Fabrication and Control of an Electrostatically Levitated Rotating Gyro

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ABSTRACT

There are significant efforts to develop gyroscopes using MEMS technology; accuracies of gyroscopes varying from rate-grade, through tactical-grade, to inertial grade. The random walk varies from 0.5 $^o/\sqrt{h}$ through 0.05 $^o/\sqrt{h}$ to 0.001 $^o/\sqrt{h}$. The most common approach is to use vibratory gyros, which use mechanical elements (proof-mass) to sense the rotation. There are several types of vibratory gyroscopes now commercially available from Robert Bosch, BEI Syrtron Donner, Silicon Sensing Systems, MEMSens, and Analog Devices. Any higher accuracy gyroscopes require a rotating disk which is electrostatic levitated and spun. This device also does not have bearings and with large spinning velocity very high accuracy can be obtained. There are two publicly known attempts to develop MEMS rotating gyroscopes, one in Japan by the group associated with Tokimec and a similar concept is being developed in Europe led by M. Kraft. The European approach has more theoretical character. At AMNSTC we developed and fabricated another rotating gyroscope, which differs from the Tokimec design in several ways: three instead of four levitation electrodes are used, new 6 phase or 4 phase spinning concepts are implemented, better layout of vertical electrodes was used, new concept of vias were developed, and new fabrication method was developed, which used standard MEMS processing with as few as 5 masking steps, allowing the realization of low cost inertial measurement systems. Several batches of gyroscopes were fabricated and measured.

Keywords: Gyroscope, Electrostatic, Inertial Measurement System

INTRODUCTION

MEMS technology is widely used and researched in an effort to develop small, light weight, and inexpensive gyroscopes for inertial guidance systems. MEMS technology has made it possible to fabricate gyros using various methods of detection such as vibratory and levitated rotating masses. We propose design and fabrication methods to improve the levitated/rotating gyros described by groups from Europe (1) and Japan (2) who have developed MEMS based levitated gyroscope devices which achieve a high level of performance in a small, light weight package. Both devices described in the above literature use four levitation electrodes in order to balance the rotating mass. This type of electrode design has been shown to be unstable, or at best, hard to stabilize due to mechanical or charge imbalances. Contact resistances for top electrode to bottom electrode vias are typically high given the metal system used in the literature. It has been found that the conductivity of these contacts can be improved by using a different metal system along with a different contact design. New ideas for controlling and spinning the levitated mass are presented.

PRINCIPLES OF OPERATION

Electrostatic forces in the Gyro

Electrostatic forces are utilized in the control of the gyro. A view of the layout is shown in figure 1. The design includes a set of lifting electrodes along with a set of lateral control electrodes. Both sets of electrodes detect the position of the center levitated/rotating mass, as well as control it's position. The electrode pattern is symmetrical on the top and bottom of the gyro. There is also a set of spinning electrodes which are used to spin the center mass after it has been levitated. A cross-sectional diagram of the lifting electrodes and the center mass is shown in figure 2.

