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The Fabrication and Use of Micromachined Corrugated Silicon Diaphragms

J. H. JERMAN

IC Sensors, 1701 McCarthy Boulevard, Milpitas, CA 95035 (U.S.A.)

Abstract

Corrugated diaphragms offer much greater linearity and travel than the equivalent flat diaphragms. Corrugations have been produced in silicon microstructures by etching grooves in the top surface of a wafer and diffusing an etch stop. A back-side etch is then used to form the corrugated diaphragm. Corrugations have been made between 3 and 20 μm deep with diaphragm thicknesses between 0.6 and 8 μm. A capacitive pressure sensor has been fabricated using these techniques with a full-scale sensitivity of 1 mmHg.

Introduction

The vast majority of micromachined silicon diaphragms have been flat and either square or rectangular. These configuration have served well for piezoresistive pressure sensors for pressure ranges above about 100 mmHg. For very low pressure ranges, however, the non-linearity caused by membrane stresses in a square diaphragm becomes appreciable, and other, more elaborate schemes are needed. These have primarily taken the form of bossed regions on the back side of the diaphragm to concentrate stress at the periphery for piezoresistive devices or to produce piston-like travel from the central region of the diaphragm [1–3]. These bossed structures offer better linearity than a non-bossed structure, but the linear deflection possible from such structures is still very small. It has been recognized for decades in the field of conventionally formed metal diaphragms that by introducing corrugations into the diaphragm structure, the linearity of a diaphragm can be increased considerably [4]. To this point it seems that only a limited amount of work has been undertaken to transfer conventional corrugated diaphragm technology to micromachined silicon structures [5]. In the present work a generally useful technique for forming these structures has been developed that promises to open a wide range of applications where large, linear travel of diaphragm structures is desired, such as capacitive pressure sensors, valve diaphragms and optical interference structures.

Flat Diaphragms

The deflection of a flat, clamped, circular diaphragm is given approximately by [6]:

$$\frac{PR^4}{Eh^4}=\frac{5.33}{(1-\nu^2)}\frac{y}{h}+\frac{2.83}{(1-\nu^2)}\frac{y^3}{h^3}$$

where P is the applied pressure, R is the diaphragm radius, h is the diaphragm thickness, E is Young's modulus, ν is Poisson's ratio and y is the center deflection of the diaphragm. For comparison purposes, the equivalent square diaphragm deflection is given by [7]:

$$\frac{Pa^4}{Eh^4}=\frac{4.20}{(1-\nu^2)}\frac{y}{h}+\frac{1.58}{(1-\nu^2)}\frac{y^3}{h^3}$$

where a is the half sidelength. Thus a circular diaphragm with a radius equal to the half sidelength of a square diaphragm will be about 30% stiffer, for small deflections, and the non-linearity will be very similar, due to the nearly equal ratios of linear to cubic coefficients. Note that in either case the non-linearity becomes significant for deflections more than about 25% of the thickness of the diaphragm, regardless of the radius of the diaphragm. This is of great importance in the design of very sensitive micromachined diaphragms, particularly for capacitive sensing applications.

Corrugated Diaphragms

With the introduction of corrugations into the diaphragm structure, the situation can be changed dramatically. For shallow, sinusoidal corrugations the deflection is approximately given by [8]:

$$\frac{PR^4}{E'h^4}=a_p\frac{y}{h}+b_p\frac{y^3}{h^3}$$

where

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$$a_p = \frac{2(q+3)(q+1)}{3\left(1-\frac{\nu^2}{q^2}\right)}$$

$$b_p = \frac{165(q+1)^3(q+3)}{q^2(q+4)(q+11)(2q+1)(3q+5)}$$

and

$$E' = \frac{E}{1-\nu^2}$$

and for shallow, sinusoidal profiles:

$$q^2 = 1 + 1.5\frac{H^2}{h^2}$$

with q the corrugation quality factor and H the corrugation depth. Thus q varies from 1, for a flat diaphragm, to a value that approaches 1.22 times the ratio of corrugation depth to diaphragm thickness. For conventional metal corrugated diaphragms, the value of q is typically chosen to be between 10 and 30. It is clear that the coefficient a_p increases rapidly with increases in q, while the coefficient b_p decreases rapidly with increases in q. Thus the linearity of the diaphragm can be increased dramatically by providing corrugations that are as little as three times the diaphragm thickness. In this case, $q = 3.8$, and the linear term, a_p, is increased by about a factor of four while the cubic coefficient, b_p, is reduced by a factor of over 10.

