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Miniature Pressure Transducers for Use to 300° C

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Miniature pressure transducers for use to 300º C

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Abstract

A family of miniature pressure transducers is described which employs silicon strain gages bonded with silicon dioxide to shaped silicon diaphragms. A very high doping level is used in the strain gages, so that sensor performance is well assured to the 300ºC temperature limit. The performance is comparable to etch contoured diffused sensors of the same size. The 300ºC service limit is set by an integral ETFE cable and by organic resins used in the assembly.

Introduction

Integrally diffused silicon pressure transducers are in common use and provide good performance, particularly for aerodynamic studies. They are, however, temperature-limited. At about 160°C electrical leakage through the diffused junction becomes excessive and noisy. Various means have been proposed to isolate piezoresistive gages from four summing diaphragms at high temperature (1, 2, 3). We have adopted a means which allows use of single crystal material for both gages and diaphragms, and which suggests good performance well beyond our temperature of immediate interest. The temperature limit for the silicon sensor is set by our use of aluminum leads, and is well above other temperature limits in the transducer.

The complete transducer has, in addition to the sensor, a block of compensation circuitry, a stainless steel case, and an integral ETFE cable. These components and the seals between them present the real temperature limits of the transducer.

Silicon sensor

The starting point for this development was an existing family of diffused-gage sensors with etch-contouring to concentrate stress at the gages (4, 5). A moat-and-island pattern etched into the force-summing diaphragm concentrates pressure-induced strains at moat bottoms at the center and near the edge. Transverse strain gages are diffused opposite these moat bottoms (Figure 1). The concentration of stress at the gages gives both a large product of sensitivity times resonant frequency and strength to survive large overloads. The use of transverse gages offers an opportunity to manipulate linearity.

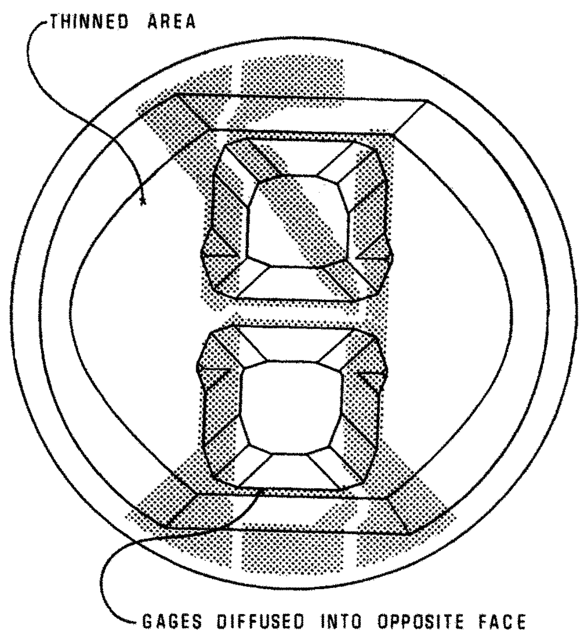

Figure 1 **Diffused, etch-contoured pressure sensor**

The available means for replacing the diode isolation of the strain gages by dielectric isolation are many and diverse. One of the oldest is bonding gages to a diaphragm with solder glass (1.2). A variation of this is to bond a film of glass to diaphragm with an electrostatic bond, then to bond the gage to the glass film by the same process (6). Another means is to use a dielectric diaphragm; silicon grown epitaxially on sapphire makes very nice strain gages. The sapphire, however, is difficult to shape into any but the simplest of diaphragms. Two other options are provided by growing onto a crystal of silicon first an insulating oxide and then a layer of polycrystalline silicon. The single crystal may be used to make a diaphragm, but the diaphragm is restricted to simple shapes. The single crystal may become the diaphragm and be elegantly etched, the polycrystalline material can be used to make gages, but the gage factor is low (7).

In this development single crystal silicon is used on both sides of the dielectric barrier, allowing both high quality gages and precise etching of the diaphragm. The dielectric barrier, which is also the mechanical bond between gages and diaphragm, is nearly pure silicon dioxide, strong, stable, and of low thermal expansion. The technique chosen is an oxide diffusion bond, in which a very thin film of low melting oxide wets the interface between two wafers, then at very high temperature dissolves and diffuses into thicker films of silicon dioxide to leave a bond of high temperature glass.

