BASIC ADVANTAGES OF THE ANISOTROPIC ETCHED, TRANSVERSE GAGE PRESSURE TRANSDUCER

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INTRODUCTION

Endevco's innovative design approach provides miniature pressure transducers that are not only small and have high frequency response, but have excellent linearities, high sensitivities, and stability characteristics superior to many other pressure transducers. Nonlinearities of 0.1% FS (Best Straight Line) are not unusual, along with 300 mV output at full scale with 10 V input. Ranges to as low as 2 psi (~14 kPa) are feasible in a case diameter of 0.092 inch (2.34 mm).

Are these transducers subminiature flat-diaphragm diffused silicon designs? In one word, no! They use four piezoresistive silicon elements in a Wheatstone bridge, but their similarities to earlier designs end there. The patented design implementation is novel and provides basic advantages to earlier designs.

Traditionally, miniature silicon pressure tranducers have been made similar to most large flat diaphragm strain gage transducers. When pressure is applied to a flat diaphragm, bending stress is distributed over its surface, changing from compression in one area to tension in another. Strain gages can be positioned on a diaphragm to provide increasing and decreasing resistance. For more than two generations four-arm Wheatstone bridge transducers have been made this way, by simply cementing gages to one side of a metallic flat diaphragm.

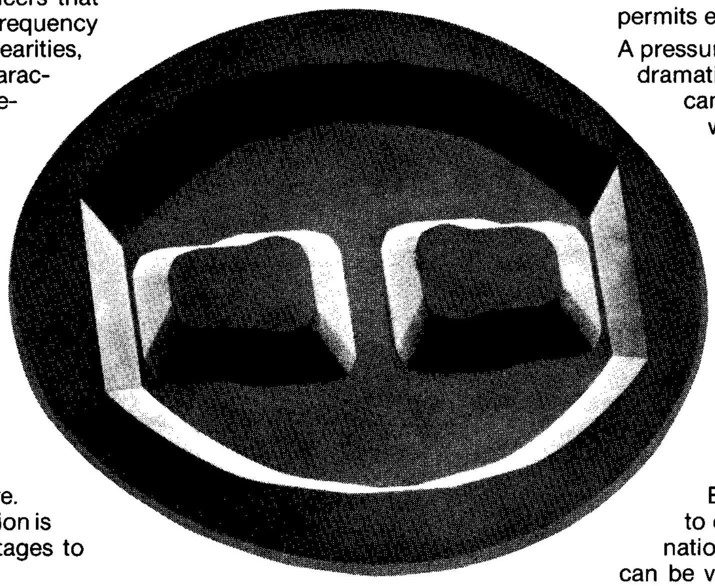

Figure 1 — Photograph of diaphragm taken with scanning electron microscope 0.05 in. (1.25 mm) O.D.

Now for almost a generation transducers have been made with piezoresistive gages diffused into flat circular diaphragms of silicon, thus providing atomically bonded elements. By using silicon semiconductor technology, miniaturization was achieved. The process has not, however, provided other technical advantages. It simply reduces the diameter of the circular diaphragms and permits extremely thin diaphragms.

A pressure transducer design can be made dramatically more efficient if the stresses can be concentrated at the locations where the strain gages are placed. Stress should not be spread over a large area such as on a flat circular diaphragm. In general, if a stucture is under bending stress, stress concentration can be achieved by varying the thickness of the bending element. This is one of the *basic conceptual differences* which provides the superior performance of all Endevco transducers.

THE SCULPTURED DIAPHRAGM

Endevco diaphragms are shaped to concentrate stress using a combination of plate and beam theory. This can be visualized by referring to Figure 1 which shows a circular diaphragm having two thicknesses. It is considerably thicker at the outer edge and has two islands in the middle section. Notice how close the islands come to each other and to the edge.

Figure 2 shows a photomicrograph of a diagram sectioned to show this. One can

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easily see that a distributed load, or pressure, on one side results in stress concentrations at points A, B and C where all the bending occurs. If a stress sensitive material is placed at A, B and C, a sensor with improved efficiency results in comparison

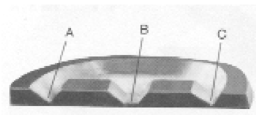


Figure 2 — Photomicrograph of diaphragm section through notches and islands.

to the flat diaphragm. The gage elements for our design are diffused into the diaphragm over the entire grooves at points A, B and C.