In many useful structures it is desirable to introduce a center boss into the structure. This makes the structure stiffer for a given diaphragm thickness and corrugation depth. Small deflections of a bossed, corrugated diaphragm can be expressed as:

$$\frac{PR^4}{E'h^4} = a_p n_p \frac{y}{h}$$

where

$$\frac{1}{n_p} = (1-r^4)\left(1 - \frac{8qr^4(1-r^{q-1})(1-r^{q-3})}{(q-1)(q-3)(1-r^{2q})}\right)$$

and r is the ratio of boss radius to diaphragm radius. This correction is less than 20% for boss ratios less than 0.4 with values of q greater than 4. It is very significant, however, for nearly flat diaphragms with boss ratios greater than 0.3. The influence of a boss on the cubic term is somewhat more complicated; a factor similar in magnitude to n_p can be used to modify the b_p term. A recent, quite extensive analysis is available in the work of Liu Renhuai [9].

There is an additional factor that needs to be considered depending on the method of fabrication of the diaphragms. The traditional approach has been to use a heavily doped boron layer as the etch stop used to form the diaphragm. It has been shown [7] that these etch stops introduce considerable residual tension in the resulting diaphragms. For large values of initial tension the deflection of a flat diaphragm can be represented by:

$$\frac{PR^4}{Eh^4} = \frac{4\sigma R^2}{Eh^2}\left(\frac{y}{h}\right)$$

where σ is the initial stress. This resistance to bending due to initial stress can be added to the terms given above using the principle of superposition to give, for a flat diaphragm:

$$\frac{PR^4}{Eh^4} = \left(\frac{16}{3(1-\nu^2)} + \frac{4\sigma R^2}{Eh^2}\right)\frac{y}{h} + \frac{2.83}{(1-\nu^2)}\frac{y^3}{h^3}$$

This initial tension in very heavily doped etch stops can be very great. Chau and Wise report a 3 mm square diaphragm, 1.7 μm thick, that is 600 times stiffer than a stress-free diaphragm. The use of an electrochemically etch-stopped diaphragm can produce a structure that has considerably less residual stress.

Corrugated Diaphragm Fabrication

The method used to fabricated these corrugated diaphragms has been to etch a series of grooves on the top surface of the silicon wafer. These grooves can be isotropically or anisotropically etched, depending on the desired final diaphragm contour. Typically they have been plasma etched using a planar etcher to produce isotropically etched contours. Since an isotropic etch is used, the grooves can follow almost any desired pattern, including circular, spiral, serpentine or radial. An example of the type of grooves used in this work is shown in Fig. 1. These grooves are about 12 μm deep and 20 μm wide. The slight

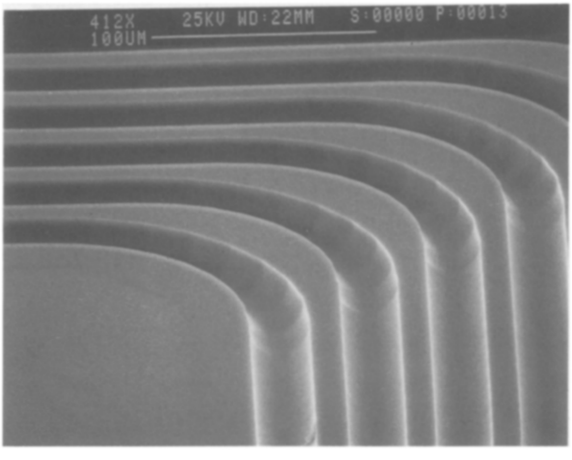

Fig. 1. Plasma etched grooves for corrugations.

sidewall features are caused by the CAD system being set to approximate a circle with a 36-sided polygon.

