MEMS Capacitive Pressure Sensors: A Review on Recent Development and Prospective

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***Abstract*—Recently MEMS Capacitive Pressure Sensor gains more advantage over micromachined piezoresistive pressure sensor due to high sensitivity, low power consumption, free from temperature effects, IC compatibility, etc,. The spectrum of capacitive pressure sensor application is increasing, hence it is essential to review the path of technological development and further prospective of micromachined capacitive pressure sensor. This paper focuses on the review of various types of capacitive pressure sensor principle, MEMS materials used in fabrication, procedures adopted in microfabrication for silicon and polymer material diaphragm, bonding and packaging techniques used. Selected result on capacitive sensitivity, effect of temperature on capacitive sensitivity was also presented. Finally, the development of smart sensor was discussed.**

MEMS Capacitive pressure sensor, Review on pressure sensor, CDPS, MEMS Fabrication, MEMS Material, pressure sensor, MEMS (Micro Electro Mechanical System)

I. INTRODUCTION

A. Overview

Day to day the spectrum of pressure sensor application in medical, aerospace, automobile, industrial and commercial application has drastically increasing. Due to the recent advancement in the microscale fabrication technology micromachined pressure sensor are being fabricated for the pressure range from ultra low pressure to extremely high. At present silicon and polymer material replaces traditional metal diaphragm pressure sensor. This helps to reduce the material and fabrication cost thereby reduces the product cost/unit. Micromachined pressure sensor are gaining importance due to its small size, lightweight, integrateable to the IC fabrication process and smart interface features. It also shows high reliability.

Piezoresistive, capacitive, optical, resonance, acoustic transduction principle used in the recent work in the development of micromachined pressure sensor modeling, design and fabrication was reviewed in [1]. Among these piezoresistive and capacitive pressure sensor principle were widely adopted in various works. Many commercialized MEMS pressure sensor [2-6] uses piezoresistive technique as transduction mechanism from pressure to change in resistance. Most researchers preferred piezoresistive technique, because the properties of silicon material were well established and the facilities of existing silicon foundry can be used for fabrication in batch production.

Piezoresistive pressure sensor has high gauge factor but it has 0.27% per °C of temperature coefficient of piezoresistivity (TCP). This limits the operating temperature and requires temperature compensation circuit.

Micromachined pressure sensors are fabricated using bulk and surface micromachining techniques [2-3], [6]. High aspect ratio structure is fabricated using bulk micromachining. Surface micromachining is preferred for larger surface area but for few micrometer depth.

B. Governing Equation for Diaphragm Membrane Deflections

In most of the work; square, rectangle or circular diaphragm structures are used in fabrication. Maximum deflection occurs at the center of diaphragm for built in edges,. Timoshenko gives the differential equation governing the deflection of a plate with uniform pressure acting normal to the surface in [7].

$$\frac{\partial^4 w}{\partial x^4} + 2\frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} = \frac{P}{D} \tag{1}$$

The maximum deflection at the centre of a uniformly loaded square plate with built in edges is given by the equation (2).

$$w_{max} = 0.00126 \frac{Pa^4}{D} \quad (2)$$

and,

$$D = \frac{Eh^3}{12(1-v^2)} \quad (3)$$

Where w is deflection at point of (x, y) coordinates, P is the differential pressure between two sides of a diaphragm, D is flexural rigidity, a is the length of diaphragm, E is young modulus, υ is Poisson's ratio and h is the thickness of the diaphragm.

The centre deflection of circular diaphragm is given as

$$w(r) = \frac{Pa^4}{64D}\left[1-\left(\frac{r}{a}\right)^2\right] \quad (4)$$

Where $w(r)$ is deflection at radial distance r from the center of diaphragm, a is radius of the diaphragm.

Design and fabrication of pressure sensor with competitive price plays important role in the product development cycle. To reduce product cost/unit, pressure sensor designer has to optimize in the areas of material selection, fabrication technique and sensor performance. The process window technique [8] helps in optimizing the selection of membrane thickness of pressure sensor, effects of pressure sensor dimensions, pressure sensitivity, resolution, and burst pressure.

C. Organization of paper

This paper focus on the review of micromachined MEMS capacitive principle pressure sensor. It is vital to selsct material for MEMS fabrication. Section II explains MEMS material and their properties for structural and packaging material used in the fabrication of MEMS capacitive pressure sensor. The principle of capacitive pressure sensor with various mode of operation is explained in section III. It also covers electrostatic and piezoelectrically tuned capacitive pressure sensor. Section IV explains acoustic pressure sensor using capacitive principle.

