MICROSTRUCTURE SENSORS

H. Guckel, T. R. Christenson, K. J. Skrobis, J. J. Sniegowski, J. W. Kang, B. Choi,
E. G. Lovell

Wisconsin Center For Applied Microelectronics
Department of Electrical and Computer Engineering
University of Wisconsin, Madison, WI 53706

ABSTRACT

Surface micromachined polysilicon pressure sensors offer an attractive, cost effective, high performance technology if material repeatability issues can be solved. This has been accomplished and fully packaged prototype devices have been tested extensively and confirm the expectations for this technology. The pressure ranges over which these devices are designable has been established and is set by the maximum allowable diaphragm stress and the minimum acceptable output level.

The low pressure limitation can be eliminated by improving the transducer sensitivity. The substitution of the resonating force sensor, another polysilicon component, for piezoresistors can accomplish this but complicates processing. This approach is justified for high performance applications. The alternative is found in a differential transducer which is furnished with double-sided over-pressure stops. One of these stops is provided by the silicon substrate, the other by an electroplated air bridge which is formed by x-ray lithography and electroplating in the presence of a sacrificial layer. The end result is a rigid, thick, accurately spaced stop which results in devices which are rugged and can measure differentials in the 1" water range. The read-out for this class of transducers can be designed in such a way that simultaneous capacitive and piezoresistive interrogation is possible.

INTRODUCTION

Sensors are devices which typically convert physical variables which are to be measured to electronic signals which become part of a control system. They consist of two parts: The sensor structure which will be discussed here and the package which protects the device from environments which are often difficult to handle.

Size reductions in the sensor structure are nearly always beneficial. They allow cost reductions via batch fabrication techniques which are borrowed from microelectronics and lead to the term micromechanics. Micromechanical sensors or microsensors can sometimes be combined with cofabricated microelectronics which produces performance improvements and can result in structures which are identified as smart sensors. Microminiaturization can expand sensor application areas. This is exemplified by physical sensors for biological systems. Blood pressure and blood gas analysis devices must be small in order to be effective.

The fabrication techniques which are most directly available for microsensor fabrication have their origin in microelectronics. The central difficulty which one experiences is based on the fact that sensors are fundamentally three-dimensional structrures and integrated circuit construction is based on the concept of planar processing which is of course two-dimensional. It is therefore not very difficult to understand that presently nearly all microsensor construction techniques are adaptations of planar integrated circuit processing with modest three-dimensional extensions. Thus, in wafer to wafer bonding IC processing is combined with silicon bulk machining and wafer to wafer bonding to achieve microsensor production. In surface micromachining, a technology which is of interest here, planar processing and lateral etching are combined to achieve the necessary three-dimensionality. This situation, and therefore the shift towards three-dimensional fabrication, is slowly changing and non-silicon technologies are becoming more important.

POLYSILICON PRESSURE TRANSDUCERS

Pressure transducers are the most used and therefore the best understood sensors. They fall into two classes: Relative or differential devices and absolute transducers. This sensor, the absolute device, has been chosen as the test vehicle for microminiaturization via surface micromachining.

Absolute pressure transducers are fundamentally vacuum sealed pill boxes which deform geometrically with applied pressure. This deformation is sensed electronically and produces the electronic pressure signal. The discussion indicates a natural subdivision of pill box formation, vacuum sealing and electronic sensing for the device. It also implies that pill box behavior and electronic sensing contribute to device performance together. Thus, very small deformations of a mechanically stiff system are acceptable if the sensing scheme is sufficiently sensitive. The concept of an overpressure stop which is either provided by the device or the package becomes apparent and necessary if one considers that increasing pressures cause increasing deflections and will eventually lead to pill box failure.

In the surface micromachined version of the pressure transducer the construction technique of Figure 1 applies [1].

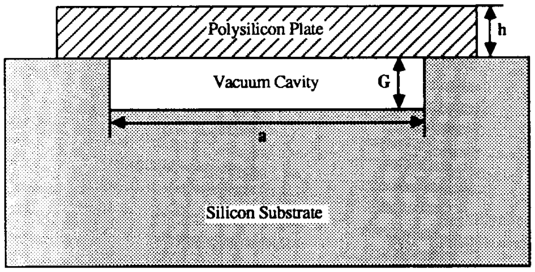

Fig. 1 Basic surface micromachined pill box.