An etch stop is then diffused into the convoluted surface so that the etch-stop layer follows the etched contours. The silicon is then etched from the back side of the wafer, with the etch stop producing the desired corrugated cross-section. With conventional plasma etching techniques it is straightforward to produce etched groove depths from a fraction of a micrometer to about 50 μm. If boron etch stops are used, the available diaphragm thicknesses range from about 0.5 μm to about 10 μm. A similar range is available with diffused electrochemical etch stops, although the maximum thickness can be increased above 20 μm with sufficiently long diffusions. A typical view of a back side of a diaphragm is shown in Fig. 2.

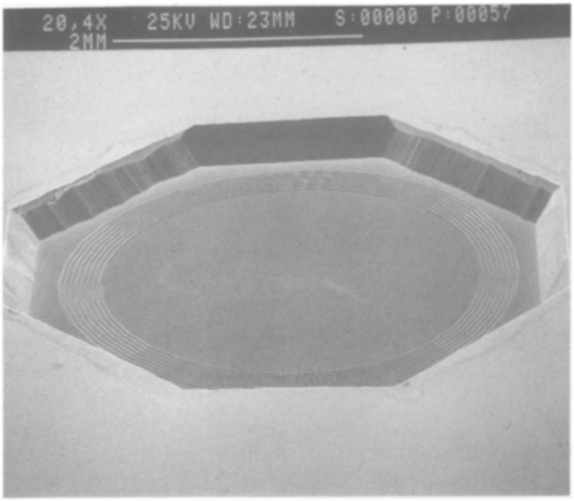

Fig. 2. Back-side view of bossed, corrugated diaphragm.

It is also possible to produce corrugated diaphragms from materials other than silicon by following nearly the same procedure. Any material which can be conformally coated to the etched silicon surface and can withstand the final silicon etch can be left as a free-standing diaphragm. Our work has produced diaphragms from thermally grown oxide and from CVD silicon nitride, which allows more design flexibility in the range of material parameters and diaphragm thicknesses. There is the added complication of the residual stress inherent in any thin-film deposition technique, which can decrease the strength of the diaphragm or affect its characteristics.

The precise shape of the corrugation profile is not particularly important in determining the characteristics of the diaphragm [10]. Work done in our laboratory has shown, however, that trapezoidal profiles fabricated by anisotropic etching from the front side of the wafer cause stress concentration in the corners of the diaphragm, which considerably reduces its maximum deflection.

Experimental Results

In the present work a number of different diaphragms have been fabricated with a range of diameters, corrugation depths, diaphragm thicknesses and boss ratios. All of the corrugated diaphragms have been made with boron etch stops. The diaphragms have been tested by applying a differential pressure to the diaphragm and measuring the deflection optically. A typical example is a 4.2 mm diameter, circular diaphragm with a center boss diameter of 1.68 mm. The diaphragm thickness was measured to be 3.5 μm and the corrugation depth was measured to be 10 μm, to give a q of about 3.6. Adjacent devices were made

