Tunneling Tip Protection for a Bulk Micromachined Accelerometer

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ABSTRACT

Ultrasensitive accelerometers are needed by NASA for the measurement of orbital drag. We have designed an accelerometer capable of measuring 1()-g g. In this paper, a method for fabricating a bulk micromachined accelerometer which incorporates a tunneling tip is presented. To meet sensitivity specifications, a weak spring anti large mass are needed. However, these re.present a delicate mechanism and a method of protection is provided by electrostatically clamping the. proof mass in a fixed position. The effectiveness of the electrostatic clamp has been measured. It is found that clamping against an acceleration of 200 g is possible with voltages as low as 30 volts.

1. INTRODUCTION

Highly sensitive accelerometers (10^{-8} g) are required for the measurement of orbital drag and for seismic measurements on other planets. Silicon micromachined devices are attractive because they are light weight and Considerably smaller than conventional accelerometers.

The minimum detectable acceleration is proportional to its spring constant times its minimum position detection capability divided by the proof mass. Therefore weak springs, large proof masses, and a highly sensitive position detector are needed for high sensitivity accelerometers. Tunneling tips can be used as position sensors with potentially two orders of magnitude greater sensitivity than capacitive sensors. The estimated sensitivity based on measurements of scanning tunneling microscopes (STMs) is 10^{-3} Å. Tunneling tips have an additional advantage over capacitive sensors because they are less sensitive to parasitic capacitance. A tunneling tip provides a current output that is strongly dependent 011 its proximity to a counter electrode. The measurement can be made by applying a small 1X: bias voltage (100 mv) to the. tip and monitoring the. cur-rent.

Tunneling tips require precise registration and are delicate mechanical structures which could be damaged during, handling, shipping and lift-off into earth orbit. Early work cm tunneling sensors has been performed by Kaiser, et al[1]. They have demonstrated the capabilities of a tunneling tip sensor for use in position measurements. Analysis of noise, has been presented[2]. Tunneling tips have been applied to accelerometers and bolometers[3]. The issue of tunneling tip protection was approached by using a two cantilever system[4]. This architecture does provide the required protection but requires additional elements to implement and the resonance and positioning of two separate cantilevers must be considered. In this paper, we discuss a simple solution to this problem which involves the use of electrostatic clamping to secure the moving parts.

2. DESIGN

For higher Sensitivity, a large proof mass is required. This suggests the use of bulk micromachining to fabricate the devices. To meet the sensitivity specification of 10' g, the ratio of the spring constant to the proof mass of the accelerometer needed is 10' /sec^2. The proof mass in our accelerometer is 10 mm on a side and approximately .8 mm thick with a total mass of approximately 2x10^{d} Kg. There fore, the required spring constant is 2. mN/m. To achieve such a low spring constant, eight 10 mm long springs, 100 µm wide and 25 µm thick are used.

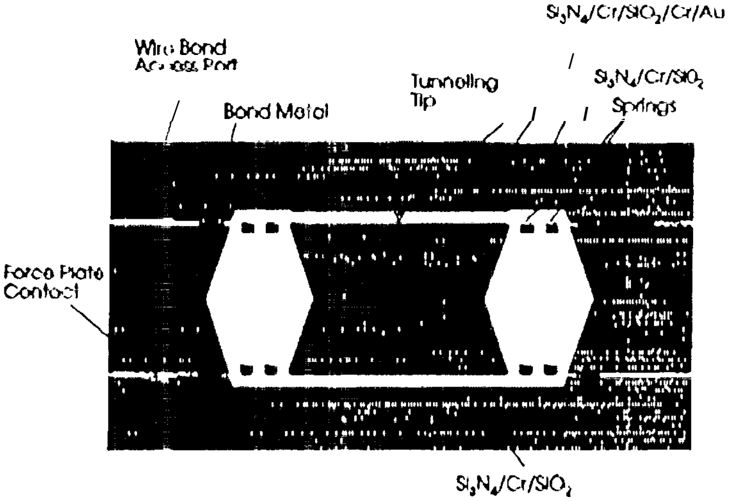

Figure 1. Cross-section of an assembled accelerometer.

In Figure 1, a cross-section of the accelerometer is shown. It consists of four bulk micromachined dice[5]. Two dice form a proof mass and spring system. The proof mass is one square centimeter in area. A third die contains a tunneling tip and four quadrature electrostatic field plates. The tip is anisotropically etched in silicon and is designed to be flush with the surface of the wafer. The fourth die contains a single electrode which is used both for controlling the position of the proof mass and for electrostatically clamping the proof mass away from the. tip.