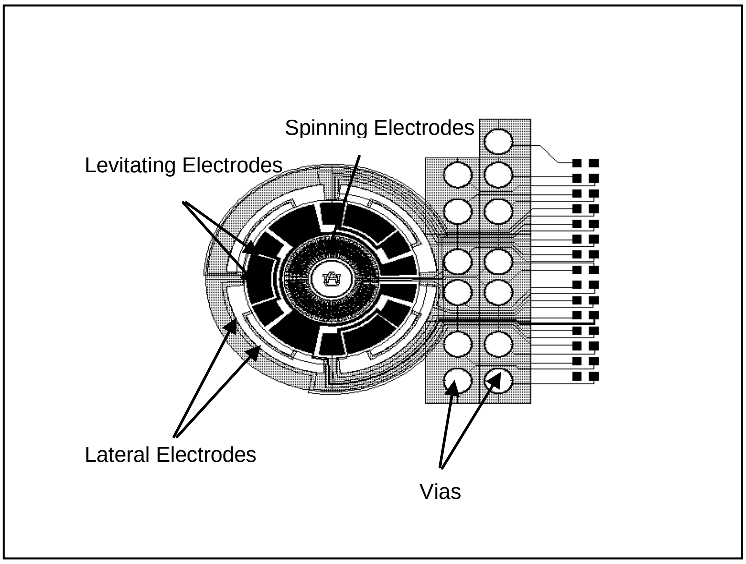

Figure 1. Gyro Layout

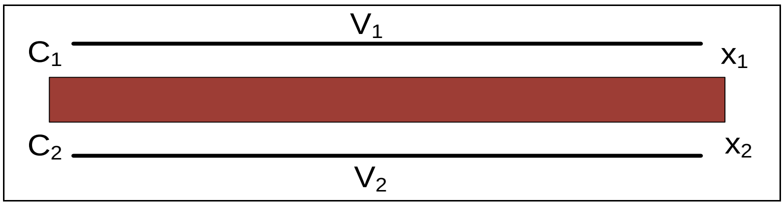

Figure 2. Electrodes controlling vertical position of floating rotor

The value of capacitances C1 and C2 are given by:

$$C_1 = A\frac{\varepsilon_0}{x_1} \qquad C_2 = A\frac{\varepsilon_0}{x_2} \tag{1}$$

Where: A A is the area and x_1 and x_2 are gap thicknesses. Energy stored on these capacitors are:

$$E_1 = \frac{C_1 V_1^2}{2} = \frac{A\varepsilon_0 V_1^2}{2x_1} \qquad E_2 = \frac{C_2 V_2^2}{2} = \frac{A\varepsilon_0 V_2^2}{2x_2} \tag{2}$$

Electrostatic forces can be found as a derivative of energy over distance:

$$F_1 = \frac{\partial}{\partial x}\left(E_1\right) = \frac{\partial}{\partial x}\left(\frac{A\varepsilon_0 V_1^2}{2x_1}\right) = -\frac{A\varepsilon_0 V_1^2}{4x_1^2} \quad \text{and} \quad F_2 = -\frac{A\varepsilon_0 V_2^2}{4x_2^2} \tag{3}$$

From equation 3 it can be seen that the forces are nonlinear functions of applied voltage and gap thickness.

Fast nonlinear controller

The electro statically controlled gyro has a very nonlinear nature. While linear control system theory has been well developed with PID type of control; the nonlinear control problems cause most challenges. Usually, a nonlinear process has to be linearized first before an automatic controller can be effectively applied. This is typically achieved by adding a reverse nonlinear function to compensate for the nonlinear behavior so the overall process of the input-output relationship becomes somewhat linear. The issue becomes more complicated if a nonlinear characteristic of the system changes with time and there is a need for an adaptive change of the nonlinear behavior. These adaptive systems are best handled with methods of computational intelligence such as neural networks and fuzzy systems.

Any dynamic nonlinear system can be described by the following set of nonlinear state equations:

$$
\begin{aligned}
y_1 &= \int f_1\left(x_1, x_2, \cdots x_n, y_1, y_2, \cdots y_n\right)\ dt \\
y_2 &= \int f_2\left(x_1, x_2, \cdots x_n, y_1, y_2, \cdots y_n\right)\ dt \\
&\cdots \\
y_n &= \int f_n\left(x_1, x_2, \cdots x_n, y_1, y_2, \cdots y_n\right)\ dt
\end{aligned}
\tag{4}
$$

Such a system can be implemented as a composition of integrators and nonlinear terms as shown in Fig. 3. Implementation of analog integrators on silicon chips is relatively simple. It requires a capacitance and an operational or transcounductance amplifier. Nonlinear terms with multiple inputs are more difficult to implement. These nonlinear blocks can be developed as universal elements using neural networks or fuzzy systems. In the case of neural networks only weights need to be digitally controlled. In the case of the fuzzy systems parameters of fuzzifiers and deffuzifiers have to be digitally adjusted. This analog type of signal processing (Fig. 4.) is especially important in systems where a large signal latency is not acceptable, such as the electrostatically controlled gyro.