A wafer of diaphragms is etched to a specified configuration. The wafer to become gages is geven a heavy surface doping of boron, and the oxide diffusion bond is made, attaching gage wafer to diaphragm wafer. Then by chemnical means all of the "gage" wafer is removed except the heavily doped layer, about one micrometer thick. The gage layer is then patterned by photolithography into conventional zigzag strain gages on the high stress portions of the diaphragms and contacted with aluminum. The result looks quite similar to an integrally diffused sensor (see Figure 2).

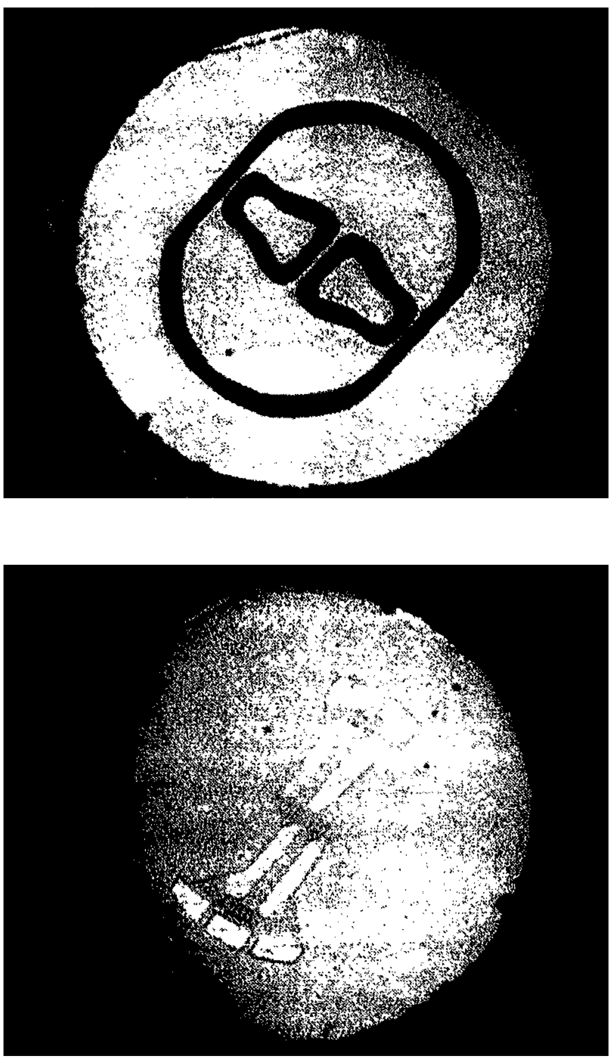

Figure 2 **Oxide-bonded die, two views**

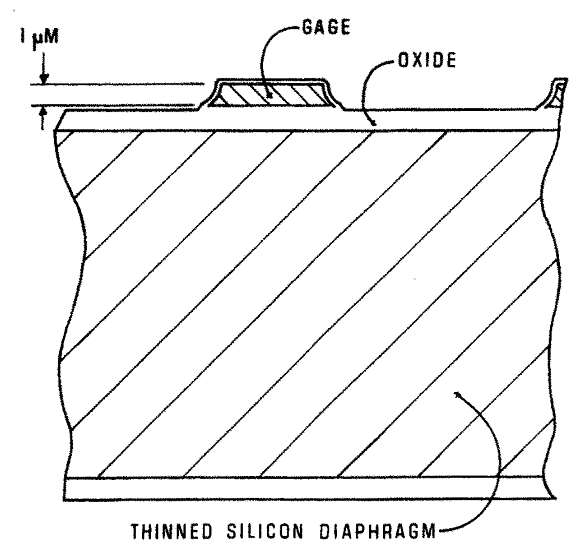

Figure 3 **Oxide-bonded gage**

On a microscopic scale there is significant difference between the oxide bonded gage and a diffused gage (see Figure 3). Where a diffused gage is mechanically continuous with its substrate, the oxide bonded gage stands well above its substrate on a layer of lower elastic modulus. This geometry makes the communication of transverse strain from substrate to gage very inefficient, and encourages the use of a lengthwise rather than a transverse strain gage. The strain field to be gaged is short in the direction of strain, broad in the direction across the strain. Gages are stitched back and forth across the strain field. The strain gages are heavily doped, P-type silicon of (111) orientation. The heavy doping reduces the gage factor but makes it less responsive to temperatuer, declining only 0.12%°C. The diaphragm with gages is bonded with solder glass to a more massive silicon ring to make diaphragm stresses more predictable and repeatable, and to make more remote the eventual connection to thermally mismatched material.