Various micromachining technique used in the fabrication of capacitive pressure sensor was also discussed in section V. This section discussed the fabrication technique adopted in the fabrication of silicon diaphragm, ceramic diaphragm for high temperature application and polymer diaphragm for high sensitivity, condenser microphone was also discussed.

Section VI explains various bonding and packaging methods adopted in micro sensor packaging. Reliability issues in MEMS components and packaging was also analyzed. Recent development and advancement took place in capacitive pressure sensor was discussed in section VII followed with an outlook of capacitive pressure sensor.

II. MEMS MATERIAL

Silicon and silicon compounds are widely used in the fabrication of micro pressure sensor [9]. Recently the application of polymer material has increased due to various advantages like structural stability, more flexible, good electrical and thermal characteristics with a limitation in high temperature application.

Silicon material was widely used in pressure sensor fabrication, which can be processed by surface and bulk micromachining. The material propertie and fabrication procedure are well defined and easily available for silicon material. Single crystal or polysilicon diaphragm membrane is used as pressure sensing material in most of the works. The sensitivities of silicon membrane are increased in two ways, one by reducing the thickness of the diaphragm membrane and other by doping with P^{++} impurity as discussed in[10]. Thickness of the diaphragm membrane decides the pressure level, thicker is suitable for high-pressure application and vice verse. The effect of temperature coefficient resistance (TCR) is another problem with the silicon; it has non-linear decrease in materials resistance with increase in temperature.

In most of the micromachined capacitive pressure sensor, silicon substrate is used as sensor structure and polysilicon or polymer materials like polyimide, kapton polyimide, SU-8, Liquid crystal polymers are used as diaphragm membrane as adopted in [10], [11].

Silicon pressure sensing membrane are preferred for high-pressure measurement, typically pressure range from (80–335)kPa yields capacitive sensitivity ranges from (0.02 to 0.2)pF/kpa. Moreover, silicon diaphragm is also used to measure ultra low pressure in the pressure range of (0-100)mTorrs [11]. Polyimide material is more suitable for low pressure sensing application with pressure range of ±100kPa with capacitive sensitivity of (0.0013 - 5)pF/kPa as reported in [10].

Table I and Table II shows, the properties of MEMS material used in various work for design, analysis and fabrication. Few important parameters of MEMS material such as Young's modulus, Poisson ratio, density, thermal conductivity, coefficient of thermal expansion, etc.

TABLE I
MEMS Material Properties [12]

Material Parameters	**single crystal silicon**	**Poly-silicon**	**SiN (LPCVD)**	**SiO_2 (LPCVD)**	**Gold**	**Al**	**SiC**	**Stainless steel**
Young's Modulus E (GPa)	130-187	120-175	254-385	73	78	70	700	192-200
Density (Kg/M^3)	2300		3100	2500	19300	2700	3200	7900
Fracture strength (GPa)	0.6-7.7	1-3	14	8.4	N/A	N/A	21	21
Poisson ratio (υ)	0.25-0.36	0.13-0.36	0.28-0.3	0.17	0.42	0.33	0.16-0.24	0.30
Thermal conductivity (W/mK)	157	34	19	1.4	315	247	71-490	33
Linear thermal expansion coefficient ($ppm/^oK$)	2.33	2.33	2.7-3.7	0.55	14.2	25	4.2-5.6	4.4-27
Thermal Conductivity (J/Kg/K)	700		700	740	128	900	590-1000	420-500
Electrical resistivity (MΩ)			N/A	N/A	$2.3x10^{-8}$	$2.6x10^{-8}$	N/A	$5.5x10^{-7}$
Piezoresistive gauge factor	~100	10-30	N/A	N/A	1-4	1-4	N/A	N/A

TABLE III
Properties of Polymer Material [12]

Material Parameters	**LCP**	**Polyimide**	**Epson(SU-8)**	**PMMA**	**Parylene**	**PDMS**
Dielectric Constant (60 Hz)	2.8	35	5.7	4	2.65-3.15	2.7
Dielectric factor (60 Hz)	0.004	0.002	0.007	0.02-0.04	0.02-0.0002	0.001
Moisture absorption (%)	<0.02	2.8	N/A	N/A	0.01-0.06	0.10
Glass transition temp (^oC)	145	360-440	195	105	160	125
CTE ($ppm/^oC$)	0-30	20	20-30	50-90	35-69	30
Tensile Strength (MPa)	180	200-234	50	48.3-72.4	45-75	6.2
Tensile modulus (GPa)	7-22	2.5-4	4-5	2.24-3.34	2.4-3.2	0.0005-0.1
Elongation at break (%)	1-5	10-150	<1	2-5.5	10-200	100
Density (g/cm^2)	1.4	1.42-1.53	1.2	0.9	1.1-1.4	1.05
Representative patterning method	Laser plasma Etch	Photo definition wet etch, plasma etch	Photo definition plasma etch	Photo definition wet etch, plasma etch	plasma etch	Molding plasma etch (slow)

