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Micromachined Pressure Sensors: Review and Recent Developments

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ABSTRACT

Since the discovery of piezoresistivity in silicon in the mid 1950s, silicon-based pressure sensors have been widely produced. Micromachining technology has greatly benefited from the success of the integrated circuits industry, borrowing materials, processes, and toolsets. Because of this, microelectromechanical systems (MEMS) are now poised to capture large segments of existing sensor markets and to catalyze the development of new markets. Given the emerging importance of MEMS, it is instructive to review the history of micromachined pressure sensors, and to examine new developments in the field. Pressure sensors will be the focus of this paper, starting from metal diaphragm sensors with bonded silicon strain gauges, and moving to present developments of surface-micromachined, optical, resonant, and smart pressure sensors. Considerations for diaphragm design will be discussed in detail, as well as additional considerations for capacitive and piezoresistive devices.

Keywords: MEMS, micromachined pressure sensor, review

1. INTRODUCTION

Microelectromechanical systems (MEMS) have received a great deal of attention in recent years. This is due not only to the excitement of a nascent technology, but also because of the great promise of increased miniaturization and performance of MEMS devices over conventional devices. In general for a new device to gain market acceptance, it must pass the 20% rule of thumb: a new product must be either 20% less expensive or perform 20% better for the same price as an existing product. Many MEMS devices will meet or exceed both requirements simultaneously[1]. The 1995 market for micromachined pressure sensors was approximately $US 1 billion, and is expected to grow to $US 2.5 billion by 2005[2]. Furthermore, the total MEMS industry as a whole is expected to grow from $US 1.5 billion in 1995 to approximately $US 10 billion by 2000[3]. While actual future market size is debatable, most agree that the market will grow at a large rate[1].

There are many real and perceived advantages of micromachined pressure sensors over their "macromachined" counterparts. These include:

- leveraging on existing IC infrastructure
- batch manufacturability
- excellent mechanical properties of single crystal silicon
- small form factor
- potential for on-chip integration of controlling electronics

1.1. Leveraging from IC industry

The above advantages of micromachined pressure sensors stem from the fact that many of the manufacturing processes and tools are borrowed from the integrated circuit (IC) industry, such as photolithography, oxidation and diffusion, wet cleaning and etching, thin-film deposition, metallization, ion implantation, and others. Many of these are used directly, while others have been modified or developed to meet the specific needs of micromachined devices[4]. This leveraging from a large industrial base reduces development costs. In addition, IC fabrication is a batch process: hundreds to thousands of units are simultaneously created on a single wafer; wafers are typically processed in lots of 25 to 100[2]. The net result is large volume and low unit cost[2,5]. For example low cost, disposable catheter blood pressure sensors are now available in volume[2,5], as are tire pressure gauges which cost about $US 10.[6]

High volumes are not only enabled by IC batch techniques, they are also required in order to achieve low cost. Despite the leveraging effect, overhead costs are still high. It is well known that in the IC industry the price of admission – equipment, clean room facilities, and highly trained staff – is prohibitive, with the newest IC foundries costing in excess of billions of

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$US to build and equip. Fortunately the actual cost of a micromachining facility is actually orders of magnitude less, since micromachinists typically use existing foundries or equipment sets that are at least one or two generations behind state-of-the-art. Nevertheless, the high overhead costs of using microfabrication techniques makes the cost of doing business roughly independent of the number of devices produced[7]. Hence high throughput without sacrificing quality is a major goal of manufacturers.

Complicating the high volume/low cost equation that holds true for IC's are the requirements of packaging and testing of micromachined sensors. While the packaging and testing of IC's is currently highly automated, packaging, functional testing, and calibration of sensors require exposure to the measurand – in this case pressure. Existing IC equipment is poorly suited to modification for pressure inputs. Trimming and calibration is commonly done for every part. All told, packaging and testing can account for 75% of the manufacturing cost of a micromachined part[8]. Because of these complications, it is generally agreed that designing the package should be done at the same time as designing the transducer itself[9].

For some applications size and weight constraints may be as important or more important than cost. For these applications, micromachined devices enable new applications and more widespread deployment. In aeronautical, automotive, and space applications, there exists the simultaneous desire of decreased weight and increased instrumentation to achieve the goals of better control and efficiency. The current faster, farther, cheaper philosophy of NASA requires drastic reduction of launch weights, which in turn requires reduction of instrumentation weight or quantity or both[10]. In biomedicine, catheter-based devices must occupy small volume, or they cannot be used at all.

