A Simple, High Performance Piezoresistive Accelerometer

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Abstract

This paper describes the structure, manufacture, and performance of a 1,000 g full scale piezoresistive accelerometer. This accelerometer has a very high resonant frequency, nominally 65 kHz, and is designed to have a sensitivity of 0.2 mV/g. The design is executed in (110) silicon. The piezoresistors and inertial system are formed in one etching step. The piezoresistors are suspended between the inertial mass and support rim, and are very small in volume, 7.8 x 10 -10 cc, thus needing very small strain energy.

Introduction

In impact testing, there is a need for an accelerometer with high resonant frequency and zero damping which responds accurately to fast rise times and short duration shock motions. The device also needs to have frequency response down to dc, or steady state acceleration, so it can measure long duration transients. Piezoresistive accelerometers respond to steady state acceleration, but they almost always have relatively low resonant frequencies.

This paper describes the structure, manufacture, and performance of a rugged undamped piezoresistive accelerometer which is designed for accurate shock measurement. This accelerometer is simple to fabricate, has high sensitivity, wide frequency range (DC to 13kHz), excellent linearity, small temperature effect, and the ability to survive high "g" shock.

Device Construction

The device is constructed from three bonded layers of silicon. The outer two layers are primarily protective, and enclose all but a row of terminals on the inner layer. The inner layer includes the principal parts of the sensor: inertial mass, piezoresistive gages, and elastic hinge. The inertial mass is suspended within an etched rim on an elastic hinge, with piezoresistive gages on either side of the elastic hinge to detect motion of the inertial mass about the hinge. By adding a protecting base plate on the bottom of the core (i.e., the inner layer) and a lid on top of the core, the moving parts are protected from environmental contamination. As may be seen in Figure 1, recesses are provided in the base and lid to allow the inertial mass to move freely. A hole is etched through the lid to allow access to the metal pads.

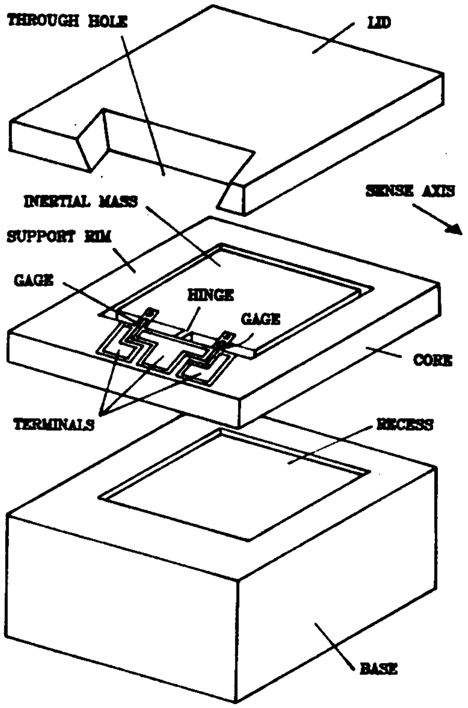

Figure 1. Exploded view of the piezoresisitve accelerometer. (Patent Pending)

Several unusual features are incorporated into this accelerometer. The sensitive axis lies in the plane of the layers. The Piezoresistive gages, although atomically continuous with the inertial mass and rim, extend freely in space between them. As the inertial mass is separated from the rim by etching, the elastic hinge is protected from etching by an oxide mask pattern while the piezoresistive gages are protected by high boron doping.

When an acceleration is applied along the sensitive axis, the inertial mass will rotate around the elastic hinge in response to the acceleration force. The piezoresistive gages are placed on either side of the elastic hinge, so that the rotation of the inertial mass due to the acceleration along the sensitive axis creates compressive stress on one gage and tensile stress on the other. Each gage constitutes a very small amount of silicon, approximately 7.8 x 10^{-10} cc, so very little strain energy is needed to produce a useful signal. Furthermore, the resistance change of the piezoresistive gage per unit displacement is greatest as the length of the gage is reduced. By the use of both short gage lengths and appropriate distances of the gages from the hinge, very large resistance changes may result from very small displacements. A prior art with one piezoresistor on each side of the substrate has been published elsewhere [1].