III. CAPACITIVE PRESSURE SENSOR

Micromachined pressure sensors are miniaturized versions of their macroscopic counterparts [1]. Diaphragm based sensors were designed to measure the characteristic of deformable diaphragms due to applied pressure. Figure 1, illustrates a schematic crosssection of a typical pressure sensor diaphragm. The reference pressure can be a sealed chamber or a pressure port, so that absolute or gauge pressures are measured respectively. The shape of the diaphragm as viewed from the top is arbitrary, but generally takes the form of a square or circle. These shapes behave similarly for a given applied stress.

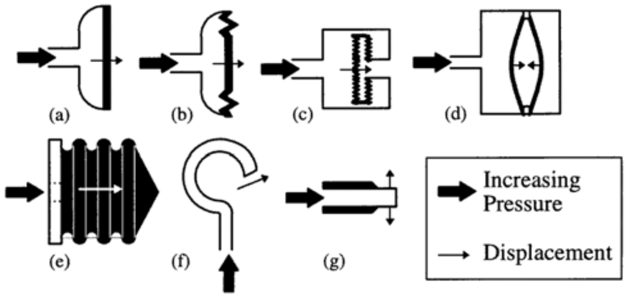

Fig. 1. Macroscopic pressure sensors : (a) simple diaphragm, (b) corrugated diaphragm, (c) capsule, (d) capacitive sensor, (e) bellows, (f) Bourdon tube, (g) straight tube (adapted from [1]).

A. Absolute Pressure Sensor

The schematic of parallel plate capacitive structure is as shown in figure 2. Capacitance of parallel plate capacitor is given by

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d} \quad (5)$$

where C is the capacitance of parallel plate, ε_0 is $8.854\times10^{-12} F/m$, ε_r is relative permittivity of dielectric medium, A is effective surface area, d is the separation distance between the membrane.

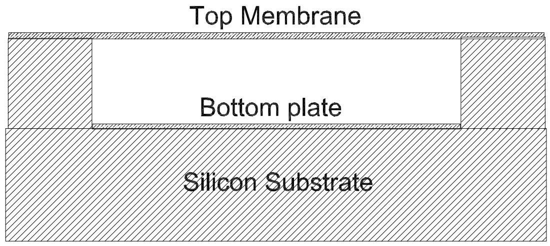

Fig.2. Schematic diagram of capacitive pressure sensor structure (adapted from [31]).

Capacitive pressure sensors are designed to measure absolute pressure are discussed in the references [13-20]. The structure has chamber with a reference pressure (absolute pressure <1mTorr) is closed off by an elastic membrane that is exposed to an extreme pressure. Together with the opposite side of this chamber, the electrically conductive membrane forms parallel plates of capacitive sensor. The diaphragm membrane is deformed due to the pressure difference between the external pressure and the internal reference pressure. The capacitance of this capacitor changes due to the variable distance between the membrane and the backside of the chamber act as a co-operating electrode. The external pressure can be determined from this change in capacitance [15].

Absolute pressure sensor has high sensitivity, but small dynamic range. The dynamic range is enhanced by electrostatic servo capacitor technique [17]. In absolute pressure sensor, most of the diaphragm membrane are planar [18] and with center bossed [17], [19-20]. The advantage of vacuum sealing is to prevent the effect of trapped gas expansion [20].

B. Touch Mode Pressure Sensor

Capacitive pressure sensor produces a quadratic change in capacitance for the applied pressure. It has nonlinear capacitive response. Smooth contact capacitive pressure sensor with parabolic shape and donut cavity was developed in [10]. Polyimide diaphragm was used to increase capacitive sensitivity. Touch mode capacitive pressure sensor produces close linear capacitance to pressure (C-P) relationship as discussed in [10], [21-24]. The schematic diagram of touch mode pressure sensor for normal and touch mode is as shown in figure 3. Most of the touch mode capacitive pressure sensor designed with bossed diaphragm membrane and its schematic as in figure 4.

