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Levitated Micro-Accelerometer

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Levitated Micro-Accelerometer

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Abstract

The objective is a significant advancement in the state-of-the-art of accelerometer design for tactical grade (or better) applications. The design goals are <1 milli-G bias stability across environments and $200 cost. This quantum leap in performance improvement and cost reduction can only be achieved by a radical new approach, not incremental improvements to existing concepts.

This novel levitated closed-loop accelerometer is implemented as a hybrid micromachine. The hybrid approach frees the designer from the limitations of any given monolithic process and dramatically expands the available design space. The design can be tailored to the dynamic range, resolution, bandwidth, and environmental requirements of the application while still preserving all of the benefits of monolithic MEMS fabrication – extreme precision, small size, low cost, and low power.

An accelerometer was designed and prototype hardware was built, driving the successful development and refinement of several "never been done before" fabrication processes. Many of these process developments are commercially valuable and are key enablers for the realization of a wide variety of useful micro-devices.

While controlled levitation of a proof mass has yet to be realized, the overall design concept remains sound. This was clearly demonstrated by the stable and reliable closed-loop control of a proof mass at the test structure level. Furthermore, the hybrid MEMS implementation is the most promising approach for achieving the ambitious cost and performance targets. It is strongly recommended that Sandia remain committed to the original goal.

Team Members

Team Member	Org	Role
Frank Peter	2614	PI, Mechanical Design
Jeff Gilkey	2614	Control System Design & Analysis
Ragon Kinney	2334	Electronics Design
Stan Kravitz	1763	Fabrication Consultation
Ken Peterson	14152	Packaging
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Carrie Schmidt	1763	Fabrication & Assembly
Larry Warne	1642	Capacitance & Electrostatics Model

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1. Introduction

1.1 Performance Goals

The objective is a significant advancement in accelerometer design for tactical grade applications. The performance goals are:

Bias stability	1 milli-G
Scale factor	1000 ppm
Cost	$200
Size	3 cubic centimeters
Power	0.25 Watt

This quantum leap in performance improvement and cost reduction can only be achieved by a radical new approach, not incremental improvements to existing concepts.

1.2 Design Approach

This novel levitated accelerometer is implemented as a hybrid micromachine. The hybrid approach frees the designer from the limitations of any given monolithic process and dramatically expands the available design space (choice of materials, feature size, and thickness). It exploits the best features from several micro-fabrication technologies with the goal of optimizing overall system performance. The design can be tailored to the dynamic range, resolution, bandwidth, electrical, and environmental requirements of the application while still preserving all of the benefits of monolithic MEMS design – precision, small size, low cost, and low power.

Electrostatic forces scale well at micro dimensions (~10 µm and less). New micro-fabrication techniques now allow electrostatic suspension schemes that eliminate the engineering challenges inherent in mechanically suspended proof mass accelerometers. A survey of the literature shows that this approach is essentially unexplored.

1.3 Design Concept

A conductive proof mass is electrostatically suspended in a cavity between two substrates that form the body of the device and support the stator electrodes. The stator electrodes are used to capacitively sense and to electrostatically control the proof mass position in five degrees of freedom. Two "outer" loops control proof mass *tilt.* Three "inner" loops control proof mass *displacement.* The restoring force vector required to maintain the proof mass displacement at null is the measure of acceleration. Rotation about the vertical axis does not need to be controlled.

The sense, control, and power conversion circuitry is implemented as one or more custom ASICs that are flip-chip bonded on the backside of each substrate. Integration of support electronics in close proximity minimizes noise and errors due to stray capacitance.

Although conceived as a 3-axis device, a single or dual axis implementation is possible and may be desirable to meet certain mission requirements.

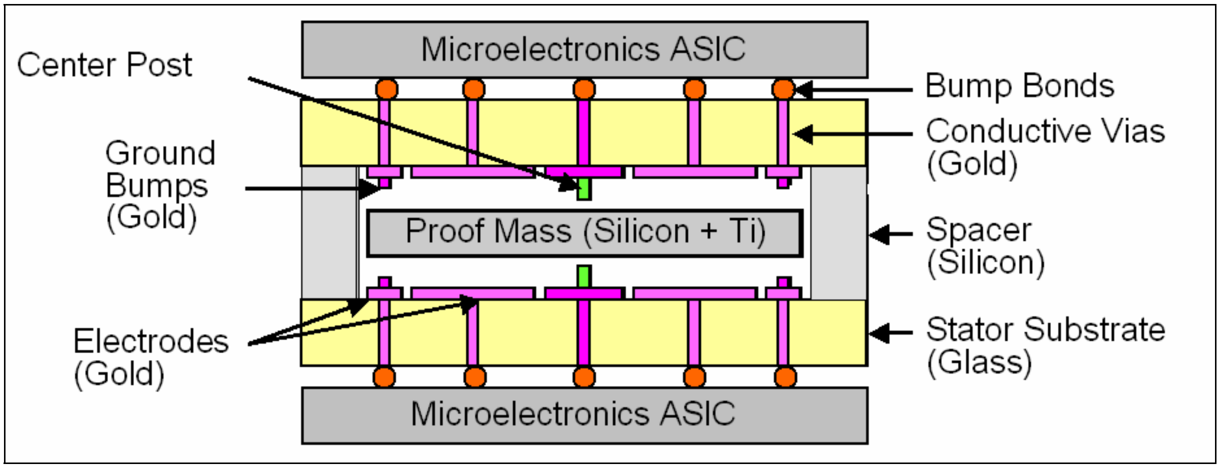

Figure 1: Micro-Accelerometer Design Concept

1.4 Design Features & Rationale

Design feature	Benefit
No mechanical suspension	Immune to the otherwise unmanageable temperature sensitivities caused by unpredictable thermal expansion and residual stress relaxation effects in the suspension.
3 axes in a single sensor	• Small size (estimated at 3 cc including electronics) • 3 axes for the price of 1 • 3 axis alignment to photolithographic tolerances
Axial symmetry	Rejection of common mode errors (stray capacitances, thermal expansion mismatch)
Large proof mass & large electrode areas	High signal to noise and greater sensitivity
Hybrid MEMS fabrication	Each micro-machined element is optimized to maximize overall system performance.
Close proximity of control electronics	Flip chip approach minimizes and balances parasitic capacitance and improves packaging density.

1.5 Applications

Targeted applications include precision-guided munitions, micro-autonomous vehicles, borehole navigation, seismic sensors, short time of flight navigation, motion detection, tamper detection, automotive control, virtual reality environment sensing, diagnostic instrumentation, and trajectory sensing for safing, arming, and fuzing.

2. Capacitive Sensing and Electrostatic Actuation

2.1 Capacitive Sensing

When the proof mass is shifted vertically or tilted, the capacitance between the electrodes change. This effect is used to create a differential capacitive sensor to measure vertical displacement and tilt as shown below.