In this structure a silicon wafer is furnished with a recess of depth G and, say, square side dimension **a**. This recess is covered with a polysilicon plate of thickness **h**. Typical dimensions for G are 0.8 micrometer or so. High pressure applications would cause diaphragm deflections which could not exceed G. Hence, with proper design Figure 1 contains a pill box with overpressure stop.

Figure 1 also identifies a deposited polysilicon film as part of the pill box. The thickness of this film, **h**, is restricted to dimensions which can be achieved in reasonable depositions times. Figure 1 also insists that the deposited film is locally defined which typically requires plasma etching. Since the etch time and pattern fidelity must fit into certain limits a second restriction of film thickness becomes evident. Practical experience based on the above points leads to the conclusion that typical film thicknesses range from 1 to 4 micrometer.

The dimension **a** depends on the intended pressure range and the behavior of the polysilicon film. It becomes a designable quantity only if the mechanical properties of the deposit are constant with processing. This very complex issue leads to the conclusion that constant film morphology is a necessary condition. Furthermore, since isotropic rather that anisotropic behavior is advantageous, morphologies with orientated crystallities are also not acceptable. A polycrystalline film with randomized, small grains is most desirable. The quality of the deposit can be evaluated by measuring Young's modulus for the film. It should approach that of single crystal material [2].

There is a second consideration. Figure 1 can be realized by forming an oxide post via isoplanar processing in the substrate. The enclosed oxide must be removed by lateral etching. This implies extended hydrofluoric acid exposure of the polysilicon. Any oxide and nitride inclusions as well as chemical modifications due to impurities must therefore be avoided because this would cause modifications in mechanical film characteristics due to the etching process. They are not acceptable and films that are modified in this manner are not applicable to microsensor production.

An optimized silicon film of this type will have three important properties. It will have a Young's modulus, E, which in the present case is 1.65×10^{12} dynes/cm^2 and does not deviate by more than 10^{10} dynes/cm^2.

The film will be able to support a maximum strain of 1.5% before it fractures. It will also have a built-in strain field. This strain level must either be controllable and therefore becomes a part of the design process or the film must have the property that processing techniques exist which cause the built-in strain to disappear. In the present case strain zeroing will be assumed even though strain field control is feasible for polysilicon [3].

In order to understand the implication of the microsensor vacuum formation in Figure 1 is postulated. It is then assumed that the transducer is square and that the maximum pressure range is defined by a diaphragm deflection at the center of the diaphragm which is equal to the cavity dimension G. This condition is given by

$$G = \frac{0.0152\, \boldsymbol{q}\ \boldsymbol{a}\ \left(1 - \nu^{2}\right)}{Eh^{3}} \tag{1}$$

where $\boldsymbol{q}$ is the applied pressure which causes touch-down and ν is the Poisson ratio for this type of polysilicon.

The above deflection induces diaphragm strain. The strain field maximizes at the clamped edge midway between the corners. This strain value is given by

$$\varepsilon_{x} = \frac{0.308\, \boldsymbol{q}\ \boldsymbol{a}^{2}\ \left(1 - \nu^{2}\right)}{Eh^{2}} \tag{2}$$

and cannot exceed the maximum allowed strain. Figure 2 summarizes and illustrates the situation.

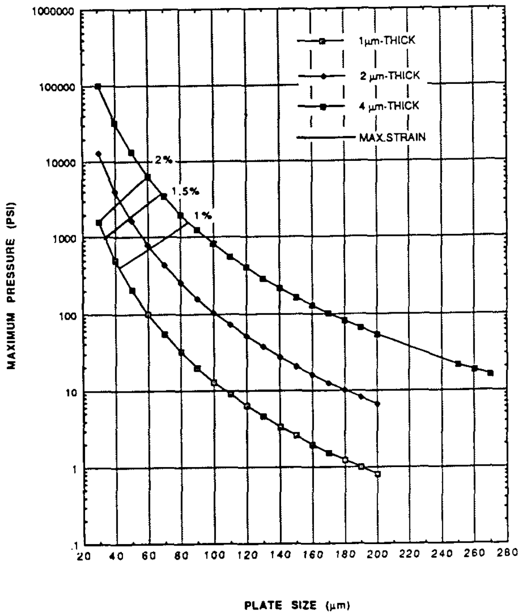

Fig. 2 Pill box behavior at the touch-down pressure in psia versus square plate width **a** in micrometer with diaphragm thickness **h** in micrometer as a parameter. The upper curves are maximum strain at touch-down curves which are measured in percent.