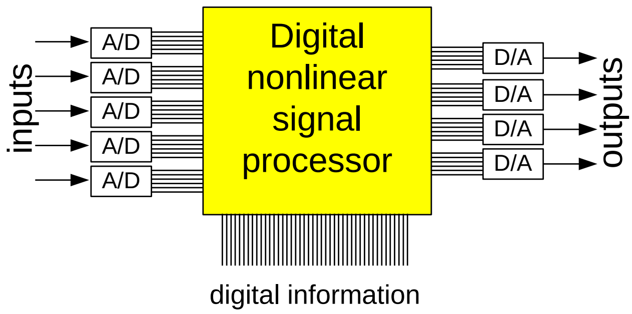

Fig. 3. Block diagram of a digital system

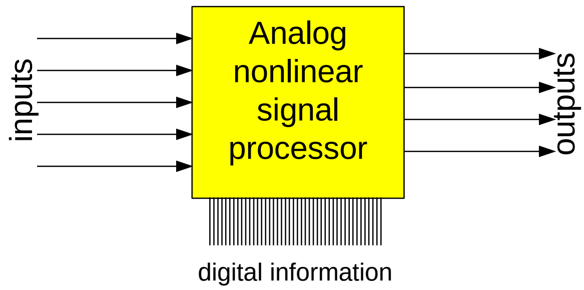

Fig. 4. Block diagram of a digitally controlled analog system

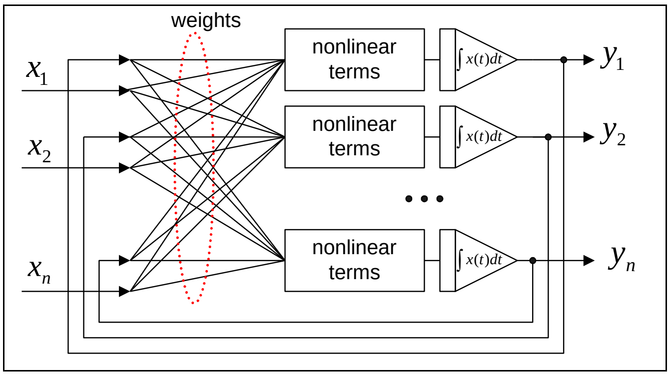

Fig. 5.Implementation of digitally controlled analog nonlinear signal processor. Weights are implemented by tunable resistor of Fig. 6.

The key issue is to develop a digitally controlled resistor to implement weights in the system shown in Fig. 5. We propose a new circuit (Fig. 6) which fulfills this requirement. Fig. 7 shows the current voltage characteristics at terminal Vout when the Vin voltage is set to 2.5V. The floating resistor of Fig. 6 can be controlled over 6 orders of magnitude from 300kW to 300GW as is shown in Fig. 8.

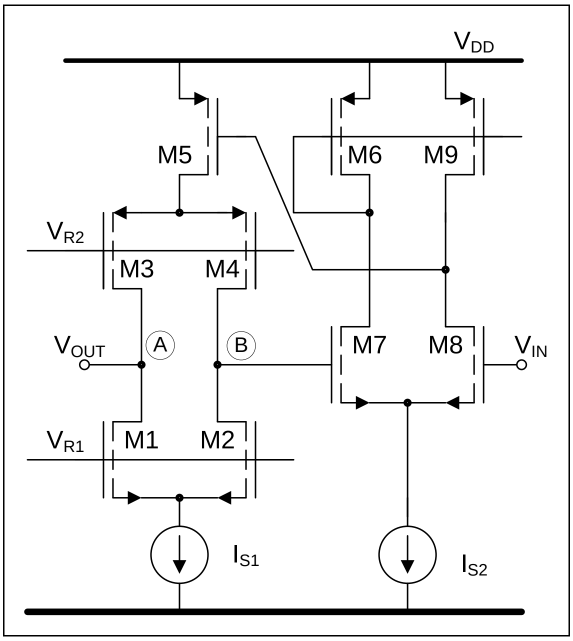

Fig. 6. Current (IS1) controlled resistance between Vin and Vout (resistance is seen from Vout terminal)

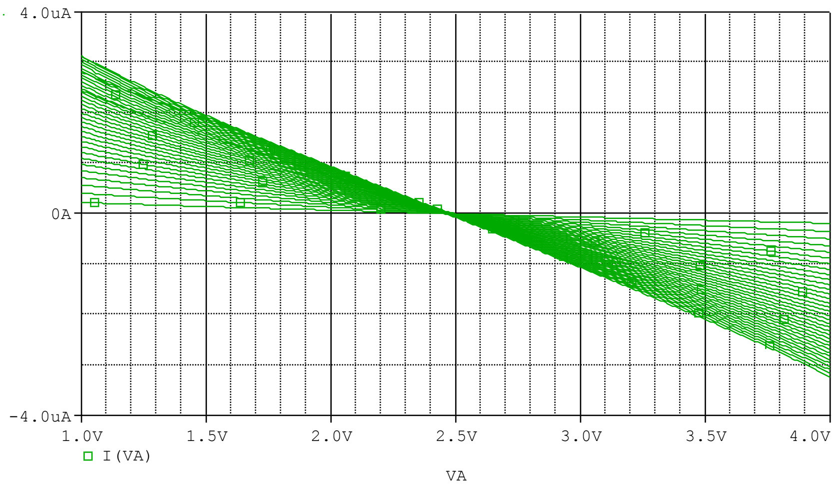

Fig. 7. Current-voltage characteristics of the tunable resistor of Fig. 4.