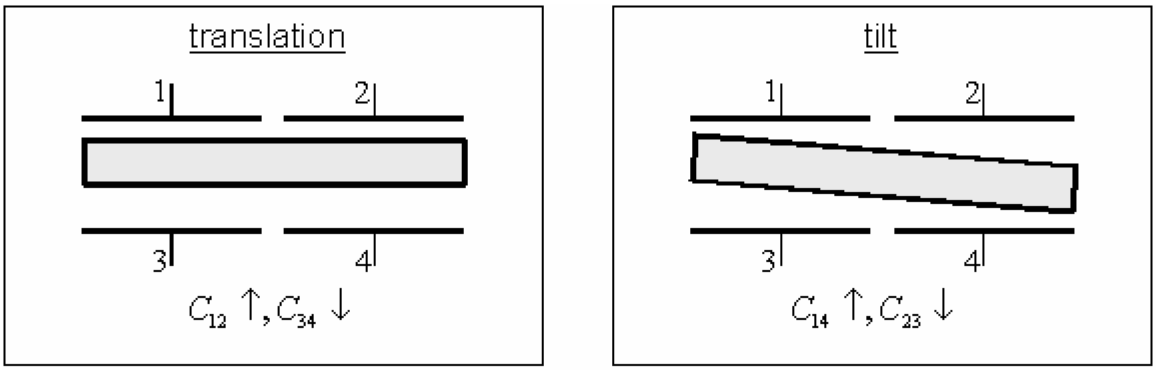

Figure 2: Capacitive Sensing

2.2 Electrostatic Actuation

Control forces and torques are generated via electrostatic induction. This is achieved by applying symmetrical voltages pairs (+V and -V) to the appropriate electrodes as shown below. The charge on each electrode generates a mirror image charge of opposite sign on the surface of the proof mass that results in electrostatic attraction.

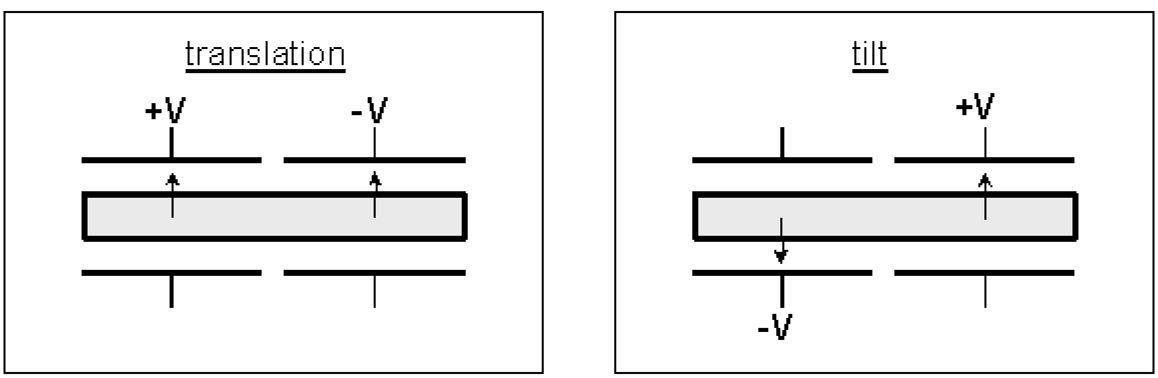

Figure 3: Actuation in Tilt and Vertical Translation

3. Control System

The block diagram below represents a single axis implementation of the levitated micro-accelerometer control system. Two loops control the tilt of the proof mass. A third loop controls the vertical position and levitates the proof mass against gravity and acceleration. The remaining degrees of freedom are uncontrolled (rotation about the vertical axis) or are passively stable (translation in the horizontal plane). The measured acceleration is calculated by dividing the control force to keep the proof mass centered by the inertia of the proof mass.

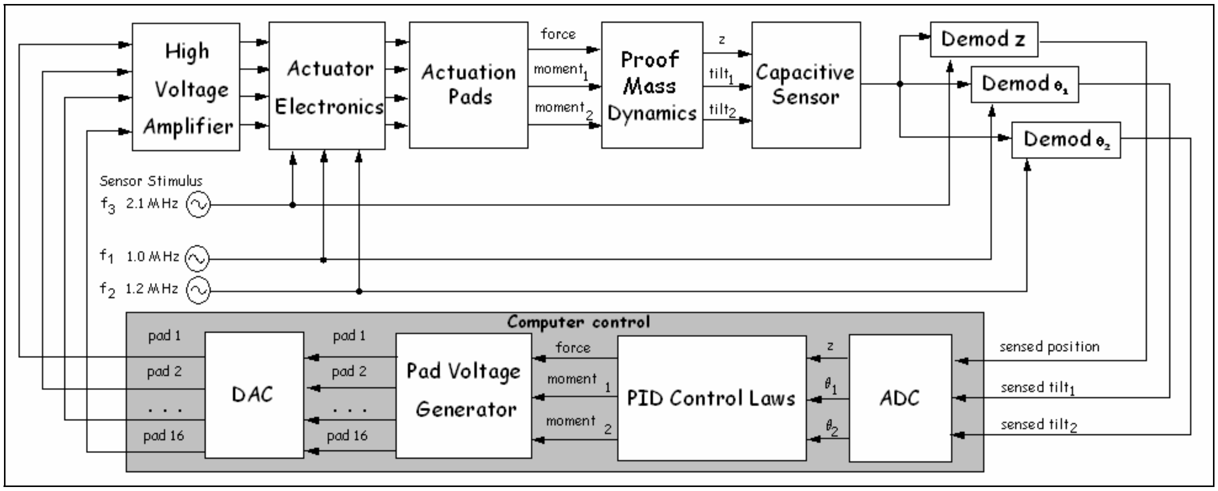

Figure 4: Control System Block Diagram

3.1 Capacitive Sensing

3.1.1 Vertical Displacement Sensing

The stimulus signals are capacitively coupled to the sense pads (see Figure 5 below) through the proof mass. When the proof mass moves up, the capacitance between the upper pads increases, while the capacitance between the lower pads decreases. These capacitance changes affect the magnitude and phase of the stimulus signal coupled to the sense pads. A charge amplifier is used to buffer the low-level sense pad signal.

The output of the charge amplifier is processed by a lock-in amplifier, which uses the stimulus signal as a reference. The demodulated output of the lock-in amplifier has zero magnitude when the proof mass is centered and varies linearly with vertical displacement of the proof mass. The sensor is calibrated by moving the proof mass to known positions, resting against mechanical stops on the upper and lower substrates.

To sense vertical displacement, a high frequency, low voltage sinusoidal stimulus signal (2.1MHz, 1V peak-to-peak) is added the control voltages on the upper/inner ring of electrodes (pads 9, 10, 11, 12 in Figure 5). The same stimulus signal, 180 degrees out of phase, is added to the lower/inner ring (pads 13, 14, 15, 16). By applying the stimulus signal in symmetrical pairs, a differential sensor with common mode error rejection is realized.