Among the considerations in the design of a spring system are its cross-axis sensitivity and spurious resonance modes. The unique design shown in figure 2 was conceived to provide a low spring constant in the measurement direction and a high spring constant for transverse and lateral modes. Four individual folded springs are combined together to support the proof mass at four central points. Each spring is folded into three sections. Two sections are 5 mm in length and one section is 10 mm. Moving around the periphery of the proof mass, it will be observed that the short sections of two consecutive. folded springs ate connected at a *corner tie*. Therefore there arc two *inner corner ties* diagonally across from each other and near the proof mass.

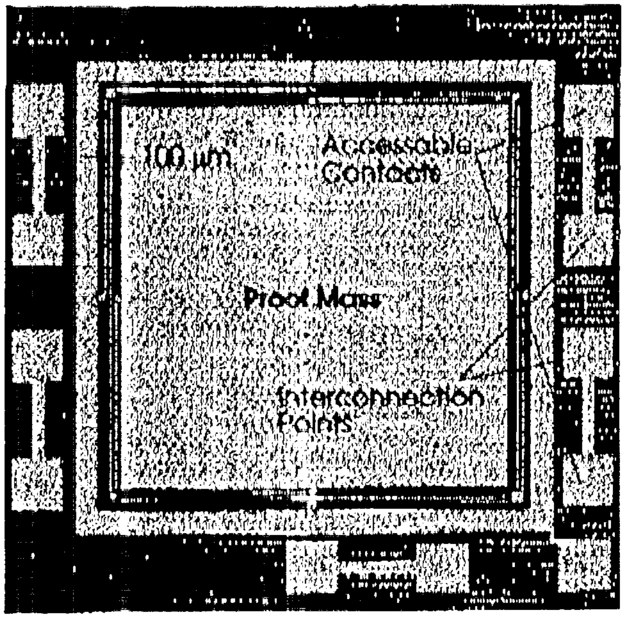

Figure 2. Top view 01 proof **mass die showing folded spring design.**

Similarly, the outer short sections are also tied together. These are located diagonally across from each other and occupied the corners of the devices left vacant by the *inner comer ties*. The short sections of the springs will only deflect approximately 1/8 as much as the longer sections and therefore only fractionally contribute to the spring constant. Their main purpose is to stiffen the device against rotation and cross axis response, however, they will also stiffen the desired mode. somewhat. A scale model of the spring system has been constructed and used to demonstrate its performance charactei kits. The following table summarizes the "results of calculated modes for the. spring-mass system.

A second feature worth noting is that the proof mass is designed to be in contact with the tip when in its neutral position. This provides two important bent.fits. First, it is observed that 'moving the proof mass out of plane and applying a cross-axis acceleration will cause the proof mass to experience a rotation and a translation along its sensitive axis. In other words, an out of plane proof mass has a greater Cross-axis sensitivity. The second benefit is related to thermal expansion. In the scheme shown with all components fabricate.d in silicon, the thermal sensitivity of the device is directly proportion to the gap between the. proof mass and the tip. Setting the gap to zero eliminates the largest source of thermal sensitivity. in practice, curvature in the bonded dice contribute to a variance in the gap. We anticipate about a *200* nm variance based on wafer surface measurements.

Table 1
Mode and it Resonant Frequency

Mode	Resonant Frequency
Axial	10HZ
Roll/Pitch	450112
Lateral	3300 Hz
Yaw	5800 Hz

3. Fabrication

Figure 1 shows a cross-section of the assembled device. The whole proof mass is composed of two eutectically bonded dice. The dice are identical. Oxidized wafers are double sided aligned to define alignment marks on both sides of the wafer. Silicon nitride is deposited and patterned to define the deep backside KOH etch. Corner compensation is employed, The back side etch continues until the remaining diaphragm is 25 microns thick. This is a timed etch and no dopant stop is used thereby minimizing stress in the springs. The wafer is stripped back to silicon and recoated with silicon nitride. TiW/Au is deposited on the front side and patterned appropriately. The wafers arc repatterned to the spring mask and subjected to a deep plasma etch which releases both the springs and the dice. Individual die are cleaned and bonded together eutectically.