1.2. Mechanical properties

The properties of materials for micromachined sensors vary according to the type of technology used. In bulk micromachined sensors, where the desired mechanical structure is formed from patterning the material of the single crystal silicon substrate, the properties of single crystal silicon are of importance. In surface micromachined pressure sensors, where the desired structure is made of thin films on the surface of the substrate, thin film properties are important. The mechanical properties of single crystal silicon are excellent, as reported in a landmark article by Petersen in 1982[11]. It has high strength, high stiffness, high mechanical repeatability, high Q, and low mechanical hysteresis. Furthermore, single crystal silicon is available in large quantities with high purity and low defect densities. Piezoresistive gauge factors in silicon are higher than in metal, but temperature coefficients of resistance (TCR) are high. Because of high TCRs, silicon microsensors often require temperature compensation techniques[2].

Surface micromachined materials do not have the same high quality as single crystal silicon. These materials are usually polycrystalline or amorphous thin films. Typically thin-film stress exists in these materials, which arises from thermal expansion mismatches and unfavorable energetic configuration after deposition[7]. Micromachinists often try to minimize these stresses, and a slight tensile stress is usually preferred to compressive stress. Two notable thin-films which are used as structural layers in surface micromachining are micromechanical or fine grained polysilicon and low stress nitride.

Micromechanical or fine-grained polysilicon[12,13] is formed by low pressure chemical vapor deposition (LPCVD) from decomposition of silane gas at below 600 °C. As deposited, the films are amorphous and compressive, but after a 1050 °C anneal in N_2 for 3 hr, the films become polycrystalline and nearly stress free. While polysilicon has gauge factors that are significantly less than single crystal silicon[14,15], the temperature coefficient of resistance (TCR) can be minimized by tailoring processing[14,16].

LPCVD silicon nitride (Si_3N_4) is an amorphous material which is deposited by reacting dichlorosilane (SiH_2Cl_2) and ammonia (NH_3) gases. Stoichiometric silicon nitride, Si_3N_4, has high tensile stress of 1-2 GPa as deposited. Silicon rich nitrides, or low stress nitrides, are deposited by adjusting the gas ratio of SiH_2Cl_2:NH_3 from 1:3–1:4 to 4:1 and depositing at 835 °C have much lower stresses, on the order of 10-100 MPa[17].

1.3. Monolithic integration

The final potential advantage, the prospect of integrating electronics, is not quite as common as one might think[5], and depends upon the actual device. For piezoresistive pressure sensors, control circuits are not essential. However, for capacitive pressure sensors, signal degrading parasitic capacitances are significant and on-chip signal conditioning is desirable. Of several companies producing capacitive micromachined acclerometers, Analog Devices has a one chip solution[18], whereas Ford Microelectronics[19] and Motorola[20] both use dual chip, single package solutions, with the electronics on one chip and the micromechanics on the other.

2. MACRO-SCALE DEVICES

While the focus of this paper is a review of micromachined pressure sensors, it is instructive to examine some of the macroscopic devices that have been made. Some of these devices are shown in Figure 1[21]. Many of these devices were based on diaphragms (a,b,d). Other devices sought to improve the amount of deflection of a simple diaphragm such as the capsule (c) and bellows (e). Strain gauges were commonly used on diaphragm based devices. Some diaphragm sensors, however, had elaborate systems of levers which were linked to electric switches or potentiometer windings. Some diaphragm sensors, instead of having strain gauges mounted directly on the diaphragm itself, had a piston which was driven into a mounted strain gauge by the motion of the diaphragm. Finally Bourdon tubes and straight walled tubes, deflected or expanded in the presence of increased pressure (f,g).

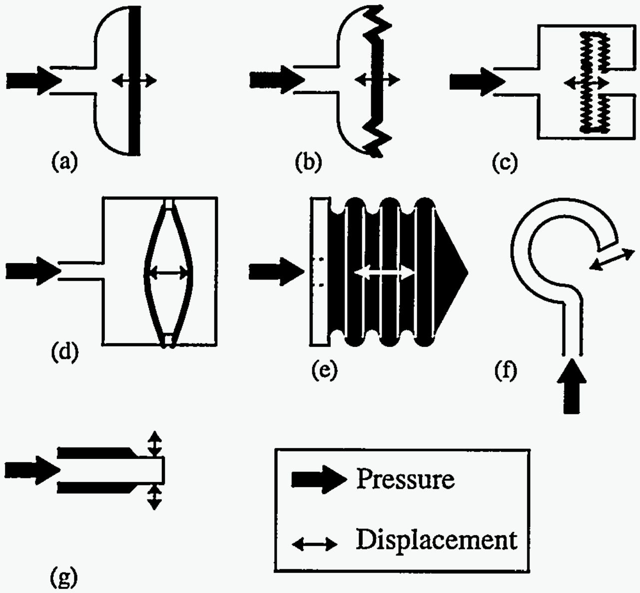

Figure 1. Macroscopic pressure sensors. Adapted from Oliver[21]. a) simple diaphragm. b) corrugated diaphragm. c) capsule. d) capacitive sensor e) bellows f) Bourdon tube g) straight tube.