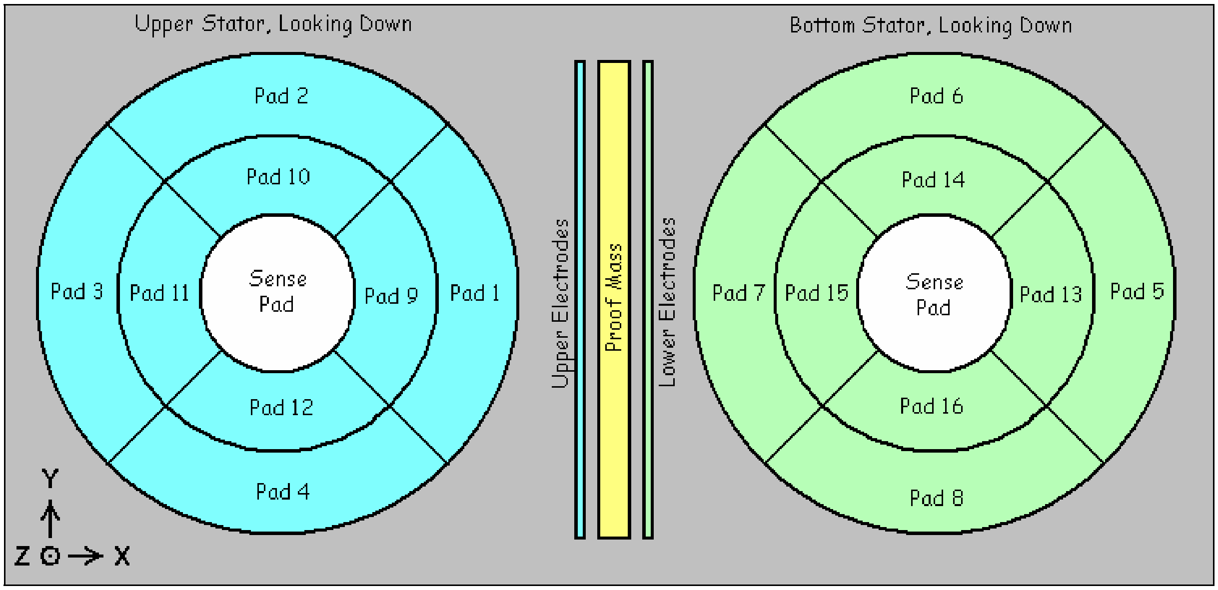

Figure 5: Sense and Actuation Pad Geometry

3.1.2 Tilt Sensing

To sense tilt about the X axis, a high frequency, low voltage sinusoidal stimulus signal (1.0 MHz, 1V peak-to-peak) is added to the control voltages on pad 2 and pad 8 (see Figure 5). The same stimulus signal, 180 degrees out of phase is added to pad 4 and pad 6. To sense tilt about the Y axis, a stimulus signal (1.2 MHz, 1 V peak-to-peak) is added to the control voltages on pad 1 and pad 7 with the 180 degrees out of phase signal added to pad 3 and pad 5. Again, by applying the stimulus signal in symmetrical pairs, a differential sensor with common mode error rejection is realized.

The same sense pad/charge amplifier circuit used to detect vertical motion also detects tilt about the X and Y axes. The output of the charge amplifier is sent to two additional lock-in amplifiers, one using the 1.0 MHz stimulus signal as a reference to extract a measurement proportional to rotation about the X axis, and another using the 1.2 MHz stimulus signal as a reference to extract a measurement proportional to rotation about the Y axis. The demodulated output of the lock-in amplifier has zero magnitude when the tilt is zero and varies linearly with rotation. The sensor was calibrated by rotating the proof mass to known angles, resting it against mechanical stops on the upper and lower substrates.

3.2 Electrostatic Actuation

3.2.1 Passive Lateral Stability

The middle ring of pads is used to levitate the proof mass between the upper and lower stators. The proof mass is grooved and the middle ring of pads (top and bottom) has a set of grounded pads that are aligned with these grooves. When the middle ring of pads is energized, an electrostatic force is generated in the horizontal plane that acts to align the grooves on the proof mass with the ground pads, giving the system passive lateral stability in the horizontal plane. The greatly simplifies the control system design.

An enhanced levitated accelerometer with active control to stabilize the proof mass in the horizontal plane would generate additional control forces that could be calibrated to provide 3-axis capability.

3.2.2 Tilt Actuation

To tilt the proof mass about the X axis, a positive voltage is applied to pad 2 and a negative voltage to pad 8 (see Figure 5 above). The electrostatic force is proportional to the voltage squared and is always attractive, not repulsive. To tilt the proof mass in the opposite direction about the X axis, a positive voltage is applied to pad 4 and a negative voltage to pad 6.

Torques that tilt the proof mass about the Y axis are generated in a similar manner. To tilt the proof mass about the Y axis, a positive voltage is applied to pad 3 and a negative voltage to pad 5. To tilt the proof mass in the opposite direction about the Y axis, a positive voltage is applied to pad 1 and a negative voltage to pad 7. To avoid developing a bias voltage on the levitated proof mass, the control voltages are always applied in positive/negative pairs.

3.2.3 Vertical Actuation

To actuate the proof mass in the Z direction, positive and negative voltage pairs are applied to the middle ring of pads. Again, the electrostatic force is proportional to voltage squared and is always attractive. To generate an upward levitation force, pads 9 and 11 are set to a positive voltage and pads 10 and 12 are set to the corresponding negative voltage. To generate a downward force, pads 13 and 15 are set to a positive voltage and pads 14 and 16 are set to the corresponding negative value. To avoid developing a bias voltage on the levitated proof mass, the control voltages are always applied in positive/negative pairs.

3.3 Control System Electronics

The control loops are implemented by a Keithley ADWIN-PRO data acquisition and control system. This system has 16 channels of analog to digital conversion, three of which are used to sample the 3 analog outputs of the lock-in amplifiers. The Keithley system has 16 channels of digital to analog conversion to generate output voltages. These voltages are amplified by a high voltage amplifier with a range of +150V to –150V. Although the control loop could have been implemented in analog form, it was decided to use the Keithley digital controller for ease of use in the lab and provide a data logging capability.

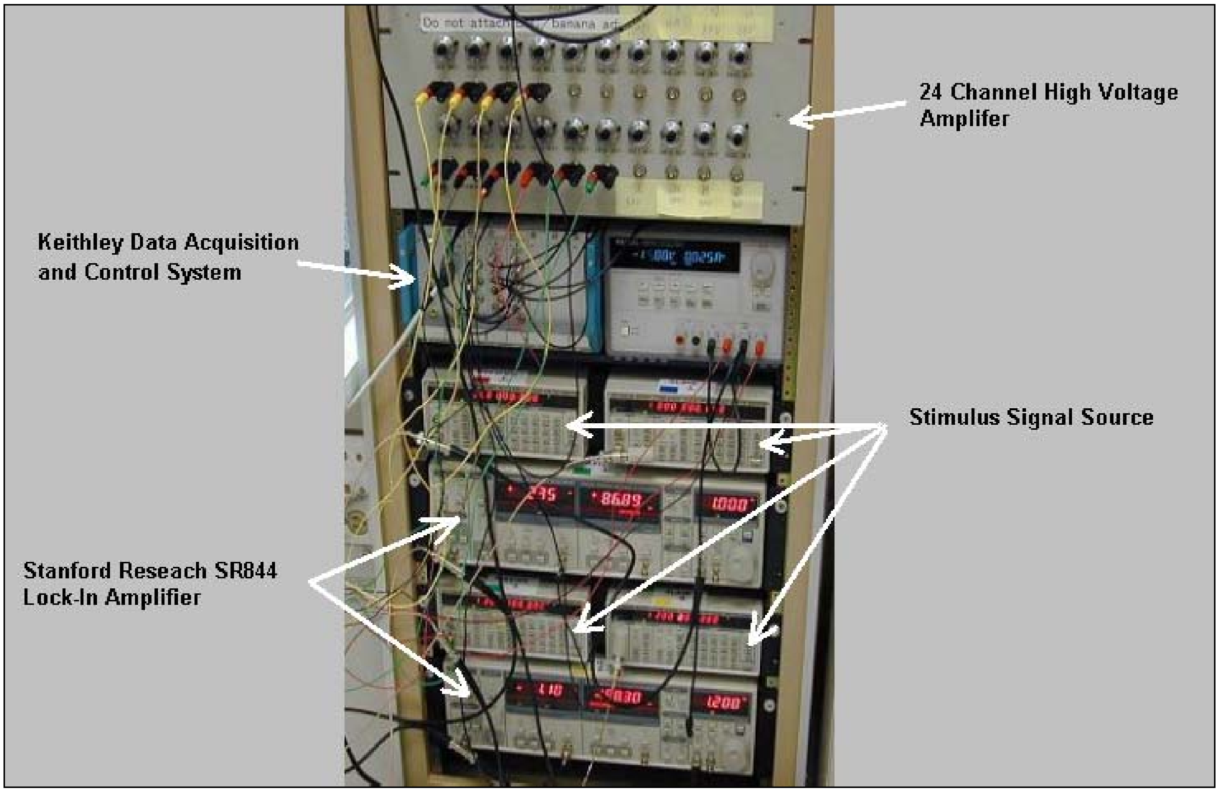

Figure 6: Control Hardware Rack

The Keithey data acquisition and control system has two processors, each with 32Mbytes of memory and an interface to a host PC system. Controller software is written and compiled on the host PC. Custom Matlab-Keithley interface software allows one to upload software to the processors and send messages to turn the controller on or off and change controller setpoints. During a "run", data is logged and stored in the onboard processor memory. After the run is complete, data is transferred over the Matlab/Keithey interface for display and storage on the PC's hard drive.