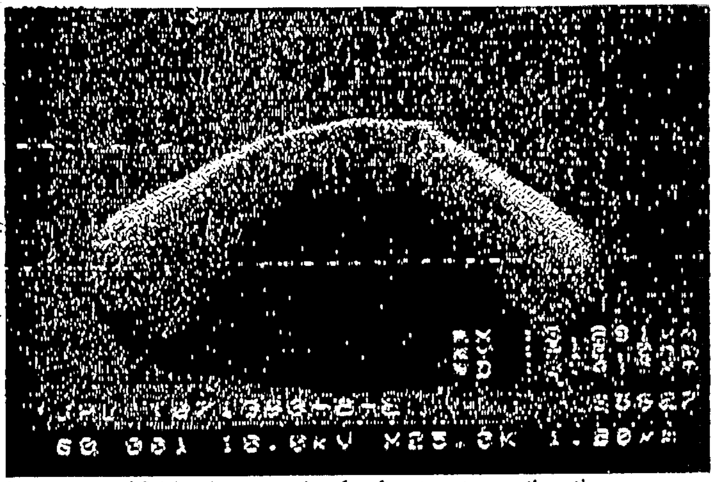

Figure 3. SEM micrograph of a flat top tunneling tip.

The tip wafers undergo a similar initial process. A deep cut is used for die separation purposes. The tip is created by a sequence of dry and anisotropic wet etch steps which result in a flat topped tip in a well (see Figure 3). The tip height is equal to the depth of the well. Grooves are also provided for a eutectic bond ring. These are needed to obtain a surface referenced bond. A two metal system is employed (see detail in Figure 4). The bottom metal is Chromium which is deposited by sputtering and patterned lithographically. It is covered with an LTO deposition. The LTO is patterned to open vias to the first metal and clear the tip. TiW/Au is then deposited and patterned, The tip is coated with TiW/Au during this operation. Finally, the eutectic bonding material is deposited. We have experimented with In/Au, In/Cu, Au/Ge and Al/Ge alloys. Au/Ge is preferred.

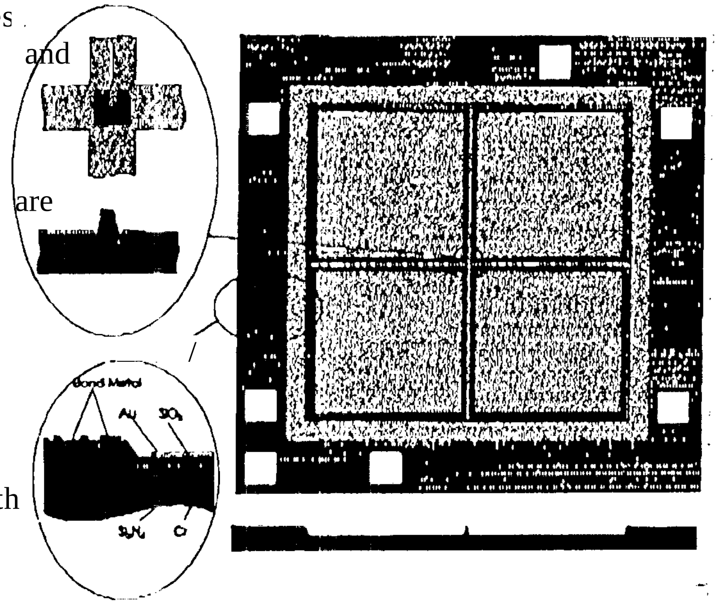

Figure 4. Top view and sections of tho tip dlo.

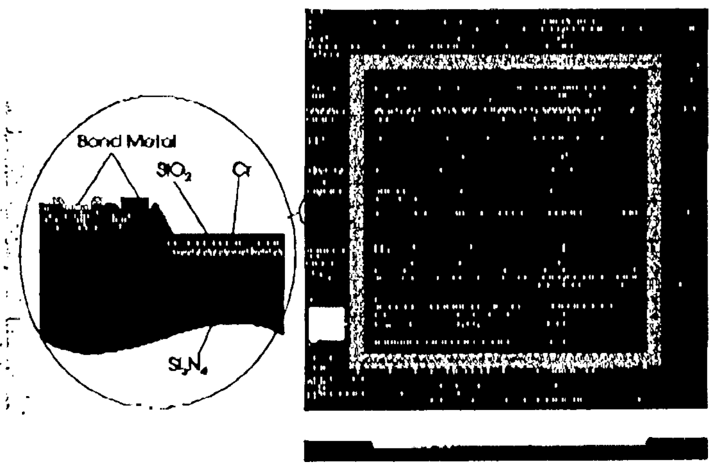

Figure 5. Top view and section of force plate die.

