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A Diffused Silicon Pressure Transducer With Stress Concentrated at Transverse Gages

Technical Paper 267

By Bruce Wilner

A diffused silicon pressure transducer with stress concentrated at transverse gages

Many Endevco Technical Papers are timeless in that the information they contain is as applicable today as when it was first published. Endevco's Dr. L. Bruce Wilner at the International Instrumentation Symposium originally presented the following technical paper in 1977. This patented process has been expanded and continues to be the basis for Endevco's high sensitivity pressure products.

Abstract

The use of anisotropic etching in silicon transducer elements allows the concentration of stress in areas selected for strain gages. Concentrating stress in gaged areas, while maintaining low stress levels elsewhere gives greater sensitivity for the same resonance frequency as a plane diaphragm. Transverse gages, gages aligned at right angles to stress, are particularly suited to the concentrated stress areas. Aligning a gage along a bending elastic hinge can provide a large piezoresistance signal from a very small volume of stressed material. The transverse gage can also provide better linearity than a similar longitudinal gage.

Background

The concept of a silicon pressure-summing member having diffused strain gages mechanically integrated with it has a fairly long history. In 1960 bulk silicon gages were items of commerce, and diffusion techniques were being advanced rapidly for transistor use. In 1961 a diffused silicon strain gage was commercially available, and there was a discussion in the literature of diffused pressure transducers. In 1962 a silicon pressure transducer with integral diffused gages was described in the literature, and at least two commercial diffused diaphragm transducers were announced.

Although these first silicon diaphragm diffused pressure transducers were not particularly successful, later designs eliminated most of the problems and are fairly widely used. Silicon diaphragm diffused transducers now compete across a spectrum from the most tightly specified aerospace applications to the most inexpensive transducers for automotive applications.

Anisotropic etching of silicon has also been known for a long time. In the early days of growing silicon single crystals the angular geometry of certain etch pits gave a quick indication of crystal orientation. The pits would etch preferentially to certain planes, and the planes could be related to the crystal axes. In the late 1960's systematic attention was given the means of shaping silicon to isolated devices in wafers, anisotropic etching was one of the means. In 1969 Lee provided an extensive description of the hydrazine etching of silicon and the anisotropy of the etch.

Anisotropic etching was applied to silicon diaphragm diffused pressure transducers by Saumun, Wise, and Angell, who found it a particularly advantageous way to thin diaphragms for a very small, very sensitive transducers.

Introduction

In general, a strain gage pressure transducer functions by using energy absorbed from the pressure of the measured fluid to produce strains that are measured by strain gages. The strain gages are usually wired into a Wheatstone bridge with an external power source, giving zero unbalance signal at zero pressure. Increasing pressure gives increasing strain that gives increasing unbalance signal.

Silicon diaphragm, diffused strain gage pressure transducers have been customarily made in the form of fixed-edge plane diaphragms. This form is convenient and predictable, the pressure to strain relationships having been worked out exactly for isotropic materials and published in textbooks.

The "fixed edge" assumption is maintained by affixing the working portion of the silicon diaphragm to a more massive silicon ring. Either a thin working wafer is bonded to a thick support, or a thin working section is etched into a thick wafer, or both.

Although the fixed-edge plane diaphragm pressure transducer is convenient and predictable, it is not optimized to its transducer function. The stresses and strains appear in their predicted patterns, and strain gages must be placed on the strain patterns in such a way as to maximize output and linearity, while allowing for the finite size of the gages and the precision with which they can be placed. Placement of diffused strain gages is further complicated by strong sensitivities both to crystal orientation and to transverse strains. Usually the strain gages occupy only a small fraction of the most highly stressed surface. In very small devices where gages occupy much of the stressed area, much of the gage area will not be properly aligned with the strain and/or the crystal axes.

The failure to optimize the geometry of the diffused strain gage transducers has two effects. It increases the probability of brittle failure due to surface defects, at any given pressure, and it increases the amount of strain energy (the product of pressure and displacement) that must be extracted from the measured fluid to produce a desired resistance change. Both effects reflect the presence in the design of surface areas, unneeded or unsuited for the placement of strain gages, which are stressed as highly as the areas where the strain gages are placed.