Vacuum pressure sensors typically use different transduction mechanisms than their greater-than-atmospheric counterparts. A Pirani gauge measures the thermal conductivity of the ambient gas, which is directly proportional to pressure in the 1–2000 mTorr range[21]. A heated resistor is used for this measurement. Ionization gauges operate at pressures from 1 mTorr down to $2 \cdot 10^{-8}$ Torr[21]. In these gauges, electrons are emitted from a cathode and accelerated towards an anode plate. Positive ions are created by electron-gas collisions. These ions are attracted to a third plate. The current on this plate is proportional to the absolute pressure of the gas.

3. MICROMACHINED PRESSURE SENSORS

Many micromachined pressure sensors are miniaturized versions of their macroscopic counterparts. A micromachined Pirani gauge has been reported for measuring vacuum[22]. Most sensors for greater-than-atmospheric pressure share the common characteristic of deformable diaphragms. In diaphragm based sensors, pressure is determined by the deflection of the diaphragm due to applied pressure. Figure 2 illustrates a schematic cross section 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 to an applied stress. For the case of a clamped circular plate with small deflections (i.e., less than half of the diaphragm thickness) the form of the deflection is[23]

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

where w, r, a, and P are the deflection, radial distance from center of diaphragm, diaphragm radius, and applied pressure, respectively. D is the flexural rigidity, given by

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

where E, h, and ν are Young's modulus, thickness, and Poisson's ratio, respectively, of the diaphragm. From the above equations, the shape of the deflection can be determined. Moreover, it is readily apparent that the amount of deflection is directly proportional to the

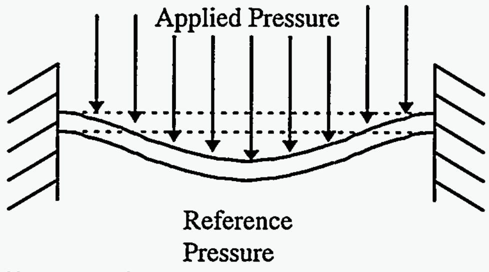

Figure 2. Schematic cross section of typical pressure sensor diaphragm. Dotted lines represent undeflected diaphragm.

applied pressure. For the case of a diaphragm with large built in stress or large deflections this direct proportionality is no longer true. In general, it is desirable to use a deflection measurement scheme that is linear with pressure, since such systems are simple to calibrate and measure.

In this paper several types of micromachined pressure sensors are reviewed, as classified by transduction mechanisms. Most of the emphasis will be placed upon capacitive and piezoresistive sensors, since they are the most common. Also, a few sensors related to pressure sensors will be briefly reviewed.

3.1 Piezoresistive

Following the invention of the bipolar transistor in 1947, a great deal of effort was put into characterizing the properties of single crystal semiconductors[24]. In 1954, Smith reported the piezoresistive effect of silicon and germanium[25], which is a change of resistance with applied stress. This discovery enabled semiconductor-based sensors. Piezoresistive pressure sensors have piezoresistors mounted on or in diaphragm. For thin diaphragms and small deflections, the resistance change is linear with applied pressure.

Silicon strain gauge, metal diaphragm sensors were first introduced commercially in 1958[26]. In these early sensors high-cost, low-volume biomedical[34]and aerospace[27,34] applications were targeted. This trend continued into the 1970s[28,29,30,31,32] when microsensor companies began to move toward higher-volume, lower-cost applications[33]: specifically, the automotive industry[32]. Into the 1980's and the present, biomedical and automotive applications are some of the most widely reported in the literature.

The evolution of piezoresistive pressure sensor technology is illustrated in Figure 3, starting with metal diaphragm sensors with bonded silicon strain gauges (Figure 3a). The strain gauges were bonded by epoxies, phenolics, or eutectics[34]. These first designs had low yield and poor stability due to such factors as thermal mismatch with the metal/epoxy/silicon interface[26].