Compensation

Sensitivity compensation and zero balance resistors are incorporated into the transducer. Thick film resistors have proven adequate for this use. The gain compensation resistors are printed directly onto a ceramic substrate in the transducer and trimmed to accommodate various die resistances. Zero balance resistors are separate parts, cemented into place and wirebonded to the substrate.

Case and cable

The transducer is packaged in the familiar 10-32 bolt configuration (figure 4). The cable is a relatively conventional instrumentation cable, four conductor, shielded and jacked. The conductors are nickel plated to endure high temperatures. The insulation is ETFE FPFA, which is nicely waterproof, tough, etc., but which imposes the acute temperature limit on the transducer.

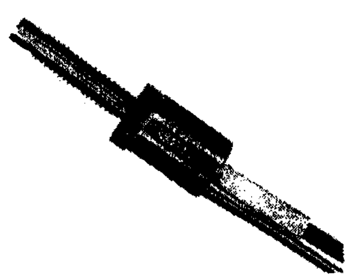

Figure 4 Completed transducer

At 316°C it melts. The ETFE is extremely difficult to seal, so is terminated just outside the case enclosure. Bare conductors are fed into the enclosure and sealed to make the case pressure tight. The case is 17-4 pH stainless steel, which is strong, oxidation resistant, corrosion resistant, and familiar. Unfortunately it is also of much greater expansion than silicon, so a soft seal is needed between silicon parts and the case. This seal is made with silicone rubber, and imopses a time-at-temperature limit on the transudcer. Heat-aging the rubber decreases its elasticity, so eventually on thermal cycling the seals leak. This limit is roughly 24 hours at 310°C or 200 hours at 285°C.

A polyamide cement is also used in the assembly. It has a greater time-at-temperature tolerance than the silicone rubber, but makes stable seals between dissimilar materials only when some very restrictive design conditions are met.

Performance

The performance of the transducer is quite similar to that of the etch contoured diffused transducers which it resembles, but extends to higher temperatures. Full scale response is cited as 300 mV at 10 V supply. Ranges from 10 psi (70 kP) to 200 psi (1.4 MP) have been built and evaluated. Resonant frequencies appear somewhat higher for these sensors than for comparable diffused sensors. A 20 psi unit was resonant at 180 kHz and a 100 psi unit at 280 kHz.

The linearity is good, but not quite so good as for diffused transverse gage sensors. The linearity is good

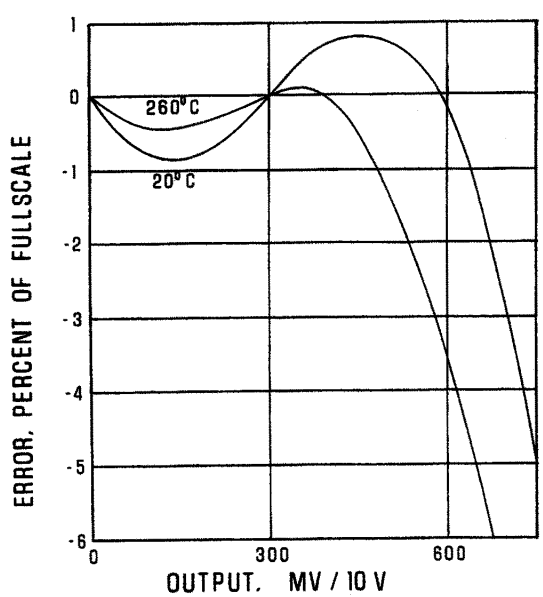

Figure 5 Nonlinearity

enough that there is little point to displaying an output vs. input curve. Linearity data are presented (Figure 5) as error relative to the line of endpoints vs. output. On this scale, error approaches 1% in the 300 mV nominal range at 20°C, but declines to 1/2% at 260°C. At the higher temperatuer, however, the sensitivity drops (error increases) not far beyond the nominal range. The shape of the nonlinearity is such that little improvement is made by deranging (using a transducer to a fraction of its nominal range).