Figure 2a shows a photograph of the inner layer (or core) of the accelerometer. The accelerometer is fabricated on a (110) oriented silicon substrate. An inverted C-shaped groove on the silicon substrate defines the inertial mass and hinge, and undercuts the piezoresistive gages. The gages, one on either side of the hinge, extend across the groove between the inertial mass and the support rim, as shown in Figure 2b. Each gage is a meandering of six tiny boron doped silicon bridges, each only 1.3 x 10^{-10} cc.

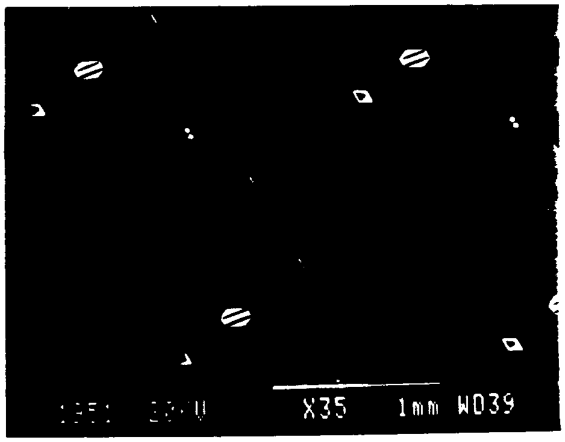

Figure 2a. Scanning electron microscope photograph of the inner layer (or core) of the piezoresistive accelerometer.

As can be seen in the photograph of Figure 2a, the device takes an unusual shape, a parallelogram of 70.5°, because the design is executed in a (110) silicon substrate. The inertial mass and the hinge are bounded by nearly vertical {111} planes which are almost impervious to anisotropic etchants [2]. The gages are aligned in the [111] direction to facilitate undercutting and to take advantage of the large piezoresistive gage factor in this direction.

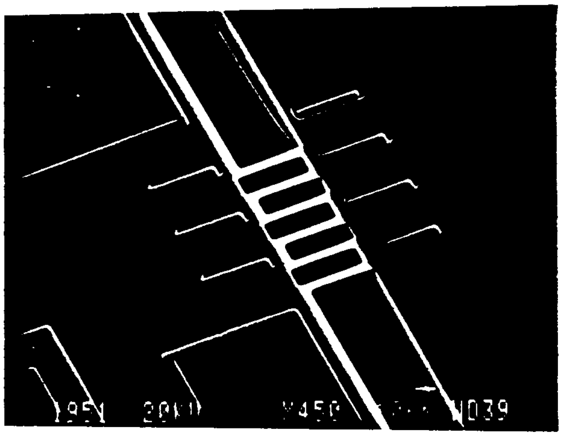

Figure 2b. A close up view of the serpentine piezoresistors bridging between inertial mass and support rim.

There are five trimming resistors serially connected to the piezoresistive gages. They are in binary code ratio and are normally shorted by aluminum fuses. They may be seen in Figure 2a as four thin bridges between five metal pads. A trimming resistor can be activated by blowing out the associated fuse with a current pulse. The resistors are used to trim the zero balance of the strain gage bridge.

As can be seen in Figure 1, there is a hole in the lid to allow access to the bonding and trimming pads. The edge of the hole is parallel to the [110] direction of the (100) substrate used for the lid. The {111} plane can be seen as a 54.7° slope at the edge of the hole.

Device Fabrication

A sequence of steps for processing this etch-freed gage piezoresistive accelerometer follows: It is a four mask process. The substrate is first oxidized, and then the oxide layer on the top surface is opened for doping. The gages, trimming resistors and connections are simultaneously defined by the opening. Thereafter, boron is diffused or implanted into the open apertures to a very high concentration.

Following the boron doping step, oxide layers on both sides of the substrate are opened for silicon etching. The openings are an inverted C-shaped pattern on the top surface and another C-shaped pattern on the bottom surface. The patterns, which are mirror images, are aligned precisely to one another. Subsequently, etching is carried out with an ethylenediamine / pyrocatechol / water mixture as etchant. The etchant does not attack the oxide protected regions and the heavily boron doped regions [3]. Mask design of the C-shaped opening must compensate for the fast attack by the etchant of the convex corner where two {111} planes meet each other.