Since the levitation sense and actuation pads are separate from the tilt sense and actuation pads, it was possible to decouple the control loops, putting the levitation loop on one processor and the two tilt loops on a second processor. The levitation loop could be closed at 10 KHz and the tilt loop could be closed at 8 KHz.

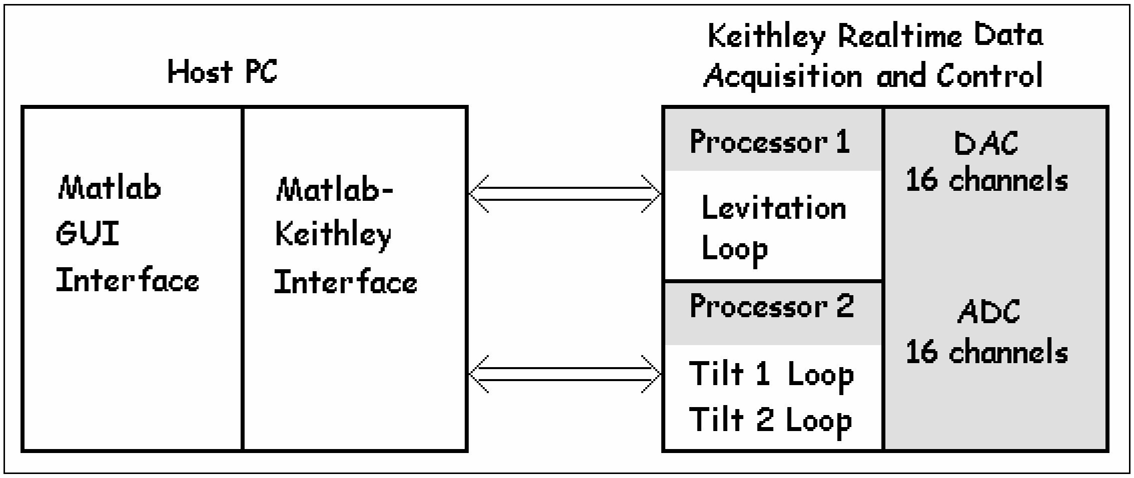

Figure 7: Control System Signal Flow

A custom interface board was designed to mix the 1 volt peak to peak capacitive sensing stimulus signals (2.1 MHz Z vertical position, 1.0 MHz X rotation and 1.2 MHz Y rotation), with the control loop signals. The board had a 24 pin socket to accept the accelerometer package. The board also contains an optional, off-chip charge amplifier circuit for the capacitive sensing. The output of charge amplifier is sent to the lock-in amplifiers to sense the two tilt angles and vertical position.

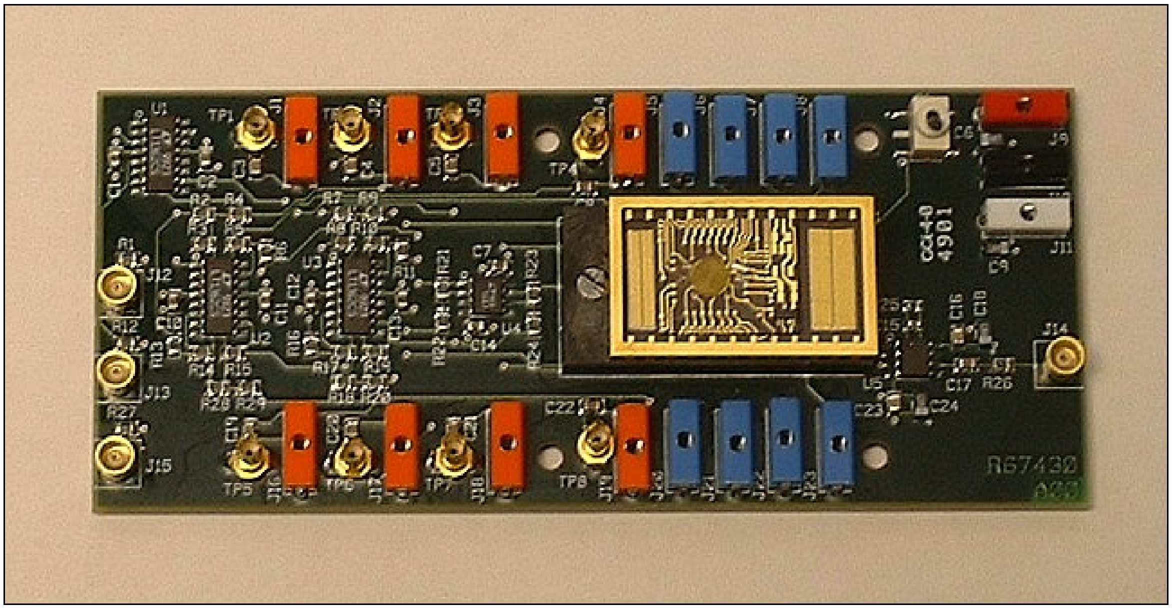

Figure 8: Interface Electronics Board with Micro-Accelerometer in Socket

4. Fabrication

4.1 Hybrid Fabrication

At first glance, monolithic fabrication seems to hold the most promise for low cost, but the penalty paid is suboptimal performance. A survey of existing monolithic fabrication technologies, such as surface micromachining, led to the conclusion that none were consistent with our performance goals at any price. The disadvantage of a hybrid design is that some assembly is required, but the incremental added cost is justified by gains in performance of several orders of magnitude. There is one caveat: as new and improved monolithic processes are developed, the hybrid approach needs to be reevaluated.

Our hybrid design uses the best features from a variety of processes and combines them with the goal of maximizing overall system performance. Features include:

- Large proof mass to increase sensitivity and minimize the contribution of Brownian mechanical noise.
- Geometrical symmetry and differential sensing to reject common-mode errors.
- Close proximity of sense electronics with sense elements to minimize electrical noise and parasitic capacitance.
- Small air gaps to increase sensor sensitivity.

Figure 9: Wafer-Level Batch Processing of Stators Enables Low Cost

4.2 Proof Mass

The proof mass is a 5 millimeter diameter, 300 micron thick disk made of single crystal silicon, which has superior mechanical strength and dimensional stability. It is batch fabricated using deep reactive ion etching (DRIE). The proof mass is extremely flat, with better than 0.1 micron flatness across the entire diameter. Some of the proof masses were grooved for passive stability in the horizontal plane. Electrostatic modeling was used to optimize the proof mass/stator geometry (aspect ratio of the grooves and air gaps) for maximum sensor sensitivity and maximum actuation forces.