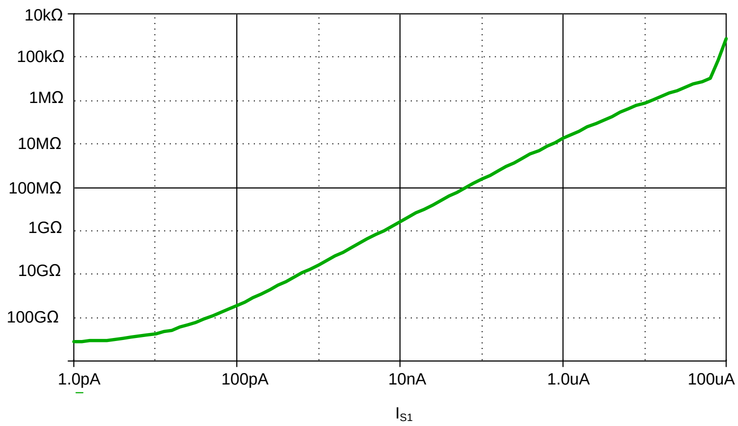

Fig. 8. Resistance change of the active resistor of Fig. 4 controlled by the tail current I_{S1}

With the concept of current controller resistor shown in Fig. 6 the digital control resistance can be simplified to the case of digital control of a current, which can be easily implemented with DA converters. Also for the practical application we need not to control resistor over 6 orders of magnitude range; therefore a simple 8 bit DAC can be used. Please notice that these DACs are not in the signal path and they are being used only to adjust system parameters and they do not affect signal latency.

Elimination of interactions between controllers

Controlling a floating rotor in the rotating gyro is not easy. Multidimensional and nonlinear interactions occur between applied dc voltages and forces in various directions. For example, if the voltage is applied on one of the vertical electrodes and the remaining voltages are zero then potential of rotor changes and so many electrostatic forces appear at different electrodes, even their potential is still zero.

One way to eliminate this undesired effect is to apply both positive and negative voltages on opposite electrodes so the dc potential of the rotor is not changing with control voltages. This is not always possible. For example, if the system is unbalanced (upper and lower capacitances are different due to different distances) the equal and opposite potential will result with the potential change on the rotor. Therefore, if system is not symmetrical we have to apply asymmetrical voltages.

The case becomes even more difficult if, for example, vertical capacitances are much larger than the horizontal ones. It means that vertical control affects the horizontal one.

Elimination of the effect of a random charge stored on the floating rotor

One of the most challenging problems was to eliminate the effect of static charge randomly accumulated on the floating rotor. This was accomplished in the system shown in Fig. 9 One notices that with this arrangement forces between identical electrodes and the static charge cancel each other. For example, a negative charge on rotor will be attracted by the positive voltage on electrode A and it will be pushed away by the negative voltage on electrode B. If voltages are the same and area of electrodes are the same then value of both forces are also the same, but they have an opposite direction.

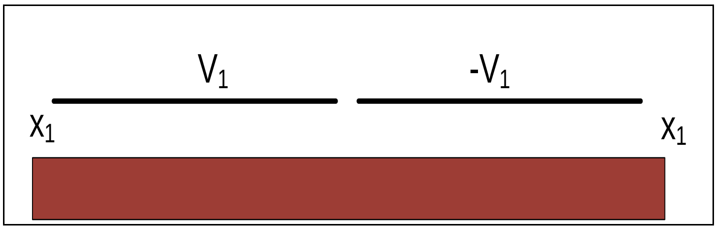

Figure 9. Electrode scheme for random charge elimination

Rotor vertical stability

The concept of four electrodes for vertical position of the rotor, used in other rotating gyro faces difficulties if mechanical dimensions are not perfect or if electronics have imbalanced drift. The four control systems for vertical control may not be stable and in case of mismatch these controllers work against each other. The situation is similar to the stability of a table with four legs of unequal lengths. Let us assume (Fig. 10(a) that positions A, B, and C are being established by three controllers, then in order to change position at point D the controller associated with this point has no other option but to work against other controllers at points A, B, and C. In our gyro we use the concept of three vertical controllers so each controller works independently. This is not only a simpler design but it makes the system more stable.