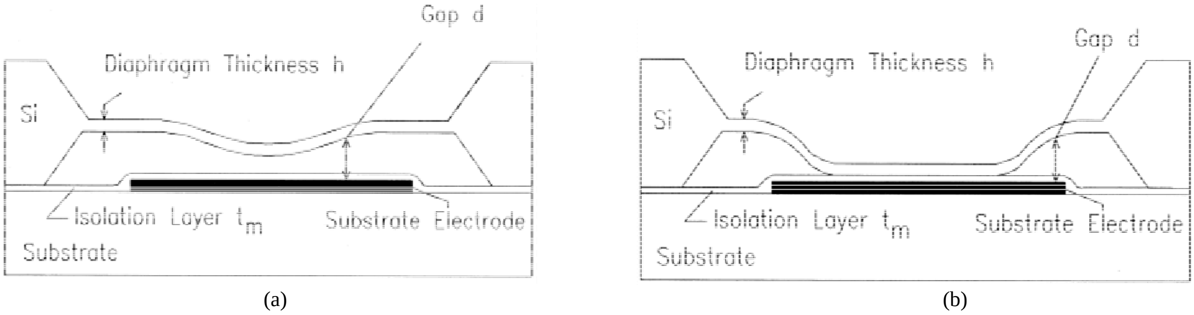

Fig.3. Schematic diagram of principle of Touch mode pressure sensor (a) Normal mode operation (b) Touch mode operation (adapted from [21]).

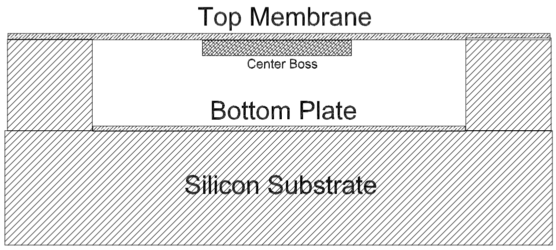

Fig.4. Schematic diagram of bossed diaphragm capacitive pressure sensor [29].

C. Capacitive Differential Pressure Sensor (CDPS)

The capacitive differential pressure sensor uses the pressure difference between two pressure sources. CDPS measures the change in pressure from the deflection of diaphragm due to the measurand pressure [25-34]. The pressure cavity is filled with the reference pressure sealed with the diaphragm membrane. This sensor is capable of measuring pressure below or above the reference pressure. When the measurand pressure is below the reference pressure the diaphragm deflects outwards the cavity. The distance between the plate increases there by effective capacitance decreases, and vice versa. The schematic of CDPS structure is as shown in the figure 5.

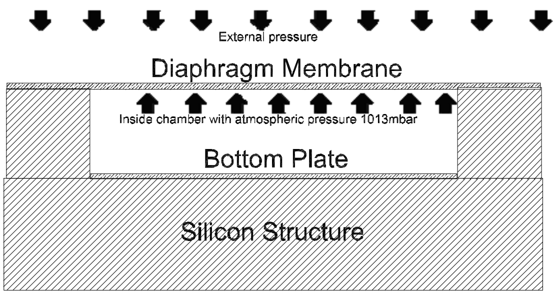

Fig.5. Schematic diagram of principle of CDPS Structure (adapted from [26]).

D. Capacitive Pressure Sensor in Biomedical Application

Capacitive pressure sensing technique gains more importance in biomedical application due to high sensitivity and dynamic response [35-40]. Polymer material is mostly preferred due to biocompatibility property. Microfabricated implantable intraocular pressure sensor and home uterine activity monitoring with wireless interface capability is discussed in [36] and [38]. Interdigitized capacitive sensor was proposed in [37] and [39] for pediatric postoperative monitoring application and pulmonary function diagnosis respectively.

E. Electrostatic Tuned Capacitive Pressure Sensor

Capacitive vacuum-sealed sensor has high sensitivity, but lacks in dynamic range. The capacitance is determined by the separation between the two electrodes. This is achieved by the application of voltage across the parallel plate to generate electrostatic force. This enhances the capacitance of the sensor as discussed in [41-43].

F. Piezoelectrically Activated Capacitive Pressure Sensor

Piezoelectrically activated tunable MEMS capacitor was designed, fabricated and characterized in [44]. This result reports highest capacitive tuning ratio of 0.46pF to 10.02pF with a tuning voltage of 35V.

G. Capacitive Pressure Sensor Comb Drive

Micromachined comb drive capacitive sensing was widely used in many micromachined accelerometers and MEMS RF tuning circuits. Major advantage of this structure gives large capacitance change per unit displacement. The suitability is proposed for pediatric postoperative monitoring application [37] due to its high sensitivity and wide dynamic range.