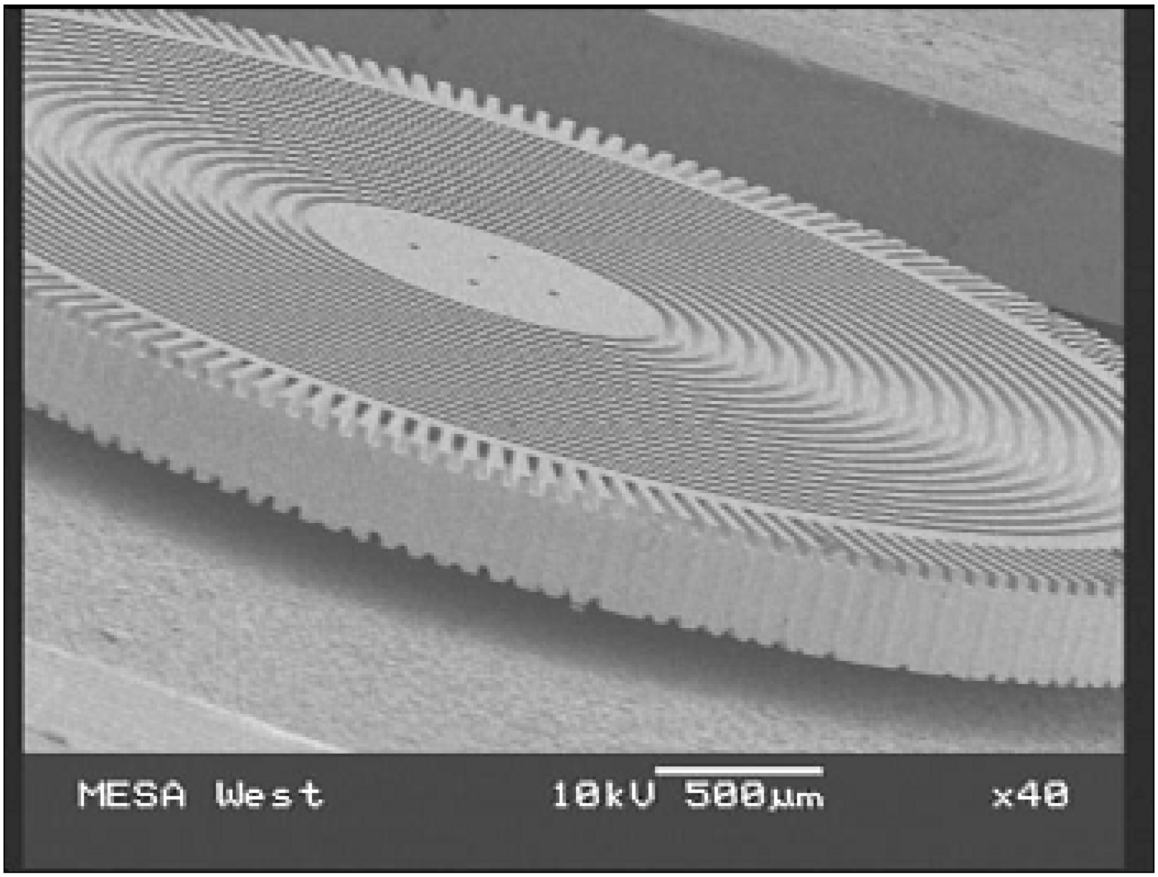

Figure 10: Electron Microscope Image of Grooved Proof Mass

4.3 Stators

The stators, fabricated on Pyrex wafer substrates, form the upper and lower layers of a 3-layer micro-accelerometer “sandwich”. A silicon spacer sets the air gap between the stator electrodes and the proof mass disk.

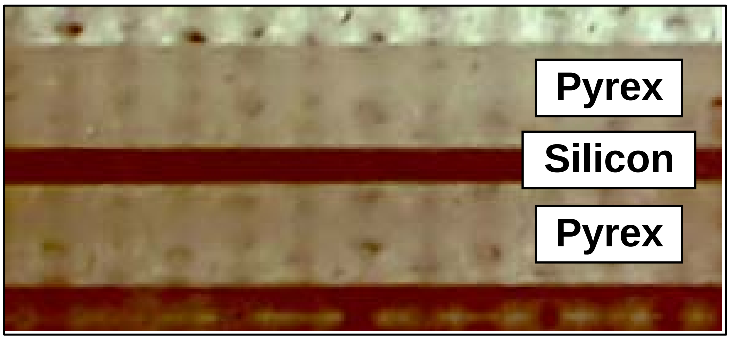

Figure 11: Anodic Bonding is Used to Create Accelerometer “Sandwich”

Common electrodes are connected together with buried interconnects. Each electrode is electrically connected to the outside of the sandwich by conductive vias through the wafer.

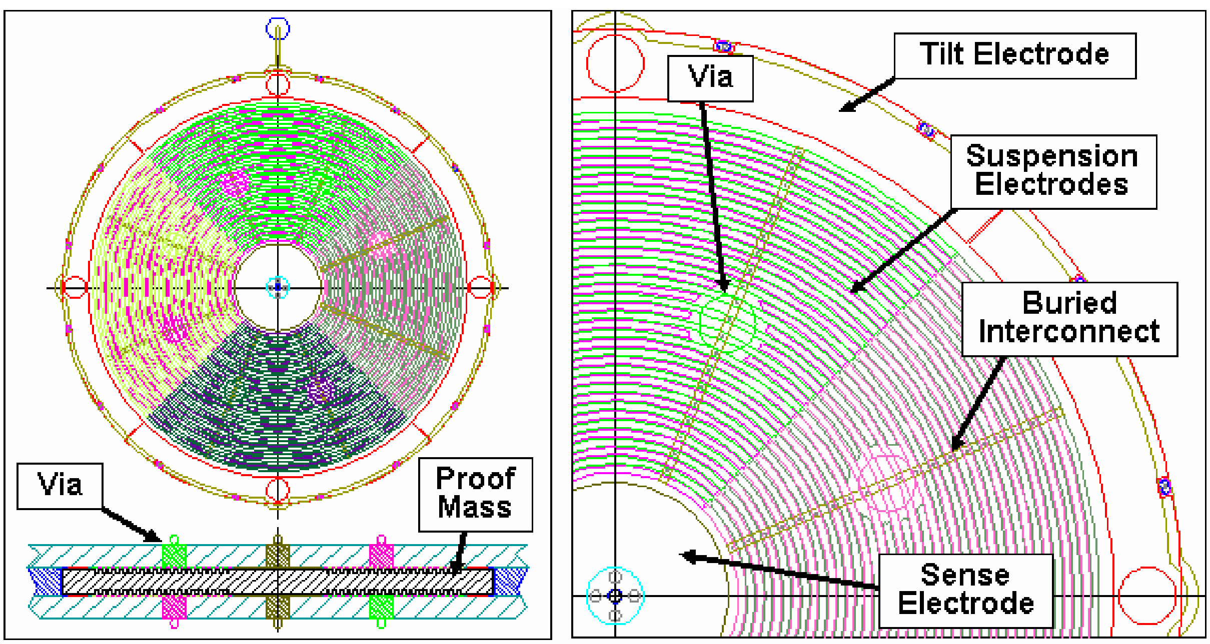

Figure 12: Stator Electrode Design Detail

The vias were formed in three steps:

1) Laser drill holes in Pyrex substrate.
2) Electroplate gold into the holes.
3) Lap surface smooth in preparation for patterning of stators.