Metal diaphragms were quickly superseded by single crystal diaphragms with diffused piezoresistors. These types of sensors had many advantages related to the properties of silicon and the availability of high quality silicon substrates. Hysteresis and creep, which were associated with metal diaphragms and plastic deformation, were eliminated. At low temperatures (< 500°C), silicon is perfectly elastic and will not plastically deform[28], but instead will fracture brittlely. Silicon obeys Hooke's Law up to 1% strain, a tenfold increase over common alloys[28]. Also, the ultimate tensile strength of silicon can be three times higher than stainless steel wire[11]. As a piezoresistive material, silicon has gauge factors that are over an order of magnitude higher than metal alloys[25].

The first silicon diaphragm were created by mechanical milling spark machining followed by wet chemical isotropic etching, to create a cup shape(Figure 3b)[27]. These diaphragms were bonded to silicon supports by a gold-silicon eutectic ($T_{eutectic}$= 370 °C). While this technique of fabrication had the advantages of increased sensitivity and reduced size, cost was still high, and diaphragms were created one at a time, rather than in batch mode.

By the late 1960's and early 1970's, three key technologies were being developed: anisotropic chemical etching of silicon[35,36,37], ion implantation, and anodic bonding[38,39]. Ion implantation was used to place strain gauges in single crystal silicon diaphragms. Ion implantation is generally better than diffusion for doping because both the doping concentration and doping uniformity are more tightly controlled[40]. Anisotropic etching improved the diaphragm fabrication process in a

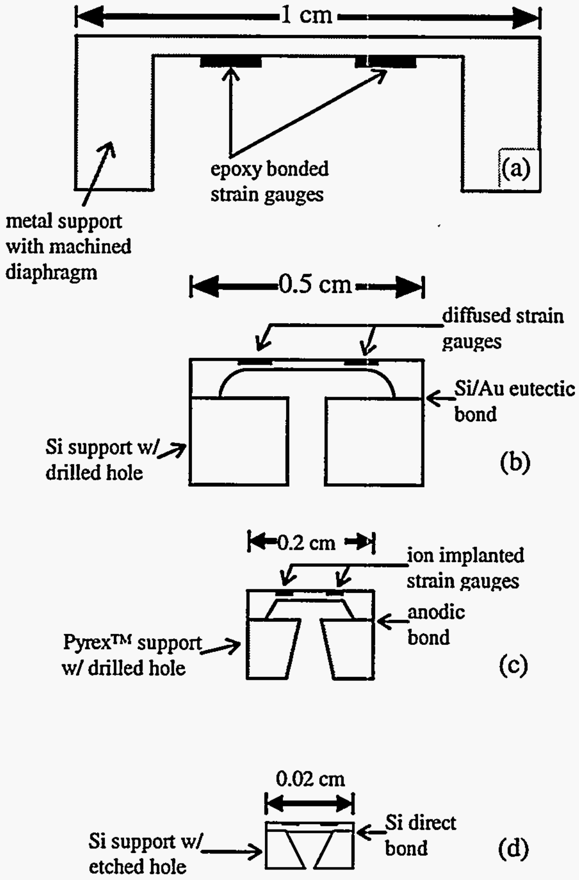

Figure 3. Evolution of diaphragm pressure sensors. Adapted from Bryzek *et al.*[26].

number of ways:

- diaphragm sizes and locations were now well controlled by IC photolithography techniques
- strain gauge placements were improved.
- anisotropic etching was well suited to batch fabrication, allowing hundreds of diaphragms to be created simultaneously.
- overall size was decreased further.

Anodic bonding, which uses voltages (500-1500 V) and heat (400-600 °C), was used to bond finished silicon diaphragm wafers to Pyrex™ glass supports. Several types of glass formulations were used, and were designed to reduce thermal mismatch to silicon. Anisotropic etching and anodic bonding were batch techniques, and hence hundreds (or more) of pressure sensors could be manufactured simultaneously on a single wafer. This amounted to a significant cost reduction. A representative sensor from this period is shown in Figure 3(c).

The 1980's to the present has been called the micromachining period[26], since diaphragm dimensions are shrinking to hundreds of microns and minimum feature sizes are shrinking to microns (Figure 3d). Also anisotropic etching[41,42,43,44] and bonding technologies are being improved. In 1985, the direct bonding method was first reported[45]. This method was first used for making silicon-on-insulator (SOI) material, but was quickly applied to micromachined devices[46]. Also, surface micromachined devices have been reported, which have silicon nitride[47,48,49] or polysilicon[16,50,51] diaphragms. These sensors decrease required die size and may simplify integration with electronics, but at the cost of reduced sensitivity and reproducibility of mechanical properties.