The maximum pressure sensing ability of this technology is clearly illustrated by this graph.

The structure in Figure 1 can be converted to a pressure transducer if the sensing mechanism is added. Piezoresistive and capacitive techniques form the most direct approach. Piezoresistive sensing is the most directly implemented technique and profits in this technology from the availability of polysilicon which can be used to produce excellent, stable and dielectrically isolated sensing structures. This is accomplished by covering the structure in Figure 1 with a silicon nitride layer, a patterned and doped polysilicon layer and a protective nitride layer. The issue becomes then one of performance evaluation for particular resistor doping levels and resistor placements.

Polysilicon resistors are quite different from diffused silicon resistors. The piezoresistive effect in these devices is roughly a factor of five smaller than that of a well designed single crystal counterpart. Longitudinal gage factors are typically slightly above 20 and transverse gage factors are near -8. The temperature coefficient of resistance, TCR, can be positive or negative and can be close to zero. The noise figure for these devices involves only thermal noise which is normally only found to be true for very good metal film resistors. Polysilicon resistors are dielectric isolated which allows for higher temperature applications because junction leakage currents are absent.

The placement issue for these devices is again quite different than single crystal placement. Here the rule is simply to locate them in the maximum stress regions on the diaphragm. This would imply longitudinal sections which enter the diaphragm at the support midway between corners. There is, however, a problem. Diaphragm sizes according to Figure 2 will typically be less than 100 micrometer on the side. The resistors will therefore be quite small with typical linewidths of 4 micrometer. This implies that alignment tolerances as well as line width shifts during polysilicon etching must be considered. These problems which can become very significant have led to an implementation which follows the rule of one resistor per diaphragm. Figure 3 shows the layout.

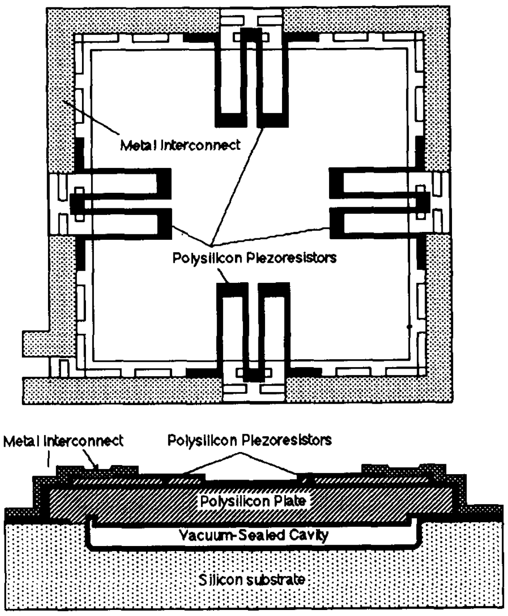

Fig. 3 Resistor layout for alignment error tolerant manufacturing.

This layout is reasonably insensitive to alignment errors but does not avoid the linewidth tolerance issue.

A full transducer uses four devices in the bridge configuration. The procedure involves two resistors which are pressure sensitive and two resistors which are insensitive to pressure because their pill box oxide has not been removed. With this configuration, the half-active full bridge, the maximum output in millivolt per volt of bridge excitation can be calculated at the touch-down pressure. The results are shown in Figure 4.

The difficulties, small output over span, for the low pressure ranges are clearly evident in Figure 4. This data and Figure 2 identify the expected design ranges over which this technology is useful. Within this design range experimental performance is very good and, in particular, always results in a very small device. One can take advantage of this and produce a device which contains multiple sensors. This is indicated in Figure 5 where four pressure ranges are supplied on a single die which eventually is mounted in a single package.