The force plate is created by essentially the same process as the tip wafer. Its cross-section is shown in figure 5. Here, the LTO layer is only 500 nm thick. This layer is used to prevent the proof mass from shorting to the force plate. Again, a two metal process is used, where the second TiW/Au deposition patterns the bond regions and the wire bond pads. A eutectic alloy is deposited and patterned to complete this die.

The dice are assembled individually using eutectic alloy bonding. This bonding is the subject of another paper in this conference[6]. After assembly, die are mounted in the package shown in figure 6 using conductive epoxy. The gold wire is epoxy bonded to the bond pads and package leads. The package is mounted in a specially design zero insertion force holder which is mounted on a pc board.

4. MEASUREMENTS

In this work, we show that electrostatic clamping is an effective tool for protecting the accelerometer during lift-off. This was done using the following test procedure. A test station (Figure 7) was assembled which consists of a mount-fey the circuit board shown in Figure 6, and a micrometer with a non-rotating spindle. A device, consisting of a force plate and a proof mass is assembled and packaged and clamped electrostatically. A hook is glued to the center of the proof mass using epoxy. A weight with an axial eye-screw is set on the spindle such that the eye is placed over the hook but not supported by the hook.

An HP 4277A capacitance bridge is used to monitor the capacitance between the proof mass and the force plate. It contains a built-in DC bias supply which is used to apply an electrostatic field between the proof mass and force plate during the test. The bias is initially adjusted to a high voltage. The spindle is lowered until the proof mass is supporting the entire weight, The bias voltage is then lowered until the electrostatic force can no longer support the weight and the capacitance decreases as the weight falls.

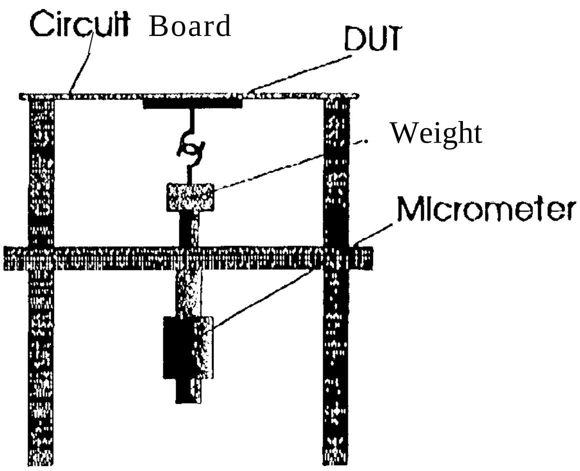

Figure 7. The test fixture used to measure the strength of tho electrostatic force.

By varying the weight we can determine the ability of the system to withstand specific acceleration levels. Because the proof mass weighs 0.2 grams, an effective increase of 1 g in acceleration is simulated for each 0.2 grams of weight added. It is a simple matter co obtain a 200 g simulated acceleration by adding 40 grams of weight, Figure 8 shows the holding voltage as a function of the acceleration.

The electrostatic force is given by

$$F_e = \frac{\varepsilon_{ox} \cdot A \cdot V^2}{2 \cdot d_{ox}^2},$$

where

ε_{ox} is the dielectric constant ($4\times8.85 \times10^{14}$ Newtons/Volt^2),
A is the area (1 cm^2),
V is the applied voltage,
and d_{ox} is the thickness of the LTO (0.5 µm).

This relationship is also plotted in Figure 8. As can be seen, the correlation between the two is not good, and the voltage to hold the proof mass is greater than expected. To account for this variance, we assume that the entire 1 cm^2 surface of the proof mass is not in contact with the force plate. Therefore, the gap really consists of 500 nm of silicon dioxide and some percentage 01 air. A gap between the proof mass and the force plate can occur in a number of ways. Particulate in the LTO layer may hold the proof mass away. Alternatively, if the proof mass is not flat, then it will not be completely in contact with the force