Figure 3 — Photograph of diaphragm, glass-bonded to heavy silicon ring, 0.1 in (2.5 mm) O.D. by 0.02 in (0.5 mm) thick.

FORMED BY ANISOTROPIC ETCHING

Our diaphragms are fabricated from single-crystal silicon. This material is anisotropic, meaning that its physical properties vary according to the direction in which they are measured. Another characteristic of anisotropic materials is that their chemical reaction rates may vary according to crystalline directions. When placing a crystal of silicon in a caustic bath, such as hot hydrazine, the material is etched faster in certain directions than others. Simply put, the material seems to have a mind of its own, and it forms well defined patterns and contours. By controlling etch bath parameters, the ratio of etching rates with direction can exceed 30 to 1. This results in precise control of shape. As can be seen by Figures 1 and 2, the technique provides deep notches and flat bottoms to the thinned sections. To obtain optimum transducer performance, the crystal must be correctly oriented. Then, using a multiple step lithographic, etching, and diffusing process, the part is fabricated. This technology is basic to the semiconductor industry. It should be mentioned that varieties of etch petterns and contours can be achieved which permit the concept to be used over a wide range of pressures and sizes.

TRANSVERSE GAGE APPROACH

The sculpturing of the diaphragm explains a significant part of the benefits of the Endevco design, but not all. Optimizing the piezoresistive characteristics is also important. The piezoresistive coefficients of silicon semiconductor materials vary with the direction of stress in the crystal and with the dopant material and its amount. Most prior art devices have been designed to stress the gage material so that the gage increases its length. If such a gage were placed in the stress concentration groove of the sculptured diaphragm, it would be stitched back and forth from one end to another — a miniaturization of the larger wire and foil gage approaches. As the groove bends, the effective gage length would change. Another approach is to use a transverse gage; that is, one that is laid lengthwise in the groove. As the groove bends, this gage is strained so that it effectively changes width[1].

P-Type (110) silicon gage material has an important peculiarity. Its response to transverse strain is equal and opposite to its response to strain parallel to its length. With the appropriately doped material in the groove and with pressure applied, the strain is transverse to the length of the groove and the groove is protected from strain parallel to its length by the full thickness material. In other words, it does not bend in that direction. The piezoresistive sensitivity of this P-Type (110) gage is quite high and its variation with temperature is fairly low. The companion advantage to this approach is that the silicon diaphragm lends itself to anisotropic etch patterns which facilitate this configuration.

LINEARITY ADVANTAGES

A fundamental benefit from using the stress concentrated transverse gage is that pressure transducer amplitude linearity can be excellent. The change of resistance with stress for a single parallel P (110) gage is a more linear function than that for a transverse gage. When used in a bridge configuration, however, with one element in tension and the other in compression, the transverse gage approach can be better. A parallel gage has decreasing sensitivity with increasing stress in both tension and compression. The bridge nonlinearity is the average nonlinearity of both. The transverse gage has decreasing sensitivity in tension and increasing sensitivity in compression, so that the average nonlinearity is close to zero.

The requirement for equal and opposite strain fields is a restraint on transducer design. This is the reason for the relatively wide central groove shown in Figure 1. On the other hand, the designer can counteract other nonlinearities in a design by shifting the strain balance between the increasing and decreasing gages. In production practice, the balance of strain levels can be maintained closely enough to provide nonlinearities to full scale of about 0.1% to 0.4% BSL, depending on product and range. The combination of using stress concentration and transverse gages provides about three times better linearity to full scale than the alternative flat-diaphragm approaches. This advantage can be even greater for pressures above full scale. Many of the Endevco pressure transducers provide 1 volt of output with less than 1% nonlinearity.

SENSITIVITY AND STABILITY ADVANTAGES

The output from these transducers is about 300 mV at full scale when 10 Vdc is applied. This higher than normal value is a result of two factors:

1) The transverse gage approach, which is more linear than the parallel gage approach, permits higher outputs for equivalent nonlinearities.
2) Concentration of the stresses over the entire area of the 4 strain gages, and only over that area, increases efficiency.