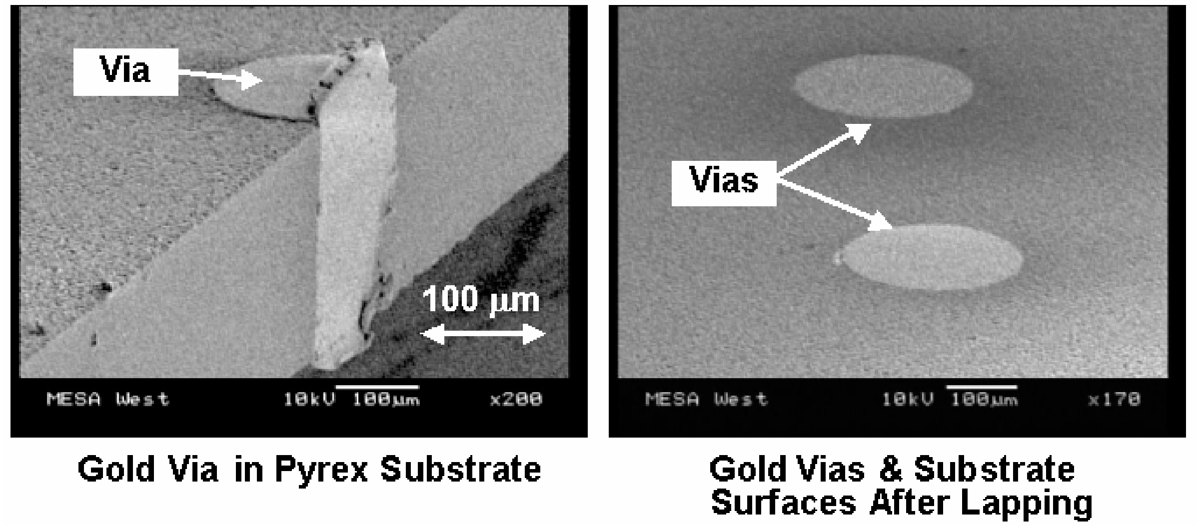

Figure 13: Electron Microscope Image of Conductive Vias

The stator electrodes and other surface features are patterned using photolithographic liftoff techniques on both the front and back sides of the Pyrex wafer.

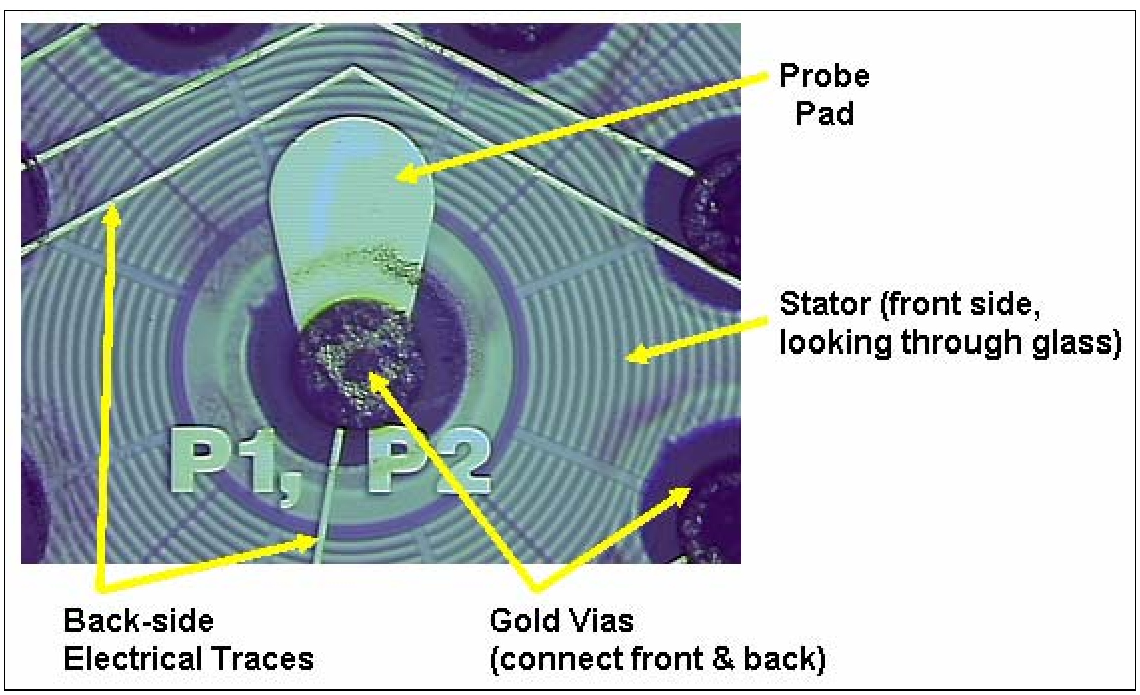

Figure 14: Vias and Front/Back-Side Patterning

5. Test Structure Experiment

Before attempting to control the proof mass in levitation, a simpler test structure was used to demonstrate functionality of all subsystems. This permitted the characterization of capacitance measurement concepts, noise, parasitic forces, parasitic capacitance, shielding, charge buildup, sensor/actuator models, interface electronics performance, and control system stability and tuning.

5.1 Two Degree of Freedom Test Structure

The test structure was an open faced, one-sided version of the micro-accelerometer. The test structure had only 5 pads – a central sense pad and 4 pads around it to sense and control tilt of the proof mass. An electrically isolated bump was placed in the center of the sense pad so that the proof mass could tilt about the two axes. The air gap between the proof mass and the electrodes is set to approximately 25 microns by the height of the center bump.

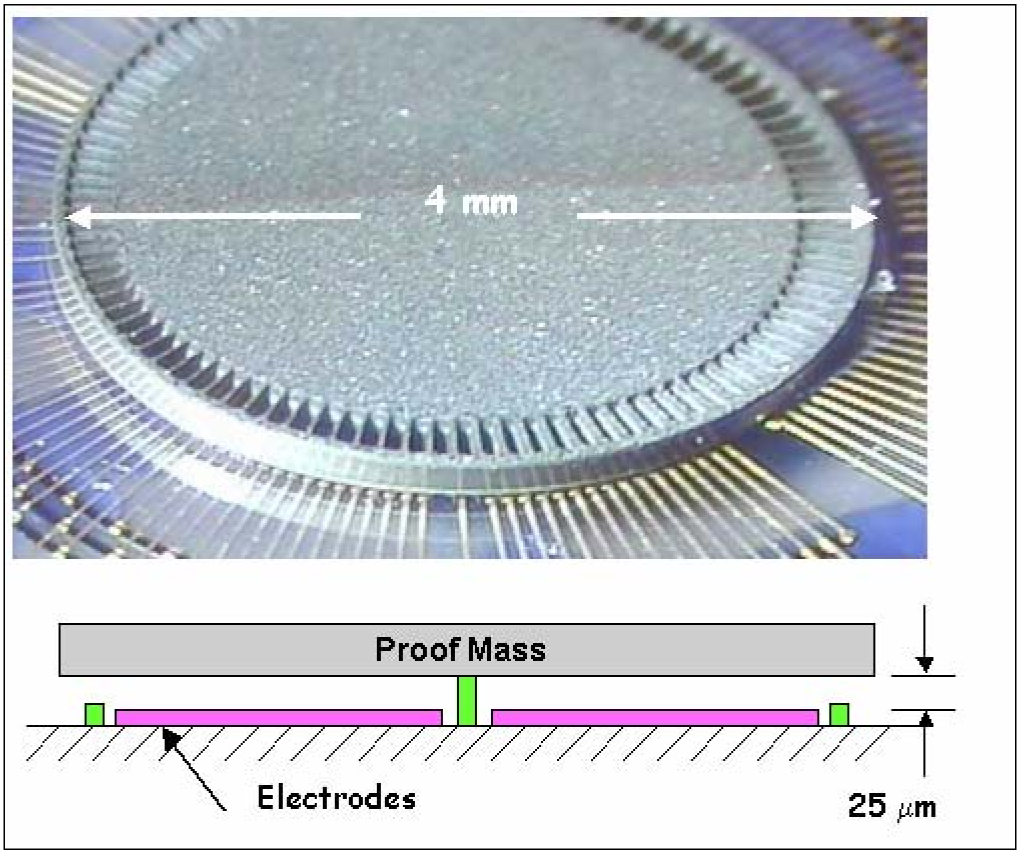

Figure 15: Test Structure Experiment

A ring of electrically isolated lower height bumps was placed under the perimeter of the proof mass to prevent it from short circuiting the control pads. Before closed-loop operation, the proof mass rests on the center and perimeter bumps. Since the heights of the bumps are known quantities, the tilt angles can be calculated and used to calibrate the output of the capacitive sensor.