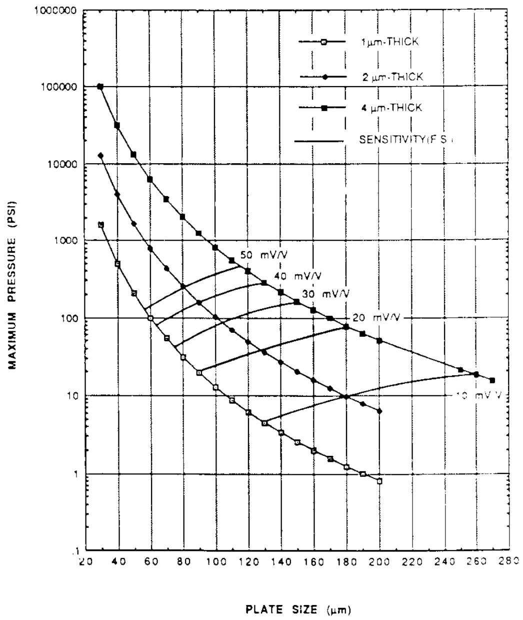

Fig. 4 This figure is related to figure 2. It contains the maximum expected output voltage per volt of bridge excitation for a half active full bridge.

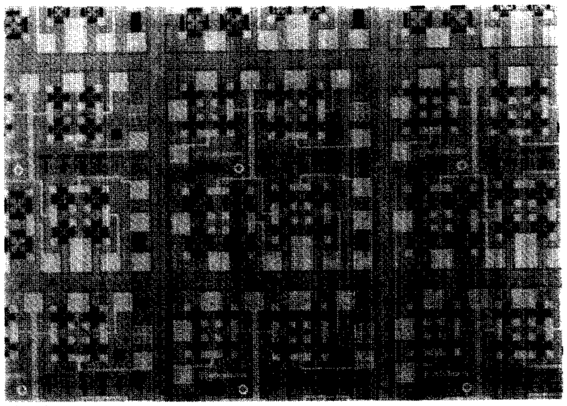

Fig. 5 Prototype pressure transducer with four pressure ranges. Touch-downs occur at 20 psia, 150 psia, 300 psia and 650 psia. The die size is roughly 0.080"x0.080".

RESONATING SENSOR

The difficulties to which Figure 4 alludes are the result of piezoresistive sensing. They can be removed by changing the sensing technique or by converting the device from an absolute pressure sensor to a differential transducer. Both approaches are receiving detailed attention. In the first case the piezoresistor is replaced by a new type of force sensor: The vacuum sealed resonating beam. This structure which is shown in Figure 6 evolves from the polysilicon technology which has been discussed here [4].

It is essentially a pill box which contains a clamped-clamped free standing beam which can be excited elecrostatically. The transduction mechanism is simply axial applied force to frequency which becomes reasonable if one thinks of pitch adjustments for a violin string. What is not intuitively obvious is the very high sensitivity which allows for simpler and more precise measurements. The draw-back is found in the increased complexity of the necessary construction technique. The device becomes expensive and most likely is useful only for the high end market where low pressure precision measurements are required.

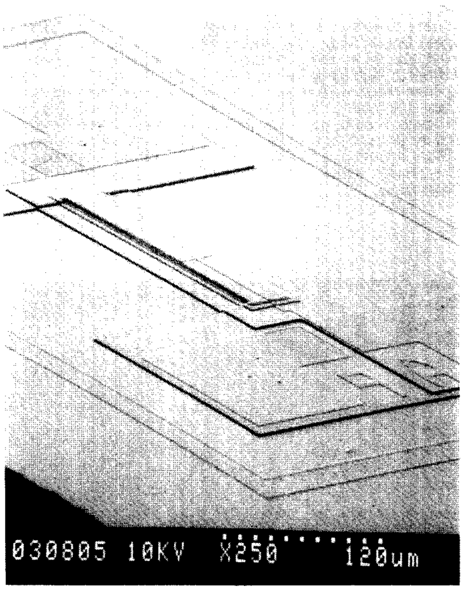

Fig. 6 Resonating force transducer. This device contains a 200 micrometer long and 40 micrometer wide polysilicon beam which is 2 micrometer thick. The beam is completely enclosed by a silicon shell which is evacuated. It is driven electrostatically at the beam center and monitored with piezoresistors at the beam ends. Resonant frequencies are near 500 khz with Q-factors near 25,000.