The design of comb drive unit consists of top and bottom membrane with comb-interdigitized electrode as shown in figure 6. The capacitance of the sensor is the function of the separation of bottom plate and top plate membrane. As the separation distance between the plates increases, the capacitance decreases and vice versa. Figure 7 shows the characteristics of capacitive sensor. The effect of temperature on capacitive sensitivity is shown in the figure 8. It is estimated the effect is very minimum (<0.03%) for capacitive technique on comparing with piezoresistive counterpart with (0.27%) TCP.

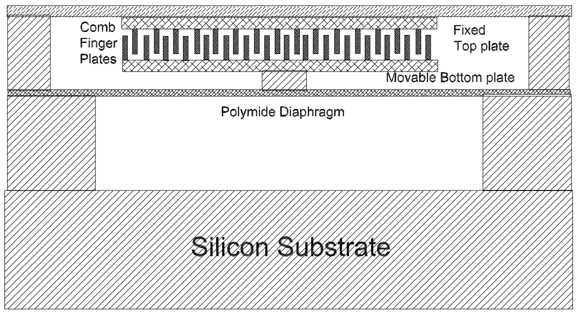

Fig.6. Schematic diagram of CDPS comb plate Structure (adapted from [31]).

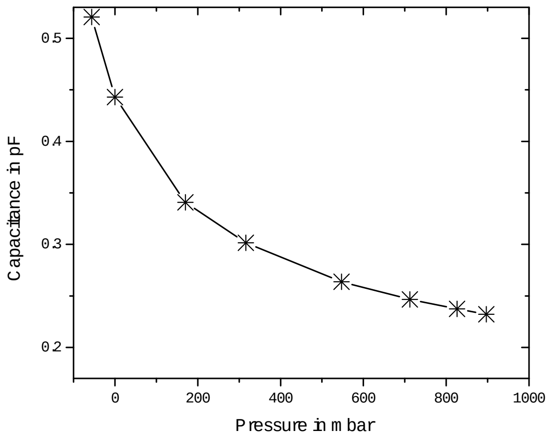

Fig.7. Characteristics of Pressure Vs Capacitance (C-P).

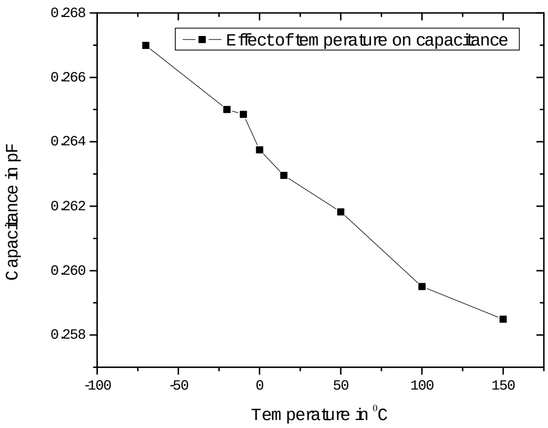

Fig.8. Effect of temperature on capacitive sensitivity.

IV. Capacitive Principle Acoustic Pressure Sensor

MEMS capacitive microphone holds largest share in MEMS components market. It is widely used in audio application. The principle of capacitive microphone is simple parallel plate differential capacitor. The micromachined microphone has three circular parallel plates, namely the middle solid diaphragm and top and bottom perforated back plates. The structured plates of the microphone are made polysilicon conductive plate, which provide capacitance between the diaphragm top and bottom back plates. The capacitance value of both is altered, when an acoustic wave impinges on the microphone and deflects the diaphragm. Finally, the differential capacitance change is converted to an output through various types of interface electronics circuit.

A. Micromachined Silicon Condenser Microphone

Capacitive or condenser microphones are mostly fabricated using silicon structure [45-46]. Microphone diaphragm is fabricated with low stress polysilicon perforated membranes that are separated by an air gap. The lower membrane bends due to a pressure difference, while the perforated membrane remains steady and the capacitance between the membrane changes.

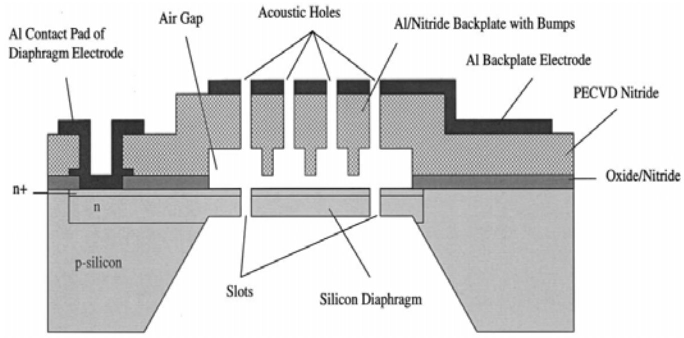

Fig. 9. Cross section of slotted silicon microphone (adapted from [46]).