The etchant attacks the opening and eventually etches through the substrate to completely form the inverted C-shaped groove with near vertical walls. The groove defines the hinge and inertial mass, and undercuts the piezoresistive gages. The formed gages extend across the groove to the support rim at one end and to the inertial mass at the other end.

Subsequently, the masking oxide is stripped from the substrate and a thin oxide is grown. The gages are surrounded and protected by the thin oxide coating. Following the growth of the thin oxide layer, contact windows are opened. A metal layer is deposited and patterned to define the pads and connecting links.

The base and lid are separately processed. Both of them are made of (100) silicon substrates. Shallow recesses are etched in both the base plate and the lid. These recesses are later placed over the inertial mass and hinge of the core, as shown in the exploded view in Figure 1, allowing the inertial mass to move freely. There is also a hole etched through the lid to allow access to the bonding and trimming pads on the core. The base plate, core, and lid wafers are aligned and sandwiched together with solder glass to bond them together. Finally, the individual dice are cut from the sandwiched substrates.

Performance Tests

The sensor has been mounted into an accelerometer housing and has been evaluated for linearity, resonant frequency, frequency response, thermal zero and sensitivity shifts, transverse sensitivity and shock survivability. Figure 3 tabulates the performance of the device.

The sensitivity and linearity of the accelerometer were tested on an Endevco Model 2965C Comparison Shock Tester. Figure 4a shows a plot of the output versus acceleration of a typical accelerometer. Figure 4b illustrates that the nonlinearity within the design range (1000 g), is less than ± 1%. Beyond 4000 g, the sensitivity of the sensor decreases rapidly.

The resonant frequency of the accelerometer was determined by impact testing. The accelerometer output was captured by a Digital Storage Oscilloscope (DSO), and the waveform was simultaneously analyzed by the internal signal processor of the DSO. The results show that a sensor of 0.16 mV/g sensitivity has a resonant frequency of 73.2 kHz. Sensors of 0.16 - 0.24 mV/g sensitivity have resonant frequencies in the range of 62 to 74 kHz.

CHARACTERISTICS OF THE PIEZORESISTIVE ACCELEROMETER	
Range	± 1,000 g
Die Size	1.65 x 1.78 mm (.065 x .070 in.) (parallelogram of 70.5°)
Sensitivity	0.16 - 0.24 mV/g
Resonant Frequency	62-74 kHz
Non-linearity	<±1%
Zero offset	<±10% FS
Thermal zero shift	<±0.5% FS (0-150°F)
Thermal sensitivity shift	<-0.04 %/°F
Transverse sensitivity	<2%
Shock survivability	> 10,000 g
Resistance	2000Ω
Excitation	10 Vdc

Figure 3. The performance of the piezoresistive accelerometer.

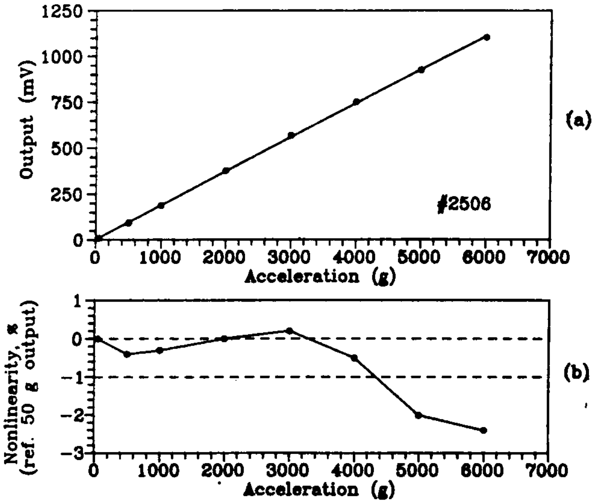

Figure 4. (a) The output vs. acceleration plot of a 1000g FS piezoresistive accelerometer, and (b) the nonlinearity of the curve in (a).

The amplitude frequency response of the accelerometer was recorded using an Endevco Model 28952 Automatic Accelerometer Calibration System. Figure 5 shows sensitivity versus vibration frequency. The sensor used for this test was not mounted in a finished package.