By using etching techniques to concentrate stress in a silicon diaphragm, the geometric efficiency can be improved. Anisotropic etching is particularly suited to this function because of the sharpness with which details can be outlined.

Anisotropic etching

A hydrazine or a caustic etchant applied to silicon will etch more rapidly (see Figure 1) in a (100) or a (112) direction than in a (111) direction. By controlling etch bath parameters, the ratio of etching rates can be made greater than 30:1, and an etch cavity with an astonishingly flat bottom can be produced. The anisotropic etching is most effectively employed etching into a (100) plane. This plane allows the production of flat-bottomed (110) etch patterns, and mask lines running in the (110) direction can be maintained with very little undercutting.

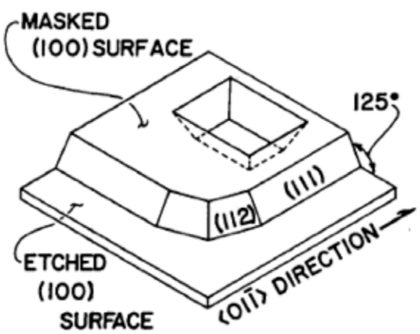

Figure 1: Anistropic etch patterns in silicon

Figure 1 gives an impression of anisotropic etching into silicon. In a cavity, the planes are stable, and even an irregular opening in a mask will eventually produce a pyramidal hole bounded by four planes. A fairly tidy mesa can be formed under a rectangular mask aligned with the directions, where the planes intersect the masked plane. The planes are stable along the sides of the mesa but are attacked at the corners of the mesa where rapid undercutting forms planes. The planes meet the planes at 125° angles, so the base of a mesa is wider than its top by 1.41 times the mesa height.

Aligning a rectangular mesa with the directions is not rewarding. Undercutting proceeds about as rapidly as etch deepening, giving a rough surface sloping about 45º. Etching into planes other than 100, produces quite complex patterns, usually with rough surfaces. The use of anisotropic etching clearly favors rectangular geometries in the plane, with the principal directions aligned.

Piezoresistance

The piezoresistance coefficients of silicon tend to favor gage alignment in the rectangular direction. In this direction P-type silicon has the highest gage factor available in silicon. Unfortunately, the plane does not include a direction.

The principal directions available in the plane are 100 and 110. N-type silicon has a substantial gage factor in the 100 direction, about 70% of the P-type 111 gage factor, but its temperature coefficient is substantially greater than that for any P-type gage. In the 110 direction, a P-type gage will have a gage factor ¾ that of the 111 direction, roughly equal to that of the 100 N-type gage and with a lower temperature coefficient.

The P-type 110 gage has an important peculiarity; its response to transverse strain is equal and opposite to its response to strain parallel and its length. If such a gage were placed in the middle of a plane circular diaphragm, where strain is the same in all directions, its response would be approximately zero. Because anisotropic etch patterns seek to align themselves with the 110 directions, and because of the lower temperature coefficient of gage factor, the P-type 110 gage is the most promising gage to use for an anisotropically etched device.

Transducer design

In attempting to optimize the transducer function of a diffused gage on an anisotropically etched substrate, there is an advantage to using the 110 gage in its transverse mode. Etching a groove with a narrow bottom is easy with the anisotropic etch. If this groove bottom is bent, using full thickness material for leverage and anchoring functions, a narrow band of strain is produced at the groove bottom and on the opposite surface. The direction of the strain is transverse to the length of the band, and the band is protected from strain parallel to its length by the full thickness material. See figure 2