Figure 9 shows the cross section of slotted silicon microphone. Electrical insulation between the membranes has been achieved with silicon dioxide and silicon nitrate layers deposition, aluminum is used for making electrical contacts in packaging. The mechanical parameters have been converted in to the electrical equivalents, such that the effective moving mass of the bending membrane plus the attached air appeared as inductance, the spring constant of the membrane and the back chamber as capacitance and the flow resistance of pressure equalization holes and upper membrane perforation holes as resistances.

B. Back Plate Condenser Microphone

The micromachined pressure sensor consists of a thin silicon membrane supported by a thicker silicon rim [47-51]. The membrane is fabricated by electrochemical etching; etch away the bulk silicon on a defined region. The structure plates of the microphone are made of phosphorus-doped polysilicon to make them conductive, which provides two capacitors between the diaphragm and top/bottom back plates [49]. Dual back plate condenser microphone for aero acoustic environment was developed [50] and the physical model schematic is as shown in the figure 10.

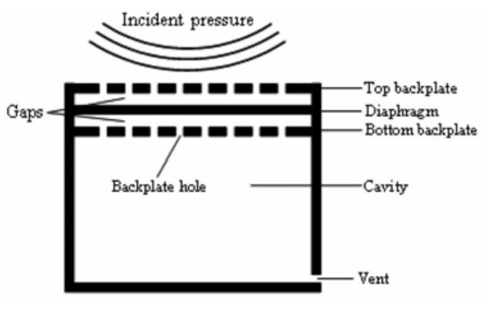

Fig. 10. Models of a dual backplate capacitive MEMS microphone physical model (adapted from [49]).

C. Corrugated Diaphragm Condenser Microphone

The diaphragm converts pressure into mechanical stress. The major advantage of using the corrugated diaphragm membrane is to reduce the residual stress on diaphragm [52] in turn to increase the sensitivity. The cross section of corrugated silicon microphone is as shown in figure 11.

A flexible perforated aluminums diaphragm was also used to measure the acoustic pressure, which is kept over the back plate [53]. Polysilicon corrugated diaphragm was also fabricated and tested was reported in [46].

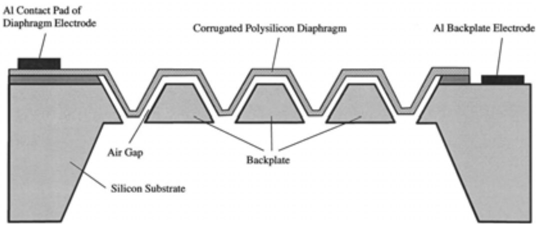

Fig. 11. Cross section of corrugated silicon microphone (adapted from [46]).

D. Sensitivity and Frequency Enhancement in Condenser Microphone

Condenser microphones are fabricated with monocrystalline silicon as one body with a wide air gap and a stiff back plate [54]. This thin diaphragm is vibrated by sound pressure and fixed back plate make up the condenser, which is charged by an external bias voltage. The capacitive change is converted as voltage change. Sensitivity is increased by increasing the back plate biasing voltage. The diaphragm structure should have natural frequency higher than the working frequency range.

V. FABRICATION OF CAPACITIVE PRESSURE SENSOR

Microfabrication technique or process involves physical or chemical treatment on materials. Fabrication engineer should have knowledge on various fabrication techniques such as photolithography for patterning, Ion implantation to alter electrical properties of material, oxidation process for electrical isolation and to create process window, chemical vapor deposition to develop thin film microstructure, physical vapor deposition for thick film deposition, Bulk and surface micromaching process by wet or dry etching.

A. Silicon Diaphragm Fabrication

Most of the capacitive pressure sensors used silicon or polysilicon diaphragm membrane. Mono crystalline silicon uses bulk micromachining process. This is accomplished using suitable mask with KOH etchant [17], [19-20], [55-57]. Surface micromachining process has been adopted for polysilicon membrane fabrication.

B. Ceramic Capacitive Pressure Sensor

Silicon carbide (SiC) diaphragm membrane proposed for high temperature application [58-60] is grown on the surface of silicon substrate. This is polished by chemical mechanical polishing (CMP) to remove surface roughness and bonded to the cavity substrate by heating the wafer to 1000°C. Then it is annealed at room temperature. Silicon substrate is removed using TMAH solvent. Screen printed technology is also used in the fabrication of ceramic diaphragm membrane [59].