From a practical standpoint each of these transducers can be used over a very wide span of pressures. They can even be used for measurements above the specified full range. The Endevco specifications show a value for typical nonlinearity for pressures to 3 times full scale, and all transducers are tested to 3 times full scale. In many ways, this suggests that full scale has been chosen conservatively. It is a pressure level where the transducer still has an unusually high overrange capability.

Because silicon is an excellent spring material the transducers have low hysteresis, usually below 0.05%. At temperatures below 600°C, the silicon stress-strain curve has no plastic zone and the material has essentially no creep. Even at pressures above full scale, and sometimes to diaphragm fracture, the transducers perform with little error.

Single crystal silicon is a strong material whose strength depends significantly on the quality of the material. The tech-

Model	Linearity Over Normal Range	Linearity Over Three Times Range	Burst Pressure	Resonance Frequency
8510-2	.4% to 2 psi	1.2% to 6 psi	40 psi	45 000 Hz
8510-15	.2% to 15 psi	0.4% to 45 psi	200 psi	100 000 Hz
8510-100	.1% to 100 psi	0.3% to 300 psi	500 psi	240 000 Hz
8510-2000	.1% to 2 000 psi	0.5% to 6 000 psi	10K psi	900 000 Hz
8514-20	.1% to 20 psi	2.9% to 60 psi	220 psi	180 000 Hz
8514-100	.1% to 100 psi	0.5% to 300 psi	650 psi	410 000 Hz
8530-15	.1% to 15 psi	0.5% to 60 psi	110 psi	120 000 Hz
8530-200	.1% to 200 psi	0.6% to 600 psi	950 psi	360 000 Hz

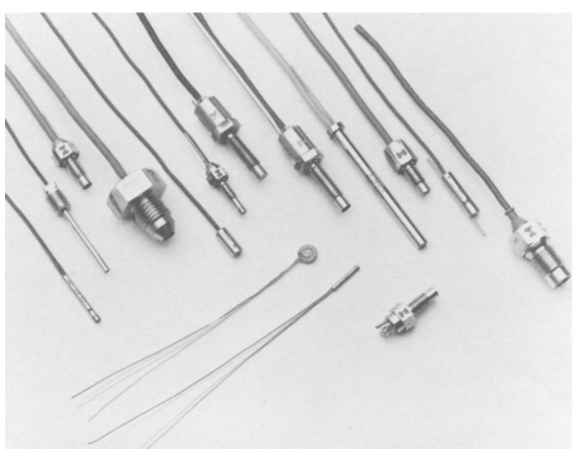
Figure 4 — Tabulation of Transducer Calibration Data (Typical BSL Linearity)

nique for growing the crystal, the technique for forming the part, the resultant dislocation density, surface scratches and micro-pits are all important factors. Because less of the effective area of the diaphragm is under high stress with this design than with others, the probability is better that the diaphragm will withstand higher pressures. These aspects are particularly advantageous for the low range transducers. For example, a 2 psi full scale transducer withstands typically 40 psi, or 20 times full scale.

So that the performance inherent in this sculptured diaphragm is not degraded when it is used to produce a finished transducer, the diaphragms are first attached to a heavy ring. This ring is also made of silicon and the parts are joined with glass at high temperature. The end result is essentially an all silicon assembly having a thickness ratio from the edge of the diaphragm to the working areas of about 20:1. An example of this construction is shown in Figure 3. By taking this design approach the diaphragm is rigidly supported and the strain takes place in the strain gages where it should.

RESULTS AND CONCLUSIONS

The performance of pressure transducers using the anisotropic etch diffused silicon diaphragm is best described by the product specifications. Transducers with normal ranges of 2 psi (~14 kPa) to 20 000 psi (138 MPa) are available. A simplified comparison showing a few of the characteristics which highlight the technical factors discussed above is shown in Figure 4. As one can see, this approach provides a low range capability, high sensitivity, improved linearity, good stability . . . all resulting from an innovative design approach.



Examples of Endevco's Line of Pressure Transducers