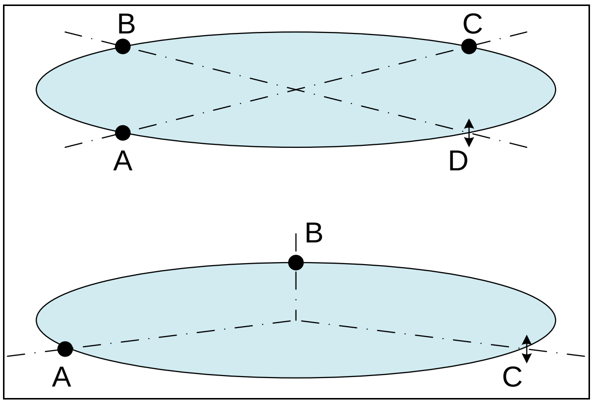

Fig. 10 Comparison of four and three controller cases: (a) Four controllers interact (fight each other), (b) Three controllers work independently

Rotor Spinning

The floating rotor can be spun using the same force concepts described above. Our spinning electrodes are designed in a circular array which allows the silicon "spokes" to be pulled under the metal and by timing the phases of the applied voltage to coincide with the position of the silicon "spokes". The electrode areas are carefully balanced to insure the same area, on the positive and negative electrodes, is always covering the silicon. This insures there is minimal charge imbalance on the rotor, and that the spinning force is equally distributed along the electrode array. The design is shown in figure 11. The spinning voltage is applied to array electrodes a,b (positive and negative)and then c,d (positive and negative) (Fig. 11) and repeated at a rate to insure a continuous spinning. The pulling force starts at the "point" of the electrode and proceeds to the back, wide portion of the electrode. As the spoke aligns with the back of the electrode the next set is actuated to continue the spinning motion.

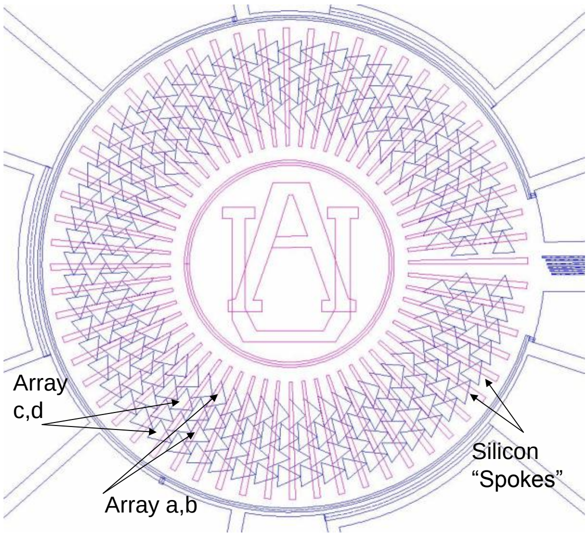

Figure 11. Spinning Electrode Design

GYRO FABRICATION

Overall process sequence

We have developed a 5 mask process which uses standard MEMS techniques to fabricated a complete gyro device. The structure consists of 2 glass (pyrex 7740) plates bonded to both sides of a patterned silicon rotor/frame. The rotor is unattached and has space to float between the glass layers. The full process is shown in figure 12. the first step is to pattern and etch the glass surfaces to form recesses which provide the gap between the glass and the rotor, along with trenches which provide isolated paths for the metal conductors (Fig.12a). Once the glass has been deep reactive ion etched (STS Advanced Oxide Etcher) to a depth of 7 um, the conductor pattern is delineated using 20 um thick photoresist (AZ4620). Aluminum (1.5 um) is then deposited and patterned by a lift-off technique to form the conductors/electrodes (Fig. 12b). Next a double sided silicon wafer with a thickness equal to the desired rotor thickness is anodically bonded to the bottom glass. The silicon is then patterned using 7 um thick photoresist (AZ 4620) to mask the following Deep Silicon Etch (STS Advanced Silicon Etcher) (Fig 12c). A photo of the structure after this etch is shown in figure 13. (note: the rotor has been removed). Next the etched and metallized top glass is aligned and anodically bonded to the silicon to form the upper electrodes (Fig. 12d). The completed devices are then diced and separated. The devices are then epoxy bonded to a patterned ceramic substrate or FR4 PCB and then wirebonded to allow access to the Gyro electrodes.