3.2. Capacitive

Capacitive pressure sensors are based upon parallel plate capacitors. A typical bulk micromachined capacitive pressure sensor is shown in Figure 4. The capacitance, C, of a parallel plate capacitor is given by

$$C = \frac{\varepsilon A}{d} \tag{3}$$

where ε, A, and d are the permittivity of the gap, the area of the plates, and the separation of the plates, respectively. For a moving, circular diaphragm sensor, the capacitance becomes

$$C = \iint \frac{\varepsilon}{d - w(r,\theta)} r\,dr\,d\theta \tag{4}$$

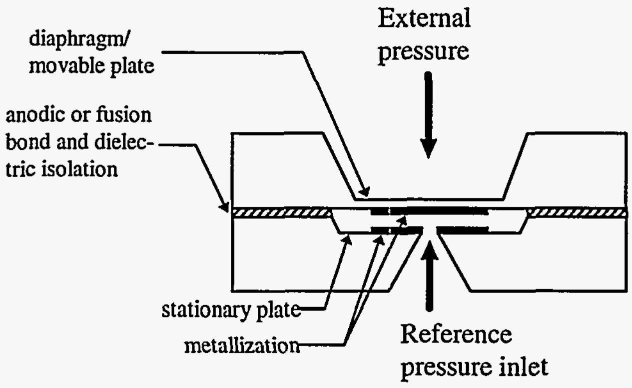

Figure 4. Crosssection schematic of bulk micromachined, capacitive pressure sensor. Adapted from Clark and Wise[52].

where $w(r,\theta)$ is the deflection of the diaphragm. Using the deflection of a uniform thickness, circular diaphragm from Equation 1 yields

$$C = \int_0^{2\pi}\int_0^{a} \frac{\varepsilon}{d - \frac{P(a^2 - r^2)^2}{64D}} r\,dr\,d\theta \tag{5}$$

Solving the integral gives

$$C = 8\pi\varepsilon\sqrt{\frac{D}{Pd}}\tanh^{-1}\left(\frac{a^2}{8}\sqrt{\frac{P}{Dd}}\right) \tag{6}$$

which can be expanded in a Taylor series to

$$C = C_0\left[1 + \frac{1}{3}\left(\frac{w_{center}}{d}\right) + \frac{1}{5}\left(\frac{w_{center}}{d}\right)^2 + \frac{1}{7}\left(\frac{w_{center}}{d}\right)^3 + \ldots\right] \tag{7}$$

Where C_0 is the undeflected capacitance given by Equation 3 and w_{center} is the center deflection of the

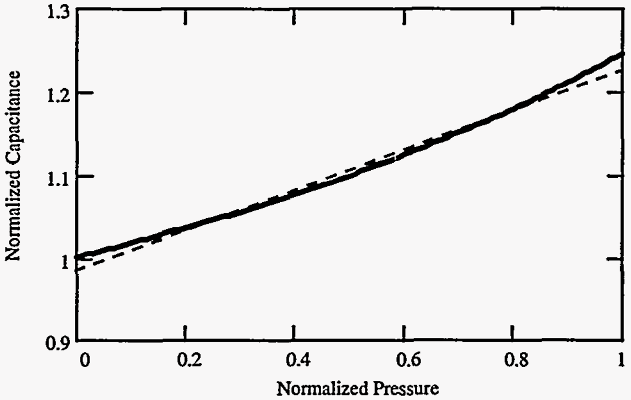

Figure 5. Capacitance vs. pressure curve for circular diaphragm with zero built in stress. Capacitance is normalized to C_0. Pressure is normalized to the pressure required to deflect the diaphragm to w=½h. Solid line is theoretical curve, while dotted line is a first order least squares fit with a maximum deviation of 1.5%.

diaphragm (i.e. $w(r=0)$ from Equation 1) The capacitance with respect to applied pressure, then is generally nonlinear due to the nonlinear deflected shape of the diaphragm. Equation 7 is plotted Figure 5 along with a first order least squares fit. The largest deviation of the fit is 1.5%, which is quite small when compared to the error in the small deflection model of 11% at $w=\frac{1}{2}h$[23].

Another possibility for increased linearity is to operate a capacitive sensor in contact mode (Figure 6). In contact mode, the capacitance is nearly proportional to the contact area which in turn exhibits good linearity with respect to applied pressure[53]. This holds true over a wide range of pressures. However, this linearity comes at the expense of decreased sensitivity.

