction with the force balancing plate form a parallel plate electrostatic actuator. The top restoring plate also forms protective shell forms a vacuum cavity that completely encloses and seals the force balancing plate from the external environment.

For this device, the balancing condition is the same as Eq. (5); hence, \( P_o = (A_d/A_s) P_e \) and the drive electrode voltage obeys Eq. (6), where \( h_o \) is the nominal actuator gap. In this device we have used an area ratio of \( A_d/A_s = 100 \), and actuator gap of 0.5 μm, resulting in a drive voltage required to balance one atmosphere of 7.5 V.

Figure 14 shows a schematic of the actual device. The actuator is enclosed in a protective shell formed by the top restoring plate and the pressure sensing diaphragm. The bottom square plate of the actuator is formed with doped polysilicon. The plate is suspended by four crab leg beams that achieve a high vertical compliance in a small area.

In this device, the scaling of drive voltage is determined by the ratio of the electrode and sensing plates. The minimum sensing plate area is also set by the minimum diaphragm thickness which determines the plate rigidity. Both of these parameters are limited by the fabrication process. The maximum electrode area is limited by the maximum undercut distance that can be used without compromising the structural integrity of the device layers, and the minimum diaphragm thickness is determined by the finite selectivity of the process etchants.

The force balancing plate is formed by a 2 μm film of doped polysilicon. The suspensions beams are 175 μm long and 10 μm wide. The gap spacing is 0.5 μm. The outer shell and actuator restoring plate electrode is formed with a layer of polysilicon 3.2 μm thick that seals the balancing plate at a low vacuum. For the proper functioning of the device, this electrode should not experience any deflection. This is achieved with an array of support columns spaced 40 μm apart anchored to the substrate. These posts protrude through perforations in the enclosed force balancing plate. Electrical contact to the force balancing plate is established through the suspension beams using a dif-
fused polysilicon layer that is dielectrically isolated from the shell anchors.

The bossed sensing diaphragm is formed with a 0.15 \( \mu \)m layer of low stress polysilicon that deflects \( \approx 0.1 \mu \)m under a pressure of 100 kPa yielding a change of about 100 fF in the capacitance of the actuator. Since the diaphragm is mechanically connected to both actuator electrodes, it is necessary to use a 0.2 \( \mu \)m-thick silicon nitride dielectric spacer defined at the joint region of the sensing diaphragm in order to maintain good electrical isolation.

### A. Fabrication Process

The device is fabricated using conventional surface micromachining techniques with a 15 mask process. The device cross-sections at the major processing steps are shown in Figure 15. The process starts with the etch of an alignment key on (100) p-type 100 mm silicon wafers with a boron concentration of \( 10^{15} \text{cm}^{-3} \). Next a 1.6 \( \mu \)m layer of thermal oxide is grown. This thick oxide layer reduces the parasitic capacitance of the device to the substrate. This is followed by the deposition of a 0.4 \( \mu \)m layer of low stress silicon-rich silicon nitride.

The first structural layer of the device is the buried contact to the sealed force balance plate. This layer is formed by depositing 2 \( \mu \)m of LPCVD low stress polysilicon at a pressure of 160 mT at 590 \( ^\circ \)C. Contact regions to the suspension anchors as well as bonding pads are defined by selectively doping the polysilicon layer through ion implantation of \( 10^{16} \text{cm}^{-2} \) of As at 100 KeV. The next step is the deposition of a 0.4 \( \mu \)m dielectric layer of low stress silicon-rich silicon nitride at 835 \( ^\circ \)C and 350 mT that isolates the buried diffusion from the device plates. We use low stress nitride because of the reduced etch rate in HF or BHF. In this device, the distance that needs to be undercut is on the order of about 150 \( \mu \)m; therefore the nitride isolation layer must be thick enough to withstand the time necessary to remove the sacrificial layers completely.