Via process details

In order to form connections between the top and bottom electrodes, it was decided that silicon vias would be used to simplify the process as well as save space. The via process consists of a cylindrical section of silicon which is isolated from the frame and is connected to conductors from the top and bottom glass. The aluminum/silicon connection is formed when a section of the aluminum conductor is patterned on the top of the glass (I.E. extending out of the trench onto the original surface of the glass). The silicon delineation/etch provides a cylinder of silicon which is designed to overlap the aluminum conductor extension on the glass surface. A 3-D diagram of the trench/metal/silicon structure is shown n figure 14. When the silicon is anodically bonded to the glass the conductor is "squeezed" between the glass and the silicon allowing for an intimate contact (Fig. 15.) This contact is formed on both sides of the silicon via forming a conducting path between the top and bottom electrodes. The silicon is heavily doped (0.01 ohm-cm) p-type silicon which readily forms an ohmic contact to the aluminum conductor. For the silicon vias used in this project (250 um thick and 800 um diameter) the resistance was less than 100 ohms and very linear.

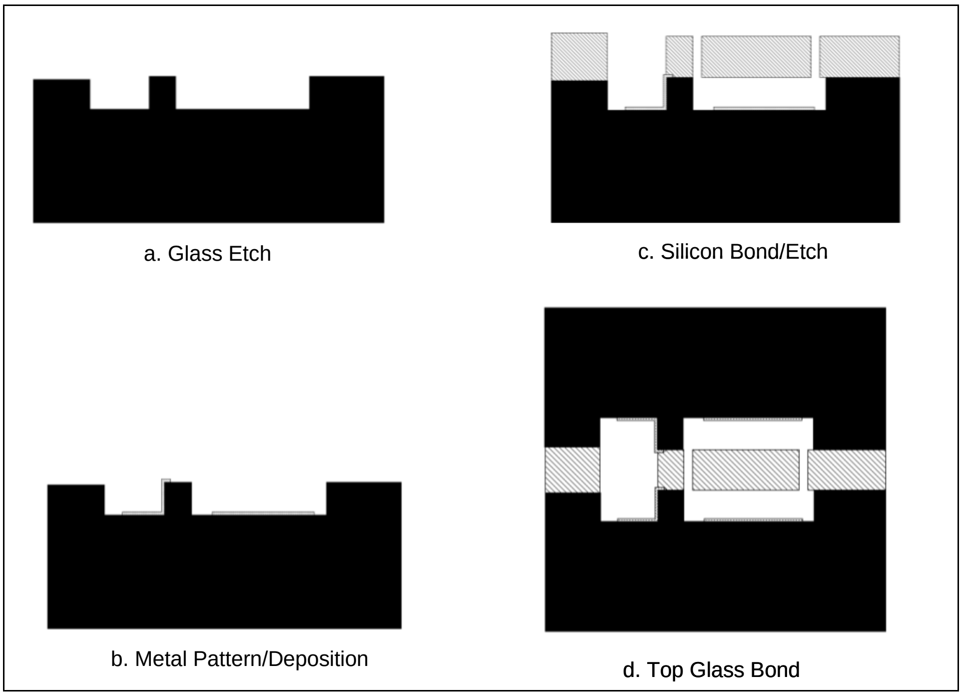

Figure 12. Gyro Process Steps

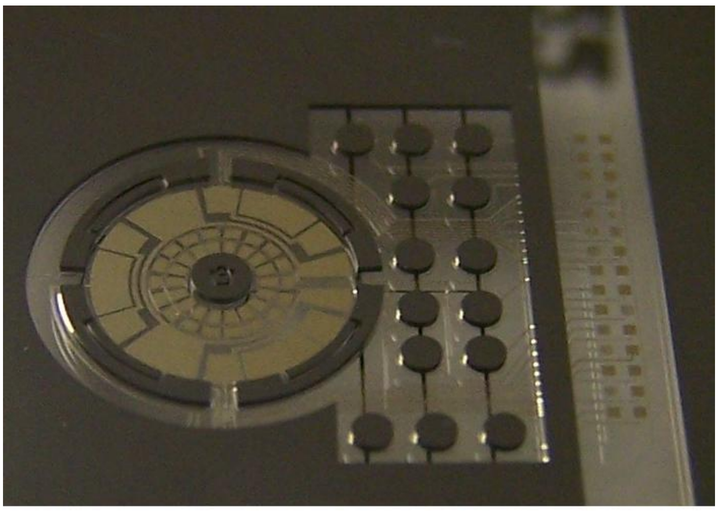

Figure 13. Photo of etched silicon on glass (rotor removed)