Sensitivity compensation and zero trim are used to keep temperature induced errors to a few percent. Uncompensated, the sensitivity would decline 25% from 20°C to 300°C. With an ideal series resistor it would be held to ±1% over the range, but manufacturing tolerances are likely to leave a few percent of sensitivity shift (Figure 6). The initial zero unbalance of the sensors has been large, but has been quite stable with temperature. Zero and zero/temperature are reduced by the addition of fixed resistors to legs of the bridge. This typically leaves one to two percent each of zero and of change of zero over the temperature span. (Figure 7).

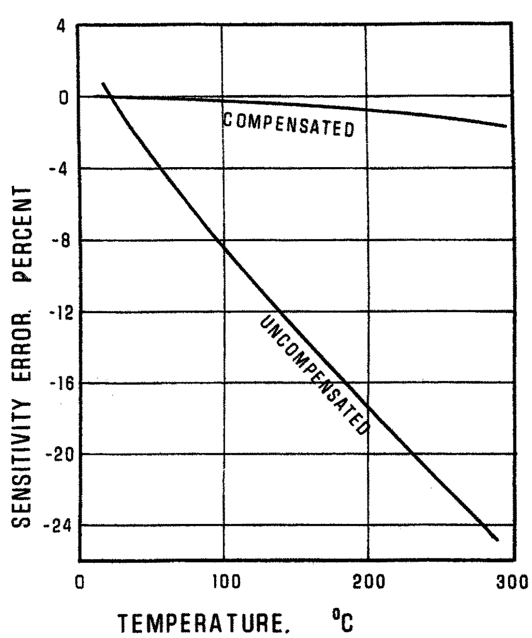

Figure 6 Sensitivity compensation

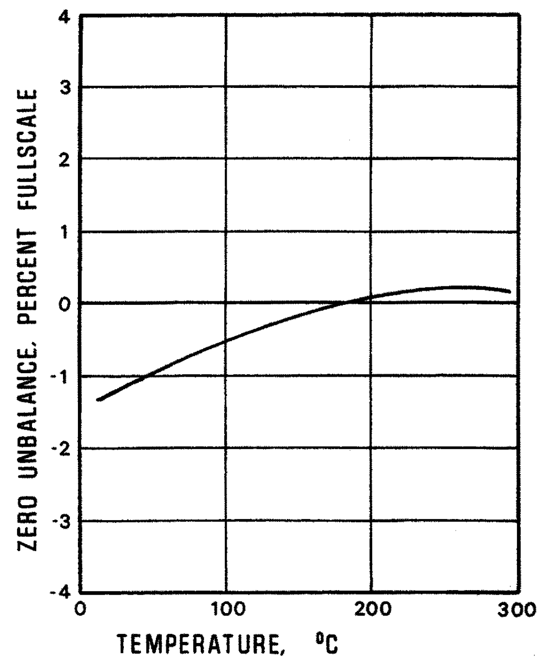

Figure 7 Zero Compensation

The designed temperature range of the transducer is 0°C to 300°C, and this is the range for which compensation and trim are applied. The transducer has been demonstrated to function properly at -180°C, but both zero balance and sensitivity showed appreciable response to the low temperature because they had been corrected only for the higher temperature. When given a thermal excursion from 20° to 290°C and back the transducers show a non-repeatability of the order of 1/4% of fullscale. This may be cumulative. It does not differ perceptibly from a 1/2 hour excursion to a 17 hour excursion. An attempt to find creep at full pressure and 290°C showed no creep above this threshold non-repeatabiity after 160 hours.

An incidental benefit of the dielectric isolation and the high doping level is an immunity to radiant energy. The response to the flashbulb flash test (ISA537.10, par. 6.7, procedure 2) is less than 0.2% F.S. It would be expected (not yet demonstrated) that ionizing radiation would be only a minor irritant to the sensor.

A penalty paid for extended temperature span is that overload capacity is diminished. Diffused contoured transducers typically have overrange survival at least 5 times nominal range. These oxide-bonded sensors have assured survival only to 2.5 times nominal range.

Summary

By employing an oxide-bonding technique we have produced a silicon-based sensor which retains the miniature size and much of the wafer-process fabrication typical of diffused pressure sensors. The sensor is comparable in sensitivity and frequency response to etch-contoured diffused sensors. The transducers made with these sensors are similar to those made with diffused sensors in size, appearance, and function but will operate continually at 260°C or with diminished lifetime to 310°C.

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