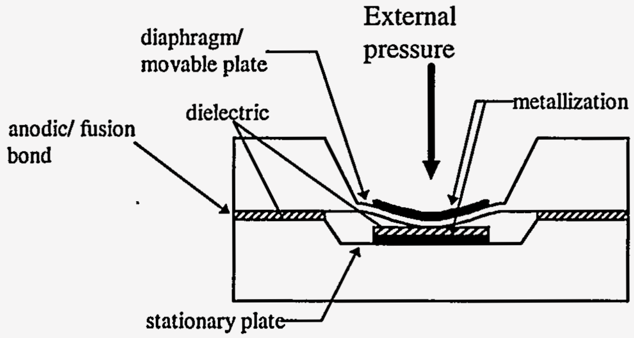

Figure 6. Cross section schematic of bulk micromachined, contact-mode pressure sensor.

One more method for achieving a linear response is to use bossed diaphragms. Figure 7 illustrates this concept. On the left is a cross section perspective view of a uniform thickness diaphragm and its corresponding cross section deflected mode shape. A non-uniform, bossed diaphragm is on the right. The thicker center portion is much stiffer than the thinner tether portion on the outside. The center boss contributes most of the capacitance of the structure and its shape does not distort appreciably under applied load. Hence the capacitance/pressure characteristics will be more linear[54,55,56,57].

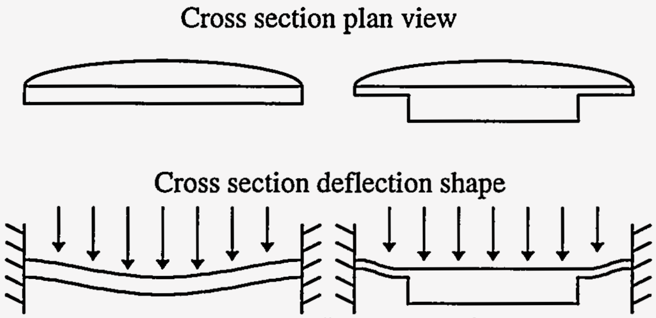

Figure 7. Comparison of deflection shapes for uniform thickness(left) and bossed(right) diaphragms.

The principal advantages of capacitive pressure sensors over piezoresistive pressure sensors are increased pressure sensitivity and decreased temperature sensitivity[32,58,59,60,61]. However, excessive signal loss from parasitic capacitance is a big disadvantage, and hindered the development of miniaturized capacitive sensors until on-chip circuitry could be fabricated[58].

Historically, capacitive sensors have benefited from the same advances in diaphragm etching and wafer bonding that piezoresistive sensors have. However, the piezoresistive approach generally has a complex transducer with simple circuit requirements, while the converse is true of the capacitive approach. For this reason, capacitive sensors have benefited more from advances in circuit design than piezoresistive sensors[60].

3.3. Optical

Many diaphragm based optical sensors have been reported which measure pressure induced deflections by Mach Zender interferometry[62,63,64] and Fabry Perot interferometry[65]. The deflection derived from these devices varies linearly with pressure, witnessed by Equation 1. Sensors which measure quantum well spectrum deformation have also been demonstrated[66].

Optical sensors can be quite accurate, but often suffer from temperature sensitivity problems[67]. Furthermore, aligning the optics and calibrating the sensors can be challenging.

3.4. Resonance

A new type of pressure sensor has been reported in recent years: the resonant beam pressure sensor. The sensors operate by monitoring the resonant frequency of an embedded doubly clamped bridge[68,69,70] or comb drive[71], as shown in Figure 8. The resonant beam, which has also been called a resonating beam force transducer[72], acts as a sensitive strain gauge[73]. As the stress state of the diaphragm changes, the tension in

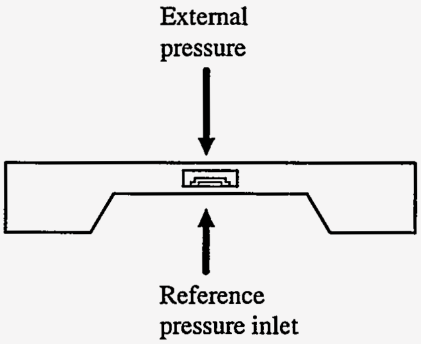

Figure 8. Cross section schematic of resonant beam pressure sensor. Not to scale.

the embedded structures changes and so does the resonant frequency.

There have been several mechanisms reported by which the structures can be driven into resonance while the resonant frequency is sensed. One method is electrostatic drive–piezoresistive sense. The structure is driven to resonance by AC applied voltages, and the resonant frequency is measured by piezoresistors[68,69]. Structures can also be optically excited by laser and sensed by a photodetector[70], or electrostatically excited and capacitively sensed[71]. Resonant pressure sensors have been shown to exhibit better pressure sensitivity and lower temperature sensitivity than pure piezoresistive sensors. Furthermore, a frequency output is more immune to noise than classical analog piezoresistive and capacitive signals[68].