Next, the first 1.5 \( \mu \)m thick phosphosilicate glass (PSG) sacrificial layer is deposited and densified by annealing in a \( \text{N}_2 \) environment at 950 \( ^\circ \)C for one hour. The PSG is then patterned with two different lithography and etch steps. The first step defines 10 \( \times \) 10\( \mu \)m\(^2 \) anchor and contact areas for the force balancing plate suspension beams. The exposed PSG and nitride isolation layers are etched down to the polysilicon buried layer by first etching the PSG in 5:1 BHF followed by plasma etching in CF\(_4 \) : O\(_2 \) at 100 mT and 100 watts. The completion of the etch is detected by measurement of the conductivity of the bottom doped polysilicon layer in some test patterns. The second step defines the mesa on which the force balancing plate rests by etching the PSG in 5:1 BHF.

A 2.0 \( \mu \)m layer of low stress polysilicon is then deposited and ion implanted with phosphorus at a dose of \( 10^{16} \text{cm}^{-2} \) at 100 KeV. This layer forms the force balancing plate.
Fig. 14. Simplified structure of surface micromachined force balanced pressure sensor.

Fig. 15. Simplified process flow

The next step is the formation of the top 3.2 μm thick polysilicon restoring plate and protective shell. The deposition is carried out in two steps. Since 0.5 μm of polysilicon is already present, the first step consists of depositing 1.0 μm of low stress polysilicon, implanting it with 2 × 10^{11} cm^{−2} P at 100 KeV, followed by deposition of the remaining 1.7 μm of polysilicon. Wafers are then annealed at 950 °C for 3 hours in N₂ to activate the dopants and reduce the residual stress in the polysilicon.
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Fig. 16. SEM photograph of a $250 \times 250 \mu m^2$ device with two suspension beams.

The small pressure sensing diaphragm is formed by first etching the thick 3.2 $\mu m$ polysilicon layer at the diaphragm area also defining the boss region. The etch is mostly done in a SF$_6$ : O$_2$ plasma with the last 0.3 $\mu m$ removed in a wet etch. A 150 nm layer of low stress polysilicon is then deposited to form the diaphragm. This is followed by a 1 hour stress relief anneal at 950 °C in N$_2$, that reduces the diaphragm residual stress to about 25 MPa. This step is crucial because the diaphragm deflection is very sensitive to the residual stress as the thickness is reduced (acting as a membrane [12]).

The restoring plate/top protective shell and bond pads are next patterned by etching 3 $\mu$m of polysilicon in in SF$_6$ : O$_2$ plasma followed by a final short wet etch in silicon etchant. The contact hole to the buried polysilicon is then opened by etching the underlying isolation nitride in a plasma with a 100 % over etch. The completion of the etch is verified with an electrical conductivity test in a probe station. Once the contact holes are defined, the sacrificial access holes are patterned with a plasma etch at the periphery of the device. These holes are 5 $\mu m^2$ spaced 10 $\mu m$ apart.

The wafer is next diced and then released at the die level. The samples are released in concentrated HF (49 % by weight) for 15 min. followed by etching in 5:1 BHF for 30 minutes. The samples are then rinsed for 20 minutes in water followed by supercritical CO$_2$ drying process to avoid stiction failure.

After releasing the device, the cavity is sealed by immediately transferring the sample to a SEMI PECVD deposition chamber. This sealing method is used because of the near line of sight deposition of the PECVD oxide film with very little encroachment into the device gap area. The chamber is evacuated to a pressure of 100 mT at a temperature of 200 °C, and a 2 $\mu$m layer of oxide is deposited so as to completely plug the 0.5 $\mu$m gap due to the PSG2 layer in the opening of the etch holes. The actuator is thus sealed at the deposition pressure of the oxide layer. The hermetically sealed actuator is thus protected from the medium in which the pressure measurement is carried out with only the pressure sensing diaphragm exposed.

The sealing oxide is then etched as a ring in the periphery of the device with an overlap of 30 $\mu$m of the etch holes. The oxide over the reference device is not etched in order to prevent the deflection of the diaphragm. The bond pads of the device are next carefully metallized by evaporation and wet etch of 1 $\mu$m of aluminum. This completes the fabrication of the device, and it is ready for testing and characterization.