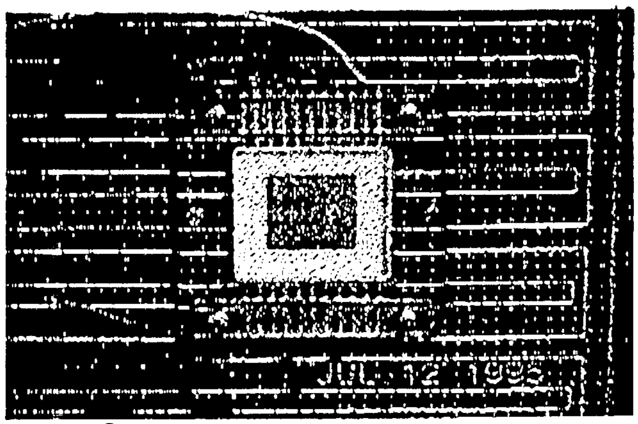

Figure 6. Photo of an assembled accelerometer mounted In Its package and to a circuit board.

plate. In either case, the nature of the gap can not be known exactly, but in both cases the result of the gap is the addition of a series capacitance. Therefore, we assume a capacitance that is based on parallel plates and has a uniform gap spacing. The relationship given above can then be rewritten as

$$F_e = \frac{\varepsilon_{air} \cdot \varepsilon_{ox}^{2} \cdot A \cdot V^2}{2 \cdot \left(\varepsilon_{air} \cdot d_{ox} + \varepsilon_{ox} \cdot d_{air}\right)^2},$$

where

ε_{ox} is the dielectric constant ($4 \times 8.85 \times 10^{-14}$ Newtons/Volt^2), and

d_{air} is a weighted average thickness of the air gap.

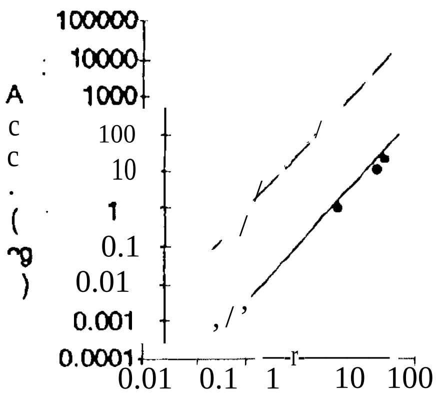

Figure 8. Experimental and theoretical data showing the maximum achievable acceleration against which the force plate can hold as a function of the voltage difference between the force plate and proof mass.

This is plotted in Figure 8 as well. By adjusting the thickness of the air gap, we can achieve a reasonable fit to the experimental data; These results indicate that there is a thin layer of air or vacuum separating the proof mass and force plate whose probable origin is either particulate in the LTO layer or low spatial frequency variations in the flatness of the wafers.

In Figure 9. the holding voltage required to withstand accelerations as high as 1 g is plotted against the weight average thickness of the air gap. The minimum value of about 0.2 volts represents the case of perfectly flat dice in contact with each other. increasing the effective gap increases the required voltage.

5. CONCLUSIONS

Accelerometers have been fabricated for ultasenitive acceleration measurements. To achieve high sensitivity, weak springs and a tunneling tip have been employed. These structures must he protected when the accelerometer is not in use. We have employed electrostatic clamping the hold the proof mass in place during transit. Measurements of to holding power of the electrostatic force indicate that with reasonable voltages we can expect to protect the accelerometer from over-range acceleration as high as 200 g. However, the required voltage is greater than anticipated. This has been associated with a gap between the proof mass and the force plate resulting from particulate in the LTO layer or warp in the wafer.

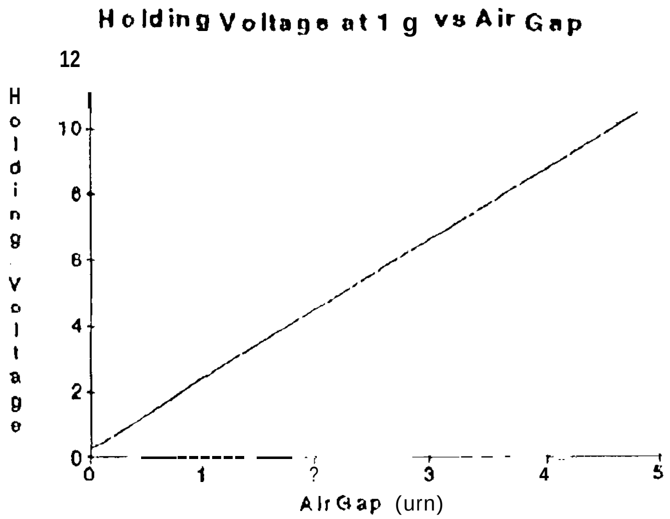

Figure 9. Assuming an air gap, the voltage required to protect the proof mass against 1 g accelerations.

6. ACKNOWLEDGMENTS

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