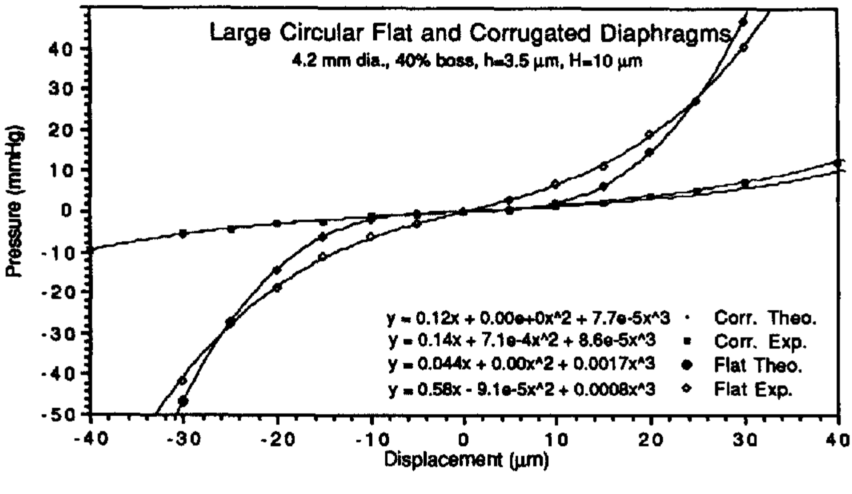

Fig. 3. Deflection characteristics of flat and corrugated diaphragms.

with and without corrugations to ensure accurate comparisons between the two types of devices. Figure 3 shows the deflection characteristics of these diaphragms with the theoretical results for comparison. The theoretical flat diaphragm curve assumes a stress-free diaphragm.

The linear coefficient for the corrugated case represents a sensitivity of 7.5 μm/mmHg. There is a factor of 13 between the theoretical and experimental linear terms for the flat case. This is due to the tension of the boron etch-stopped diaphragm used in these diaphragms. The average stress can be calculated to be 25 MPa. This ratio is less than the factor of 600 reported by Chau and Wise, which may be accounted for by different boron concentrations, silicon etching or annealing conditions. Note however, that the linear and cubic terms for the corrugated case are nearly identical, showing the degree of stress relief available even for these shallow corrugations.

Capacitive Pressure Sensor

The use of corrugated structures is very useful for the fabrication of capacitive devices. One of the primary problems with using conventional flat diaphragms for capacitive pressure sensors has been the trade-offs associated with using very thin diaphragms and narrow plate spacings [11]. Since the flat plate deflects more in the center than the edge, the point where the center deflection equals the gap sets the maximum operating pressure of the device. The total capacitance change in the device is reduced, since the deflection of the outside of the diaphragm is a small fraction of the center deflection and therefore does not contribute to the output signal. Additionally, as has been mentioned earlier, the deflection of the center of the plate becomes non-linear for deflections that are a small fraction of the diaphragm thickness, which sets a limit on the maximum gap and also affects the frequency response of the device due to damping. The use of bossed, corrugated structures introduces a new set of design considerations that reduce some of these problems.

The use of flat diaphragm, bossed structures is less attractive for capacitive sensors than for piezoresistive sensors due to the relatively larger travel desired for capacitive sensors. The use of a corrugated support can easily extend the linear travel of a diaphragm by a factor of 50 over an equivalent flat diaphragm. Figure 4 shows the theoretical deflection characteristics for a flat and a corrugated diaphragm with the same linear deflection characteristics. The corrugated diaphragm in this case has a q of 12.3 and provides the same linearity at about 10 times the deflection of the equivalent flat diaphragm.

An early prototype of a capacitive pressure sensor was fabricated with a bossed, corrugated diaphragm support similar to the device in Fig. 4. The circular diaphragm was 3.5 mm in diameter with an 80% boss. The corrugations were 12 μm deep, and the diaphragm was about 1.2 μm thick. This device was assembled with a glass cap with a 1.25 mm diameter sense electrode and a 10 μm initial gap. The capacitor gap area was vented, and pressure applied to the back of the silicon diaphragm. Figure 5 shows the experimental and theoretical results for such a sensor.

This device operates over a usable pressure range of about ±1 mmHg. The linear deflection of this diaphragm is about 7.8 μm/mmHg, and the use of a bossed structure produces piston-like travel over the entire central region of this device. When unconstrained, such a diaphragm can be repeatably deflected over 50 μm without breaking.