C. Polymer Diaphragm Fabrication

In recent works polyimide material was widely used as diaphragm membrane material [10], [23], [30-31], [61]. It has good mechanical and thermal stability up to 450°C. It has good adherence with deposited material and epoxy bonding. It is best choice for biomedical application due to biocompatibility and provides high sensitivity. Polyimide material was also used as diaphragm membrane material for aircraft altimeter to measure the pressure below 14.7Psi.

Conductive plates were developed on polyimide diaphragm by depositing Cr/Au/Cr with material thickness 100Å/1000Å/100Å [23]. Another work reports Ti/Cu/Ti materials with thickness of 100Å/2000Å/500Å [61]. The polyimide layers are anisotropically etched using reactive ion etching (RIE). Metallization can be formed by deposition using DC sputtering.

D. Condenser Microphone Fabrication

Silicon or polysilicon membrane with perforated or corrugated fabrication procedure were discussed in [46-48], [50], [54]. Perforated aluminum diaphragm membrane fabrication process was explained in [53]. The diaphragm and the back plate structure are etched out on P-type (100) silicon substrate using 40% KOH anisotropic etchant and potential dependent stop. The ventilation holes in the back plates have been realized with both dry and wet etching. The diaphragm back plate wafers are assembled by wafer bonding.

VI. BONDING AND PACKAGING TECHNIQUES

Wafer bonding involves bringing two-wafer close with proper spatial alignment to form permanent bond under proper physical and chemical conditions. Packaging provides mechanical support, electrical connection, protection for sensor and associated circuit from environment.

A. Silicon Fusion Bonding (SFB)

Single crystal silicon wafers can be reliably bonded with near perfect interfaces without the use of intermediate layer. Pressure sensor fabricated with SFB exhibit greatly improved performance over other devices, made with conventional processes. SFB is also applicable to many other micromechanical structures

[55-56], [65]. Structured wafers can be bonded by fusion bonding. The surfaces of the wafers are cleaned using a RCA solution. Bonding is performed in an EVG 520 HE bonder in vacuum pressure at room temperature, after bonding the wafers are annealed at 1000°C for 30 minutes [65-66]. Strong and void less bonds are achieved with this technique. Silicon/silicon bonded ultra miniature catheter tip transducer chip for vivo pressure measurement in biomedical application and for very high-pressure measurement for industrial application are discussed in [66].

A novel low temperature wafer bonding with process temperature lower than 160^{o}C was proposed which applies, In-Sn (Indium-Tin) alloy to form the interface of wafer bonding [67]. This gives very good tensile stress, good reliability and no traces of degradation.

Anodic bonding is another method of low temperature fusion bonding. In this method silicon wafer is bonded with pyrex glass or any metal. The bonding is done at temperature below 450°C by the application of electric field of 1000V [20-21], [68]. Glass wafer bonding based on the formation of chemical covalent bond by diels-alder cycloaddition reaction was explained in [69]. In this technique bonding done at 200^{o}C.

B. Thermo Compression Bonding

The sensor structure has different layers to be bonded together. As an example, the upper and bottom electrodes of the sensor are fabricated in different wafer, then aligned and bonded by the thermo compressive bonding. Before bonding the wafers are cleaned with a modified RCA solution, washed by deionized water, and brought into contact with bonding machine. Bonding atmosphere with a vacuum of 1.2×10^{-4} mbar [17]. To strengthen the bonding, a thermal cycle of 1000^{o}C for 60min and later at 1200^{o}C for 60min in nitrogen atmosphere was used [58]. Finally, these two parts of wafer were thermocompressively bonded. The bond quality is adversely affected by the presence of any organic material absorbed on the gold surface, they were cleared with an ultraviolet ozone exposure after which the surface were aligned, contracted, and heated to 350^{o}C on a hotplate while a pressure of about 1.5bar was applied for 2min. Thus, the upper electrode was finally transferred to the substrate. This technique is also suitable for polymer materials [62-63].

C. Polymer Bonding

Bonding of silicon with polymer was done by epoxy bonding [10]. Glues are used to bond the polymer with polymer material and the metal with polymer was bonded. The technique is more suitable for the substrate material, which have a severe temperature limitation.

D. Wafer Level MEMS Packaging

Packaging of MEMS components is similar to IC packaging technologies. The purpose of packaging is to provide environmental protection, electrical signal conduit, mechanical support and thermal management path. Table 3 shows the various wafer bonding techniques used in sensor packaging [70].