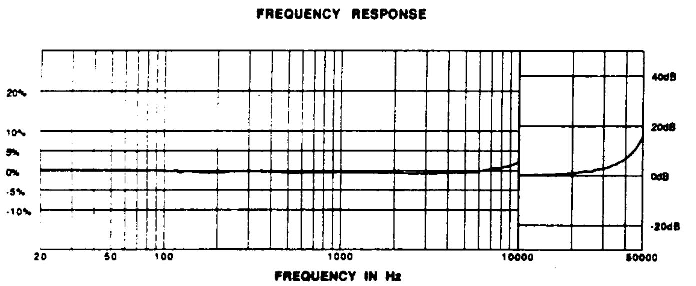

Figure 5. The amplitude frequency response of the piezoresistive accelerometer.

Thermal effects on the zero acceleration output of the accelerometer were measured. As may be seen in Figure 6a, the zero shift from 0 to 150° F was less than 0.3 mV, or 0.15% full scale. Thermal sensitivity shift was tested with a sinusoidal vibration input. Figure 6b shows that the thermal sensitivity shifts of four accelerometers were less than -0.04%/°F. It would be possible to compensate the shift in sensitivity by the addition of series resistors to the gages.

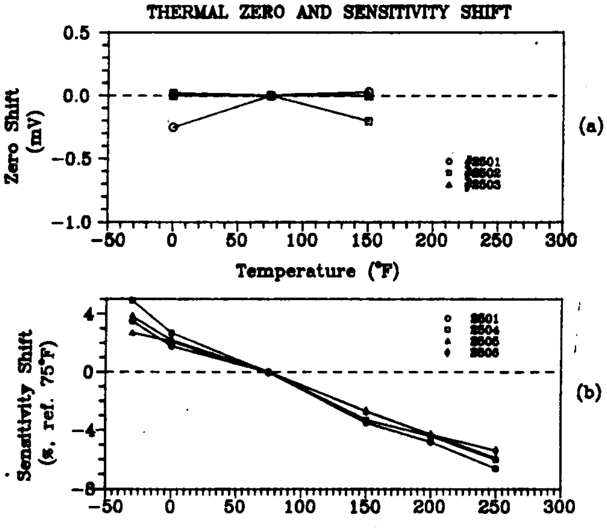

Figure 6. (a) Thermal effect on the zero acceleration output of the piezoresistive accelerometer, and (b) Thermal effect on the sensitivity of the piezoresistive accelerometer.

The transverse or cross axis sensitivities of the accelerometers were tested on an Endevco Transverse Sensitivity System. Cross axis sensitivities ranged from 0.1 to 1.7% of the axial sensitivities. The accuracy of the cut of the starting (110) silicon wafer, and the accuracy of alignment of the openings for etching from both sides of the wafer (both define the hinge's verticality) are believed to play an important role in reducing cross axis sensitivity. The test accelerometers survived five 10,000g peak shocks.

Conclusion

A piezoresistive accelerometer with high resonant frequency and high sensitivity has been designed, fabricated, and tested. This accelerometer was designed for impact testing which requires accurate response to fast rise time and short duration shock motions as well as to long duration transients.

The fabrication process is simple, thus relatively low cost. It forms the piezoresistor bridges, hinge and inertial mass in one etching step. It is executed in (110) silicon.

The accelerometer was designed for 1,000 g full scale and 0.2 mV/g sensitivity. It has been found to have excellent frequency response, very high resonant frequency (nominally 65 kHz), good linearity (< ±1% nonlinearity, ref. 50 g output), excellent thermal zero shift (< 0.15% F.S. between 0 - 150°F), good thermal sensitivity shift (< -0.04%/°F), and can survive 10,000 g shock.

References

[1] R. D. Sill, "Testing Techniques Involved with the Development of High Shock Acceleration Sensors", Endevco Tech Paper, TP 284, February 1984.

[2] D. L. Kendall and G. R. DeGuel, "Vertical Etching of Silicon at Very High Aspect Ratios", Ann. Rev. Mater. Sci., R. A. Huggins ed., vol. 9, pp.373, 1979.

[3] H. Seidl, "The Mechanism of Anisotropic, Electrochemical Silicon Etching in Alkaline Solutions", presented at the IEEE Solid-State Sensor and Actuator Workshop, Hilton Head Island, South Carolina, June 4-7, 1990.