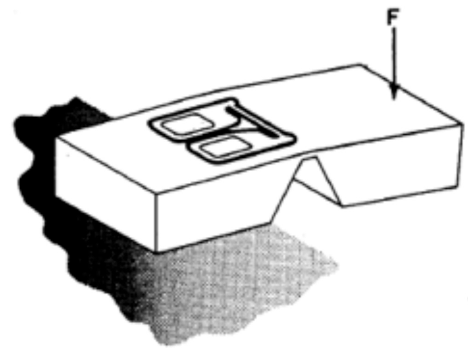

Figure 2: Transverse gage on etched bar

A strain gage could be placed on this band aligned parallel to the strain by stitching it back and forth across the band. A strain gage using the transverse mode, however, can be simply aligned with the strain band, all in the area of uniform (and maximum) strain. The groove bottom can be narrowed to approximately the width of the gage. The area to be highly stressed need be only enough to allow acceptable resolution of the gage dimensions, and to dissipate the electrical heating power of the gage.

A pressure transducer application of this concept is shown in Figure 3. Two gages are placed opposite a groove bottom in the center. Two gages are placed opposite a groove bottom near the edge. Conductive traces lead to compact pads on the rim of the device. More discussion of this device will be given later.

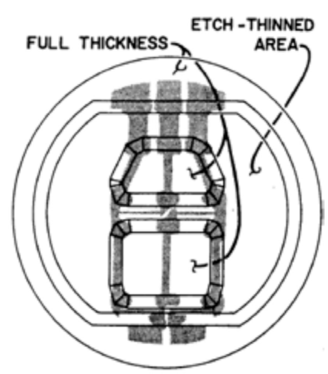

Figure 3: Pressure transducer die

Linearity

The transverse 110 gages display a surprising property; their nonlinearity is not the same as that of a 110 gage aligned parallel to the strain. As is expected, the gage factors for small strain are equal and opposite for transverse and parallel gages. The parallel gage increases resistance in tension; the transverse gage decreases in tension. Neither gage is strongly nonlinear, though the transverse gage is less linear than the parallel gage. However, where both gages show declining sensitivity to increasing tension, in compression the parallel gage again shows declining sensitivity but the transverse gage shows increasing sensitivity at higher strain.

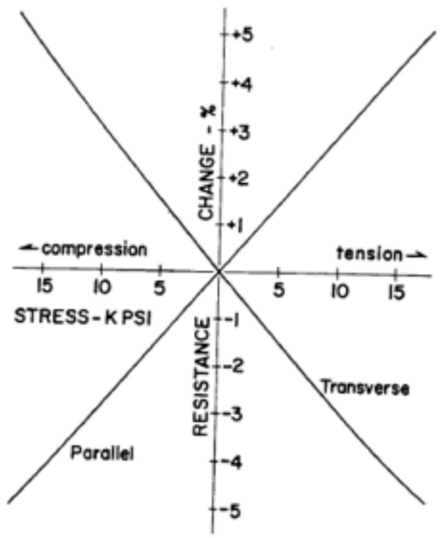

Figure 4: Response of (110) gages

This is better seen in Figure 5, in which the lines of initial slope have been subtracted from the data of Figure 4, and data replotted against resistance change. The units are the same on both axes, so at 5% resistance changes a parallel gage deviates by 0.04% resistance change for 8% of reading from a straight line.

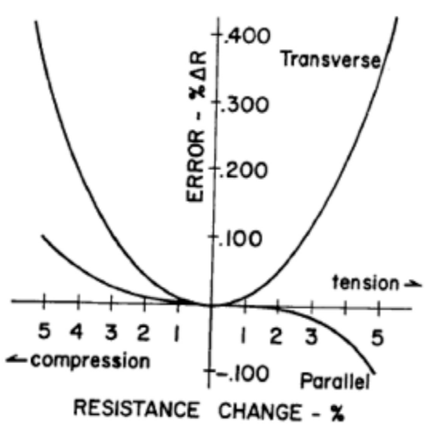

Figure 5: Deviation from line of initial slope

At first glance, the nonlinearity of the transverse gage seems to be a significant problem. However, because the gages are used in pairs, one in tension, one in compression, the nonlinearities of the tensile and compressive gages counteract each other, one increasing in sensitivity, and the other decreasing in sensitivity. For equal tensile and compressive strain, the nonlinearities balance each other extremely well. In contrast, the nonlinearities of parallel gages are the same for a pair as for individual gages. The individual parallel gage is more linear than a transverse gage, but a pair in equal and opposite strain fields is not so linear as a transverse pair.