DIFFERENTIAL MICROSENSORS

The absolute pressure transducer as discussed here can be converted to a differential device if pressures are applied to both sides of the diaphragm. This requires one or more via holes through the substrate which end in flow channels which connect the backside pressure to the diaphragm. The idea is illustrated in Figure 7.

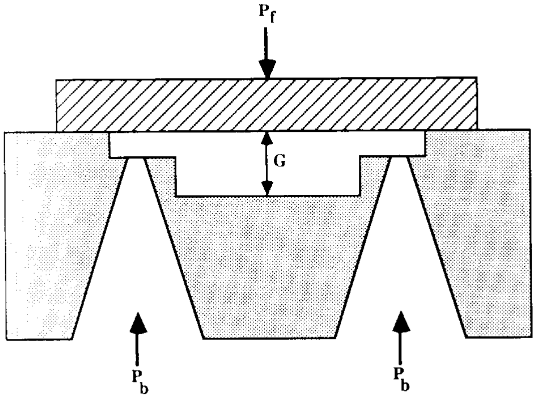

Fig. 7 Differential transducer with single over-pressure stop.

The construction technique preserves the over-pressure stop in the silicon direction. The second stop which is needed for the condition P_b>>P_f is missing. It could be provided by packaging. This will be somewhat difficult because the gap dimension G is typically less than a micrometer. Wafer to wafer bonding could be used but presents severe processing complications because high temperature heat cycles are required. A less complicated technology is required. A viable and very interesting candidate for this is a modified version of the LIGA process.

LIGA processing was first reported by W. Ehrfeld [5]. His concept is based on a substrate which is covered with a suitable plating base for subsequent electroplating. The plating base is covered with a thick layer of photoresist, say, up to 300 micrometer. This material is exposed through a suitable mask to high intensity x-ray fluxes with average wavelengths in the few Angstrom range. Diffraction effects will therefore be minimal and if the photon flux is normal to the substrate pattern run-out in the photoresist layer due to exposure conditions will be essentially absent. Optimized developing will therefore produce photoresist free regions which are bounded by vertical walls. These regions can be filled with metals via electroplating. Figure 8 illustrates results which were obtained at Wisconsin by this type of processing [6].

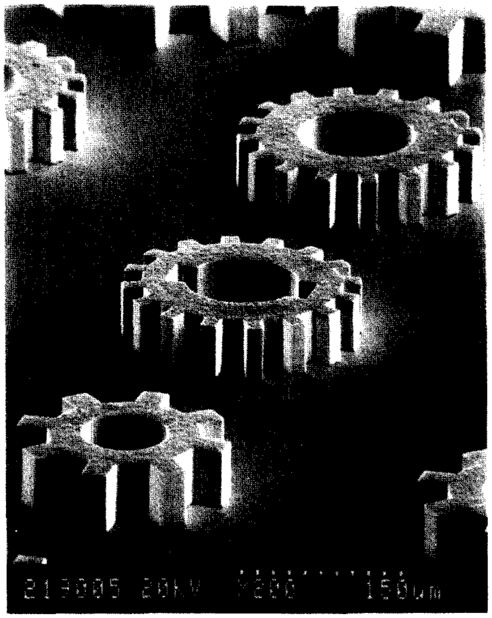

Fig. 8 Nickel gears which were produced by deep x-ray lithography at Wisconsin.

If the basic LIGA process is modified by the addition of a sacrificial layer which is locally defined the over-pressure stop which has been discussed earlier can be fabricated. Figure 9 illustrates the concept.

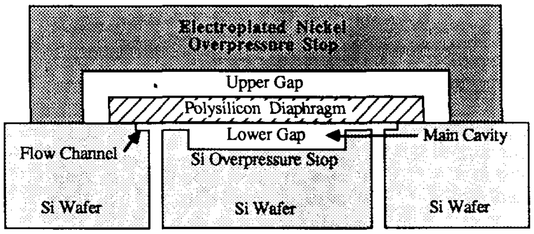

Fig. 9 Differential pressure transducer with two overpressure stops.