TABLE 3
Comparison of Various Bonding Techniques [70]

Bonding techniques	**Anodic**	**Glass fit**	**Direct Wafer Bonding**
Required Bonding temperature ^{o}C	300-500	400-500	1000
Required Applied Pressure (Pa)	N/A	100,000	N/A
Required Applied Voltage (V)	100-1000	N/A	N/A
Required Surface Roughness (nm)	20	N/A	0.5
Required Precise gaps	Yes	No	
Capable of Hermetic Sealing	Yes	Yes	Yes
Achievable Vacuum Level (Pa)	0.001	1300	0.1

Packaging a vacuum-sealed integrated capacitive barometric pressure sensor at wafer level is discussed in [71]. In this interface, circuit is integrated directly with in the sealed reference cavity to protect the device from parasitic environmental effects. The device fabrication process for BiCMOS circuitry uses a dissolved wafer process and is compatible with bulk and surface micromachined transducer [72]. There is a limitation in commercialized wafer bonding technology, such as 1000^{o}C for silicon fusion bonding and 450^{o}C for anodic bonding. A novel low temperature wafer level packaging at 160^{o}C is reported in [73]. In-Sn alloy is used to form an interface in wafer bonding and it shows high reliability.

E. Sensor Packaging

Sensor packaging based on flex circuit technology is explained in [74]. The components well packed with standard packaging cover case. For mounting, silicon adhesive was also used. To reduce the built up stress during packaging, all assembly temperature were kept to a minimum. Curing of adhesive bond was done at room temperature.

O-ring clamping is also used to provide a hermetic sealing on MEMS pressure sensor packaging. It provides simple, powerful packaging concept suitable for various environments conditions [75]. Even for large misalignment between die, O-ring packaging induces small output offset. O-ring clamping is also suitable for long-term reliable packaging [76]. It is tested with thousands of operating cycle and shows good reliability.

F. Reliability in MEMS Packaging

MEMS and microsystems packaging are more complex than ICs packaging. This is due to the complexities in MEMS structure [77]. MEMS packaging provides support and protection to the core components. It should also protect interfacing circuits and transduction elements from mechanical or environmentally induced damage. Packaging should also provide integrated protection to the sensing or actuating elements interfaces with working media.

Interface between the core elements and the working media is a unique feature in MEMS packaging. Ensuring proper functioning of the contacting MEMS components and their protection from damages inducted by interfacing media became major challenge to engineers in design manufacture and packaging of MEMS. Packaging redistributes electrical signal paths from tight path dimension to over layer and more manageable dimensions to over larger and more manageable interconnection leads. The mechanical support provides rigidity, stress reliable and protection from the environment. Power distribution also needs to be taken into account for optimum packaging scheme. Packaging provides robustness in handling and testing MEMS components that are integrated with associated electronics on the same chip produce better electrical output.

G. Reliability Issues in MEMS Packaging

Temperature is one of the major problems in most of the MEMS component failures. Thermal management provides proper evacuation of heat from the thermal stress areas, which helps to sustain proper operation for the product lifetime. Therefore, good sealing avoid such failure. Delimitation may cause catastrophic failure (or) degrade device function due to alteration of material characteristics. In anodic bond packaging, thermal stress must be controlled and maintained at low level [79] to avoid failure.

A packaging must also provide communication links through interconnects, heat produced by the functional devices are removed through heat sinks. In MEMS, several failure mechanisms occur due to primary sources, which include failure due to stiction and wear. Environmentally induced failure includes thermal cycling, vibration, shock, humidity, radiation effects, etc.

VII. SMART CAPACITIVE PRESSURE SENSOR

Smart capacitive pressure sensor has lots of potential for commercial application. It has digital read out chip are directly integrated on the same substrate by connecting chip to the sensor. This integration helps to speed up the processing and reduction of the parasitic effect. Signal processing such as multiplexing or conversion of capacitances to frequency or voltage is discussed in [80]. A fully integrated CMOS-MEMS pressure sensor including frequency to digital converter on the same CMOS die. The expert feature reduces production cost and noise sensitivity.

Wireless pressure sensor was developed to reduce package size and cost. Improved lifecycle, robustness facilitate the wide spread use of capacitive pressure sensors in process [81]. A self-validating pressure sensor is proposed including structure design of the transducer, fault detection and diagnosis method and signal transmitter based on double digital signal processors (DSPS) systems [82].

VIII. OUTLOOK

A review on capacitive principle pressure sensor reveals the advantage over piezoresistive pressure senor. It shows high sensitivity, dynamic, free from the effects of temperature, immune to environmental contamination, ease of interface and biomedical application. The fabrication is also simple on comparing with piezoresistive sensor. The only limitation lies on dynamic range of capacitance. This issue is compromised by increasing the senor area or by an array of sensor. A novel idea to improve the capacitance is by introducing a high permittivity gas in the sensor cavity.

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