3.5. Microphones and hydrophones

Most microphones reported in the literature are condenser or capacitor microphones[74]. They operate similarly to capacitive pressure sensors previously described. However, the frequency response and mechanical sensitivity of common capacitive static pressure sensors are inadequate for use as microphones[75]. This is due to acoustic resistance and squeeze-film damping between the movable and stationary plates of the sensor. These effects are reduced by perforating the stationary plate, such that air can escape into a larger chamber[74,75,76]. Such a device, implemented in bulk micromachining, is shown in Figure 9. With proper design, condenser microphones can have the advantages of high stability and flat frequency response [75].

While condenser microphones are more common, piezoresistive[77,78] and piezoelectric microphones[79,80,81] have been reported.

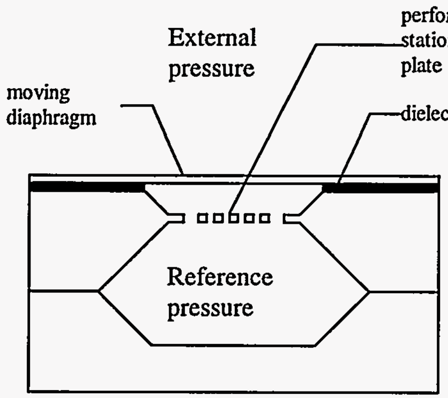

Figure 9. Condenser microphone with perforated backplate. Similatr to Kälveston et al.[75].

At least one micromachined hydrophone has been reported[82,83]. This hydrophone was based on a condenser microphone and filled with a variety of compressible fluids. The frequency response was as high as 2 kHz.

3.6. Ultrasonic transducers

Most micromachined ultrasonic transducers are bulk micromachined and use piezoelectric thin films on top of a diaphragm to sense ultrasonic energy[84,85,86,87,88]. Piezoelectric materials are discussed in more detail in Chapter 1. One advantage of using a piezoelectric material is that these transducers can both receive and generate ultrasonic waves. Applications for send-and-receive transducers are in sensing distance or imaging[87].

4. RECENT DEVELOPMENTS

Over the past several years, surface micromachined pressure sensors have been fabricated and tested at the Microelectronics Development Laboratory within Sandia National Laboratories. These sensors have been based on both silicon nitride and polysilicon diaphragms, and in planar and non-planar versions. Fabrication details and sensor characteristics have been reported elsewhere for non-planar[89,90] and planar[91,92] sensors. The principal advantage of planar sensors is improved manufacturability by reduction of topography, which leads to improvements in photolithography, dry etch, ion implantation, and metallization processes. Furthermore increased mechanical robustness of similar devices has been demonstrated[93].

Figure 10 contrasts both types of sensors. The sensors have the same basic piezoresistor and metallization layout, but differ in structure. Both sensors have evacuated reference pressure cavities underneath them. In the non-planar version, the cavity is formed above the surface of the wafer by a 2 µm thick sacrificial oxide. This sacrificial oxide, combined with the thickness of the sensor diaphragm itself, is responsible for much of the topography. In the planar sensor, the sacrificial oxide has been embedded in a sub-surface trench which has been planarized by chemical mechanical polishing[92].

Output characteristics of planar pressure sensors are shown in Figure 11 for nitride and Figure 12 for polysilicon diaphragms. Four sizes of pressure sensors are shown in each graph: 50, 100, 150, and 200 µm diameters. The nitride diaphragm sensors exhibit sensitivity clustering at low pressure for the 100, 150, and 200 µm diameter diaphragms. This behavior is due to built-in stress effects and large deflections[94] not accounted for by thin plate theory. The rollover in the