This has in fact been done. The processing uses the absolute transducer construction technique and augments it with bulk micromachined through-the-wafer pressure tabs. It then uses a spun-on film of special polyimide to produce the sacrificial layer at 0.8 micrometer thickness. This layer is locally defined via an optical mask and photoresist processing. All excess polyimide is removed with the photoresist developer. The remaining polyimide is hardened by baking at 270°C. This hardens the film sufficiently to allow plating base application via sputtering of 150µm of titanium and 150µm of nickel. However, the polyimide can still be removed in a variety of basic solutions. The plating base process is followed by thick photoresist application, x-ray exposure with an x-ray mask which must be aligned to the wafer, developing and electroplating. Removal of the plating base exposes the sacrificial layer which can now be removed by lateral etching. In essence an air bridge with very tight dimensional controls and very significant metal thickness results and forms the second over-pressure stop.

The resulting device is quite interesting. The goal, a 1" water transducer, is easily achievable with a 715x715 micrometer diaphragm at 2 micrometer polysilicon thickness. The device can survive overpressures in excess of 100 psi without damage. Its piezoresistive output is small. However, since the polysilicon diaphragm can be covered with a thin metal film without problems a pressure sensitive read-out via capacitive sensing becomes feasible. The capacitor is formed between the metal covered diaphragm and the over-pressure stop. The fact that piezoresistive and capacitive signals are available simultaneously is quite attractive because electronic data verification becomes possible and is very attractive for high reliability applications. The possibility of using the device as a pressure sensitive switch exists and is currently under investigation.

CONCLUSIONS

Construction techniques for surface micromachined absolute pressure transducers are sufficiently advanced to produce prototype pressure transducer chips which have been tested extensively. The results are very encouraging and lead to the conclusion that this type of sensor is real and economically viable.

The merging of polysilicon technologies with electroplated metal structures is just now starting. The expected performance results in the conclusion that many new structures will become feasible and that, in particular, a reasonable 1" water transducer is in the near future. The applicability of the double sided over-pressure stop to other devices such as accelerometers is already being studied and promises to have a major impact on this area. This is particularly true if these devices also include the resonating beam force transducer.

ACKNOWLEDGEMENTS

Part of this work was supported by the National Science Foundation under grant EET-8815285.

We are indebted to Dr. T. D. Flaim of Brewer Science Inc., Rolla, MO 65401 for the supply of PiRL materials which were used to fabricate the sacrificial layer for the metal over-pressure stop.

REFERENCES

1. H. Guckel, D. W. Burns, C. R. Rutigliano, D. K. Showers, J. Uglow, "Fine Grained Polysilicon and its Application to Pressure Transducers," Proceedings of the 4th International Conference on Sensors and Actuators, pp. 277-282, Tokyo, Japan, June 1987.
2. H. Guckel, D. W. Burns, H. A. C. Tilmans, D. W. DeRoo, C. R. Rutigliano, "Mechanical Properties of Fine Grained Polysilicon: The Repeatability Issue," IEEE Technical Digest for Solid State Sensors and Actuators, pp. 96-99, Hilton Head, SC, June 1988.
3. H. Guckel, D. W. Burns, C. C. G. Visser, H. A. C. Tilmans, D. DeRoo, "Fine Grained Polysilicon Films with Built-in Tensile Strain," IEEE Trans. on Elect. Devices, Vol. 35, No. 6, pp. 800-801, June 1988.
4. H. Guckel, J. J. Sniegowski, T. R. Christenson, "Construction and Performance Characteristics of Polysilicon Resonating Beam Force Transducers," Proc. of the Third Toyota Conference, pp. 23-1, 23-10, Nissin, Aichi, Japan, 1989.
5. W. Ehrfeld, F. Götze, D. Münchmeyer, W. Schelb and D. Schmidt, "LIGA Process: Sensor Construction Techniques via X-Ray Lithography," Technical Digest, IEEE Solid-State Sensor and Actuator Workshop, pp. 1-4, 1988.
6. H. Guckel, T. R. Christenson, K. J. Skrobis, D. D. Denton, B. Choi, E. G. Lovell, J. W. Lee, S. S. Bajikar and T. W. Chapman, "Deep X-Ray and UV Lithographies for Micromechanics," Technical Digest, IEEE Solid-State Sensor and Actuator Workshop, pp. 118-122, 1990.