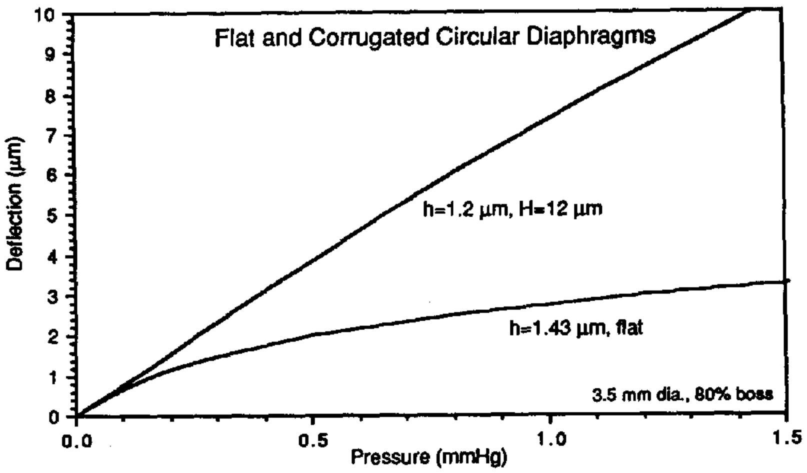

Fig. 4. Comparison of flat and corrugated diaphragm responses.

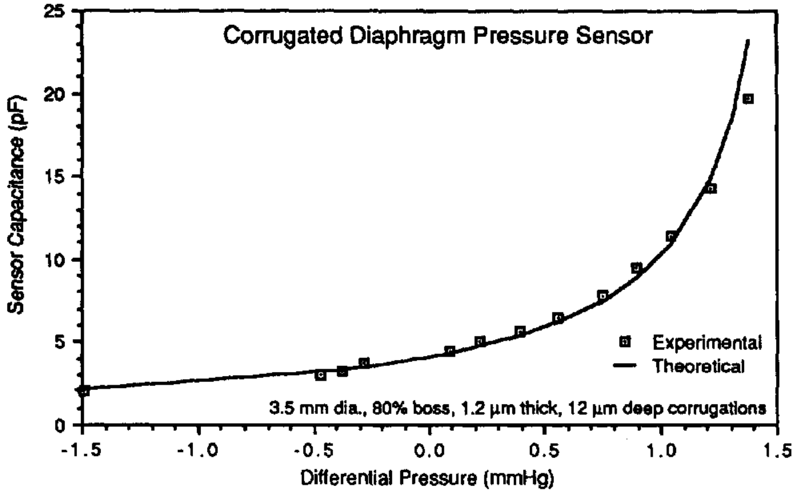

Fig. 5. Prototype capacitive sensor response.

The sensitivity of this structure can be increased by thinning the diaphragm, reducing the boss ratio or decreasing the corrugation depth. For example, a similar structure with a boss ratio of 20% would have a sensitivity of about 28 μm/mmHg, and if the corrugation depth was reduced from 12 μm to 4 μm with a 20% boss, the sensitivity would be about 150 μm/mmHg, keeping the same 1.2 μm diaphragm thickness. Further reduction of the diaphragm thickness to 0.6 μm, which has been accomplished successfully, with the 4 μm corrugation depth and 20% boss ratio would result in a sensitivity of about 440 μm/mmHg, a factor of 56 more sensitive than the original design.

Conclusions

The introduction of corrugations into the fabrication of diaphragms increases considerably the design flexibility for the use of these elements in devices. In particular, applications requiring large, linear displacement are now possible, which was not the case using traditional techniques. These corrugations are introduced using processing techniques that are compatible with most other silicon processing techniques, not through the use of incompatible materials. Thus they should be useful in a wide variety of practical devices. In addition, since the corrugations tend to relieve the residual strain in the diaphragm material, it is possible to use heavily doped boron or CVD nitride as the etch-stop material, which is more difficult when using flat diaphragms. The design information available from decades of work with corrugated metallic diaphragms appears to be applicable for use in silicon designs, again facilitating the use of these corrugated structures in practical devices. Devices which have already benefited from the use of this technology include velocity sensors, capacitive pressure sensors, acceleration switches, optical elements and valve diaphragms, although the work has really just begun.

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