5.2 Test Structure Packaging

A 24-pin package is used to mount the test structure and charge amplifier circuit and to provide the electrical interfaces to the control system electronics. The charge amplifier is located in close proximity to the stator to minimize parasitic capacitances. The stator vias are bump bonded to an adapter plate which is wire bonded to the 24-pin package.

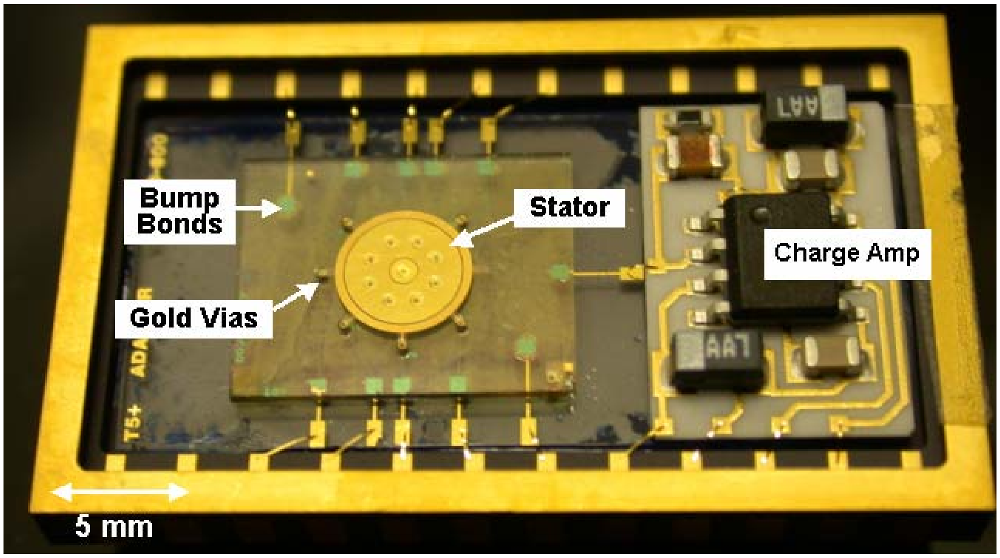

Figure 16: Test Structure Package

5.3 Test Structure Capacitive Sensing

The capacitance between each control pad and the sense pad is a function of the proof mass tilt angle. Tilt is measured using the same synchronous demodulation technique described in section 3.1. To sense the θ_1 tilt angle, a 1.0 MHz sinusoidal stimulus signal is added to pad 1 and the 180 degrees out of phase signal is added to pad 3. To sense the θ_2 tilt angle, a 1.2 MHz sinusoidal stimulus signal is added to pad 2 and the 180 degrees out of phase signal is added to pad 4.

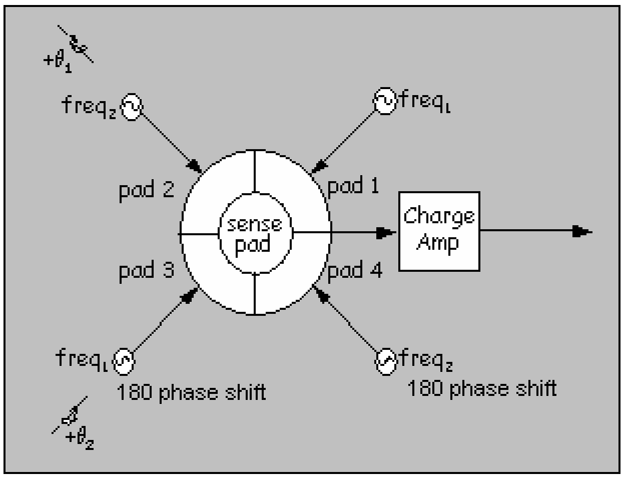

Figure 17: Test Structure Capacitive Sensing

5.4 Test Structure Actuation

To rotate the proof mass about axis 1, a positive voltage (+V) is applied to pad 1 and a negative voltage of half the magnitude of pad 1 (-V/2) is applied to pads 2 and 4. This to ensure the net voltage induced on the proof mass is zero. Figure 18 shows the voltage patterns used to generate positive and negative moments about the two rotation axes.

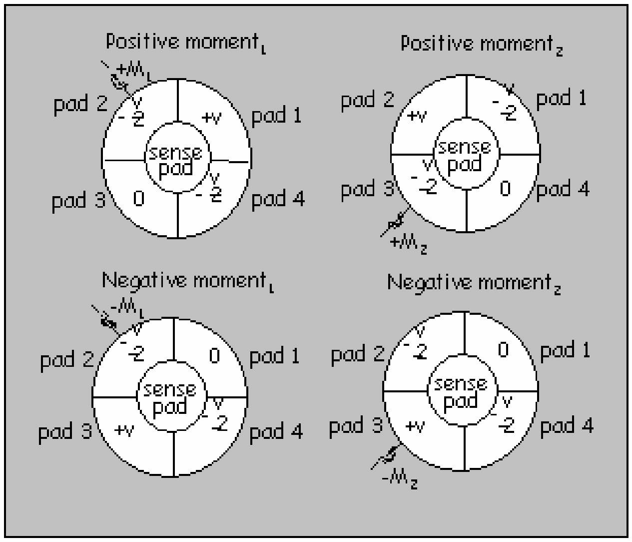

Figure 18: Test Structure Electrostatic Actuation

5.5 Test Structure Control System

The two degree of freedom test structure control system, shown below, used the operating principles and hardware described in section 3.

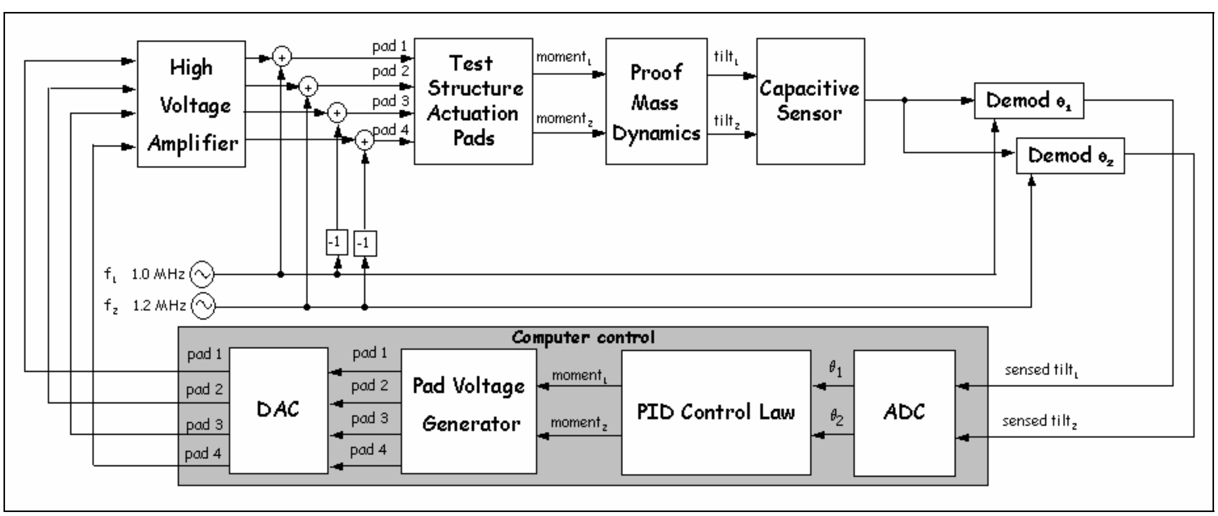

Figure 19: Test Structure Control System

5.6 Test Structure Results

Reliable, stable closed-loop control was demonstrated in two degrees of freedom (tilt about the X and Y axes). Figure 20 is a plot of sensed tilt angles as measured by the control system while the controller was commanded to follow a sequence of set points. This clearly demonstrates the feasibility of closed-loop electrostatic control in more than one degree of freedom.