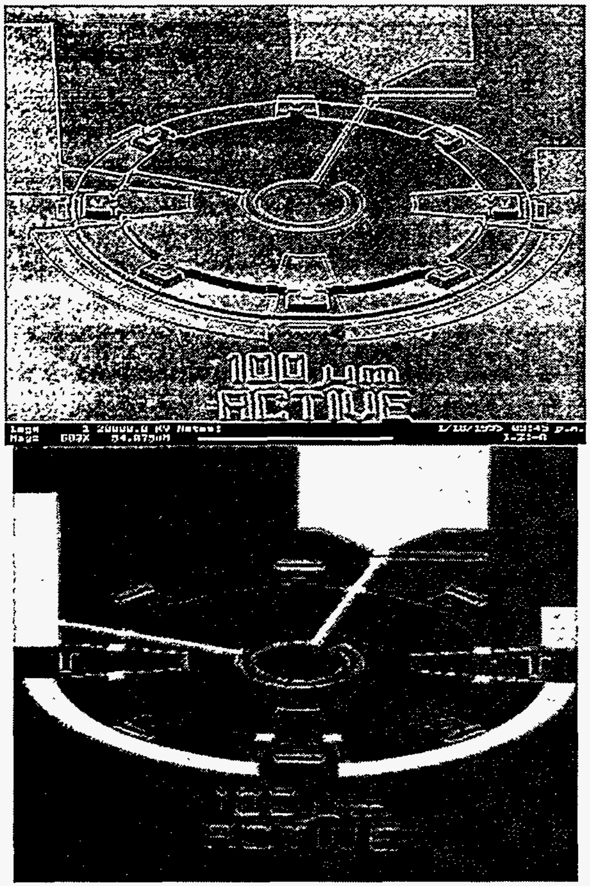

Figure 10. Finished non-planar (top) and planar (bottom) 100 µm diameter pressure sensor diaphragms.

150 and 200 µm diameter sensors is due to the diaphragm contacting the substrate.

Polysilicon diaphragm based sensors display more linear and differentiated characteristics than the nitride sensors. The cause is twofold: first the polysilicon diaphragms are 2.3 µm thick, compared to a 1.4 µm thickness of the nitride diaphragms. This causes them to be stiffer and less likely to go into the large deflection regime. Second, micromechanical polysilicon has far less stress, < 1 MPa, than low stress nitride (~ 10-100 MPa), which prevents sensitivity clustering. The negative output of the 200 µm diameter polysilicon sensor is due to an incomplete sacrificial oxide etch, which left an oxide island in underneath the center of the diaphragm, thereby rendering the circumferential resistors inactive.

Work is ongoing towards monolithically integrating these sensors with controlling CMOS electronics. Also, capacitive devices are under development. One of the advantages of capacitive devices is the monotonic dependence on pressure, even if the diaphragm deflects to contact the substrate. In contrast the piezoresistive devices of Figure 12 have a non-monotonic response.

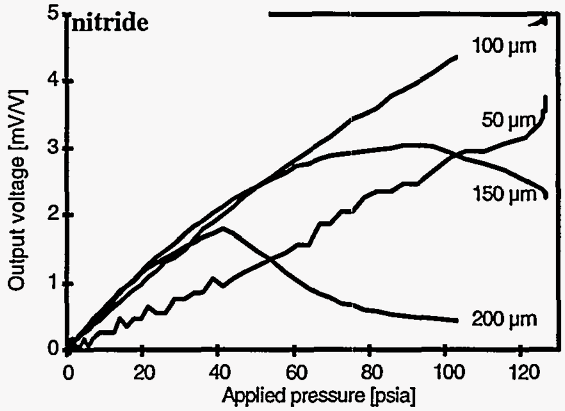

Figure 11. Output characteristics for silicon nitride based planar pressure sensors.

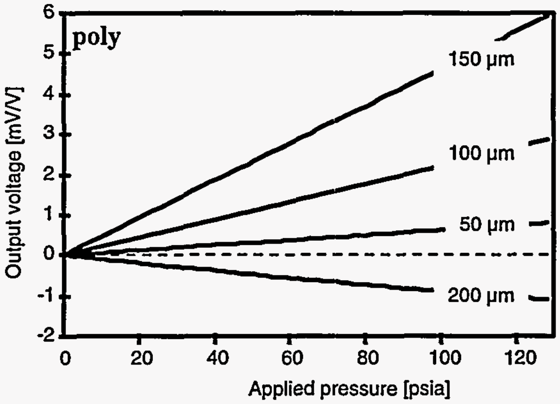

Figure 12. Output curves for polysilicon diaphragms. Curves have been normalized to have zero offset voltage.

CONCLUSIONS

Micromachined pressure sensors have an established portion of a large market which will grow for the foreseeable future. Greater levels will emerge of monolithic integration of piezoresistive, capacitive, optical, and resonant pressure sensors with controlling electronics and/or optics.

Results from surface micromachined pressure sensors at Sandia National Laboratories illustrate some of the promise and pitfalls of MEMS technologies. While IC technologies are used to advantage in MEMS processing, the thermal and mechanical properties of MEMS materials must be understood, measured, and optimized to achieve accuracy and reproducibility.

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