The requirement for equal and opposite strain fields is a restraint on transducer design. This requirement is the cause for the relatively wide central groove in Figure 3, for instance. On the other hand, the designer can counteract other nonlinearities in a design by shifting the strain balance between the increasing and the decreasing gages. In production practice the balance of strain levels can be maintained closely enough to allow a specification of 0.25% best fit straight line for a full scale of about 3.8% resistance change in each gage.

Pressure tranducer

The pressure transducer die of Figure 3, in a 2mm size, affords a higher sensitivity for a given resonant frequency than does a plane diaphragm transducer of comparable size. A plane diaphragm device with a resonance of 150kHz will have a sensitivity of 50 nanovolts/V Pascal (.36m V/V psi). A 150 kHz anisotropically etched device will have a sensitivity of 130 nanovolts/V Pascal (.9m V/V psi). This difference reflects the larger fraction of the absorbed displacement-times-pressure energy, which is applied to the strain gages.

Because a very small fraction of the surface is stressed to the high level used for the strain gages the etch contoured device allows both a higher resistance change be specified at full scale and that the overload above this full scale be greater. Typically a resistance change above 3% is specified for the contoured and a resistance change of 2% to 2.5% is specified for the plane diaphragm. A 3x overrange is specified for the contoured device compared to 2x typically for the plane diaphragm. Further, a differential burst pressure can be specified much higher, e.g.; at 200 psi for a 15 psi full scale. These ratings, of course, are subject to considerations of acceptable statistical loss rates, and reflect the economics as well as the physics of the transducers.

The nonlinearity of these devices is guaranteed as 0.25% best fit straight line, but individual devices have been studied with nonlinearity less than 0.1% from best fit straight line. In low range specimens below 1 atmosphere sensitivity tends to decline beyond full scale because of stretching of the flexing portion, a shift from diaphragm mechanics to membrane mechanics. In higher range designs, 3 atmospheres and above, this shift is unimportant, and the specimens have been measured with nonlinearity less than 0.25% deviation from best straight line from zero to a pressure six times the design full scale. Such extended linearity is not routine, to be expected of each transducer, but its occurrence demonstrates the possibility of balancing the non-linearities far beyond the 5% resistance change of Figure 6 to 20% resistance change or beyond.

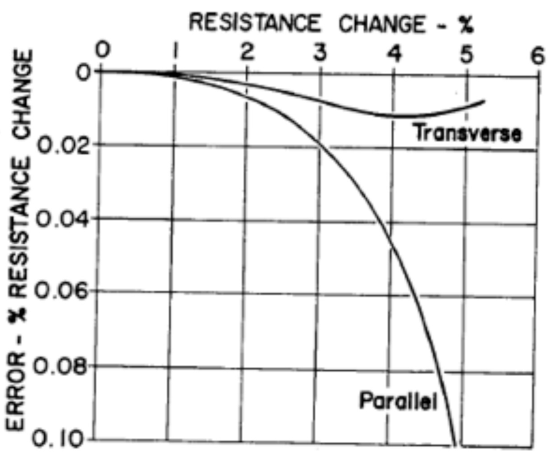

Figure 6: Non-linearity of a half–bridge pair

Conclusion

The combination of the use of anisotropic etching to form bands of uniaxial, concentrated stress in a silicon pressure transducer with the use of diffused gages lying along the bands and transverse to the stress affords a considerable improvement in the performance of the transducer. The improved performance may be seen as an increase either of resonant frequency or of sensitivity for a given die size. A significant nonlinearity of individual transverse gages is reduced to insignificance by pairing and balancing the gages. In some cases this nonlinearity can be turned to advantage to balance other non-linearities in the transducer.

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