Figure 16 shows a SEM photograph of a completed device with two suspension beams supporting the sealed force balancing plate. The device was then carefully torn apart to show the structural elements and the mechanical linkages. The three structural layers of the device are shown in the SEM of Figure 17. The diaphragm is broken to show the gap beneath it. The gap between the suspension beam and the outer shell is shown in the SEM of Figure 18. This gap is nominally 0.5 $\mu$m.

B. Experiments

The characteristics of the sensor are mainly determined by three different measurements. All capacitance measurements were recorded at 1 MHz using a high-precision HP4284A LCR meter with a resolution of 0.01fF. Pressure measurements were performed in a MMR vacuum probe station. The devices were tested as follows:

The response of the device to pressure was first measured.
The device was placed in the MMR vacuum probe station and electrical contact was made to the restoring plate and the enclosed force balance plate of the actuator. The zero bias capacitance was measured between the two plates as a function of the pressure. At a low pressure of 200 mT, the diaphragm is flat and the device shows a nominal capacitance of 2.12 pF. This capacitance is found to mostly due to the parasitic capacitance of the large bond pads of the restoring actuator plate electrode to the buried bottom polysilicon layer. It was found that during the fabrication of the device, the selectively doped polysilicon experienced considerable lateral diffusion thus forming large parasitic capacitances. The actual device capacitance is designed to be about 0.75 pF. This is measured by isolating the device area from the bond pad region and measuring the capacitance from the restoring area with reference to the bottom force balance actuator plate.

As the pressure is increased slowly to atmosphere, the diaphragm is deflected downwards resulting in a smaller capacitance. Capacitances for different pressures were recorded and plotted to obtain the C-P characteristic of the devices. Figure 19 shows a typical C-P curve for a device with support beams. The capacitance at atmospheric pressure is measured as 2.02 pF. The total capacitance change for 1 atmosphere change in pressure is about 100 fF. The capacitance change is non-linear because of the nature of the elongation developed by the boss diaphragm at large deflections.

The device was next placed at atmospheric pressure, and a DC bias voltage was applied between the force balancing and restoring plate drive electrodes as to provide a restoring force at atmospheric pressure. The restoring voltage was next increased slowly and the corresponding drive electrode capacitance was recorded. Figure 19 shows a capacitance vs. restoring voltage characteristic for a device with beam supports. The plot shows that the voltages needed to produce a capacitance equal to that due to one atmosphere of pressure change are less than 12 V.

The voltages needed to balance the deflection due to different pressures were next measured. The zero deflection capacitance of the device is first obtained by placing the device at 200 mT. At this pressure, the diaphragm is flat and the capacitance is measured as the value to which the middle plate has to be restored. The pressure is then increased in increments and the voltage needed to restore the capacitance to its nominal value at every step is recorded. Figure 20 shows a plot of the balancing voltage needed as a function of the pressure.

The plot shows roughly a square root dependence of the voltage with the pressure. The measurements indicate that a voltage of 12 V is sufficient to balance the deflection induced by one atmosphere of pressure. The measured balancing voltages also indicate that, with a more aggressive design, the drive voltages could be reduced to about 5 V.

These preliminary measurements of the the force balanced pressure sensor characteristics show that the voltages needed for closed loop operation are feasible for MOS circuitry; hence a conventional low voltage electronic circuit could be used to realize an ASIC closed-loop driver.
VII. SUMMARY

The design, fabrication and testing of two low voltage force-balanced pressure sensors is presented. The first device has an open actuator and the second an hermetically sealed actuator. Electrostatic force is used to balance the deformation of a diaphragm induced by an external pressure. A force multiplication scheme is used which balances 1 atm of pressure with electrostatic voltages of about 12-25 volts, thus proving the feasibility of a closed-loop pressure sensor using low-voltage electronics.

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