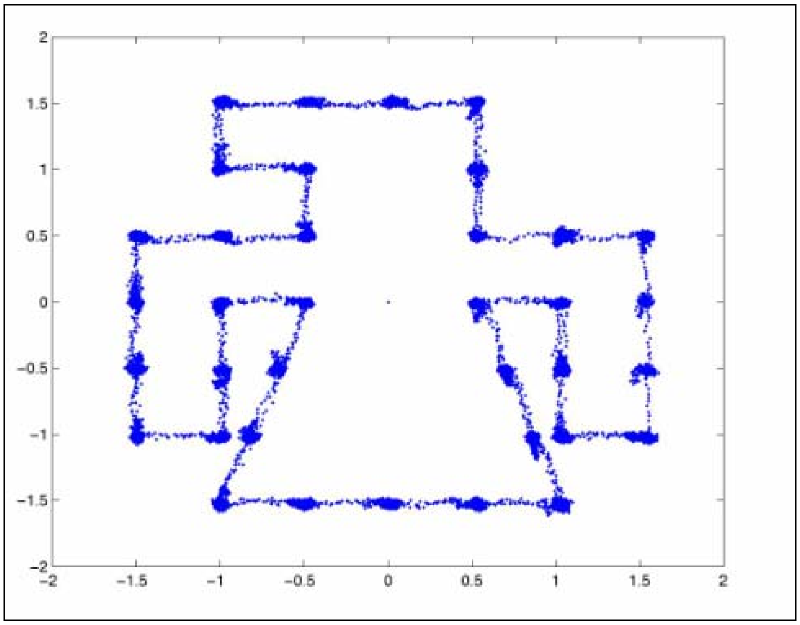

Figure 20: X and Y Tilt Angles Under Closed-Loop Control

6. Accelerometer Prototype

Given the successful demonstration of closed-loop control at the test structure level, several prototypes were designed and built in an attempt to achieve the levitated proof mass design goals described in Section 1. These required a more complex stator design than was needed for the test structure. This drove the successful development of new micro-fabrication technologies:

- Electroplated conductive vias in pyrex wafers.
- Multi-wafer alignment and anodic bonding.
- Ultra-precise wafer lapping and polishing.
- Front- and back-side wafer processing.
- Multiple insulating and conductive layers.

Unfortunately, process integration issues lead to three fabrication-related failure modes (high voltage breakdown, poor material adhesion, and short circuits). This prevented the yield of fully functional hardware. The high voltage breakdown and adhesion problems were eventually resolved, but short circuits remain an issue. The short circuits are not a fundamental design flaw, but require further process development.

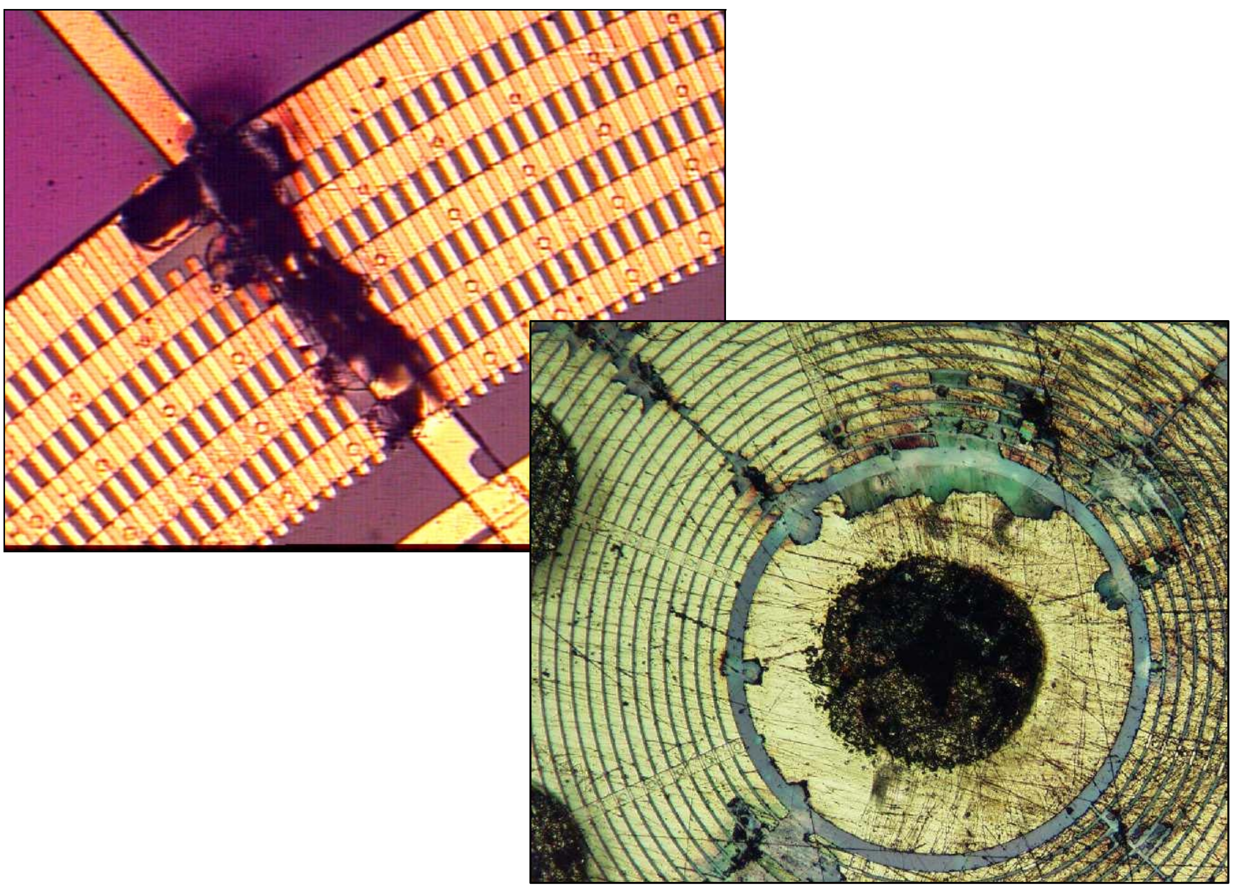

Figure 21: Stator Electrode Damage Due to Short Circuit Failures

7. Accomplishments & Recommendations

An accelerometer was designed and prototype hardware was built, driving the successful development and refinement of several “never been done before” fabrication processes:

- Electroplated conductive vias in pyrex wafers.
- Multi-wafer alignment and anodic bonding.
- Ultra-precise wafer lapping and polishing.
- Front- and back-side wafer processing.
- Multiple insulating and conductive layers.
- Low-cost semi-custom hermetic packaging.

Many of these process developments are commercially valuable and are key enablers for the realization of a wide variety of useful micro-devices:

- Integrated Hybrid Microsystems.
- Fuel cells.
- Biological fluid handlers.
- Micro-electrochemical sensors.
- Bulk silicon inertial switches.

While controlled levitation of a proof mass has yet to be realized (pending the resolution of the short circuit problem referred to in Section 6), the overall design concept remains sound. This was clearly demonstrated by the stable and reliable closed-loop control of a proof mass at the test structure level.

Furthermore, the hybrid MEMS implementation is the most promising approach for achieving the ambitious cost and performance targets. It is strongly recommended that Sandia remain committed to the original goal.

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