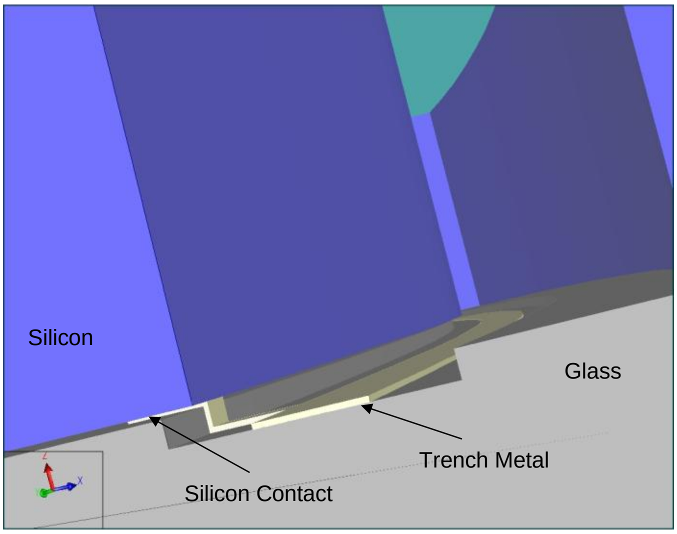

Figure 14. Cross-Section of Glass/metal/silicon

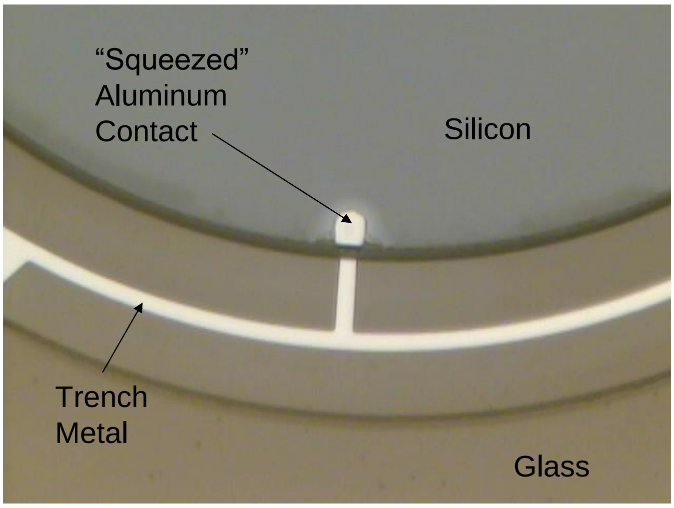

Figure 15. Photo (through glass) of "squeezed" aluminum contact

RESULTS

A variety of structures, with different spinning electrode designs, have been fabricated and tested to insure the rotor is free. At this time only preliminary testing has been performed on the fabricated devices. The tests have consisted of measuring capacitances and applying lifting voltages and determining if the rotors are moving. More testing is under way and will be reported as soon as data is available. Preliminary results are summarized in table 1. The capacitance between the rotor and the lifting pads is measured. It can be seen that the capacitance is in a measurable range. Initial tests has shown a significant change in capacitance with applied lifting voltage (the data has not been added to the table as of publication deadline). This proves that the rotor is being lifted and should be capable of being controlled and spun.

Table 1. Capacitance Measurements for gyro

Electrode (See Figure 16**)**	**Resting Capacitance (pF)**	**Lifted Capacitance (pF)**
P1TP	7.9	TBD
P1TM	9.1	‘‘
P2TP	7.7	‘‘
P2TM	9.0	‘‘
P3TP	8.9	‘‘
P3TM	10.5	‘‘
P1BP	26.5	‘‘
P1BM	26.8	‘‘
P2BP	23.7	‘‘
P2BM	24.1	‘‘
P3BP	26.8	‘‘
P3BM	26.5	‘‘

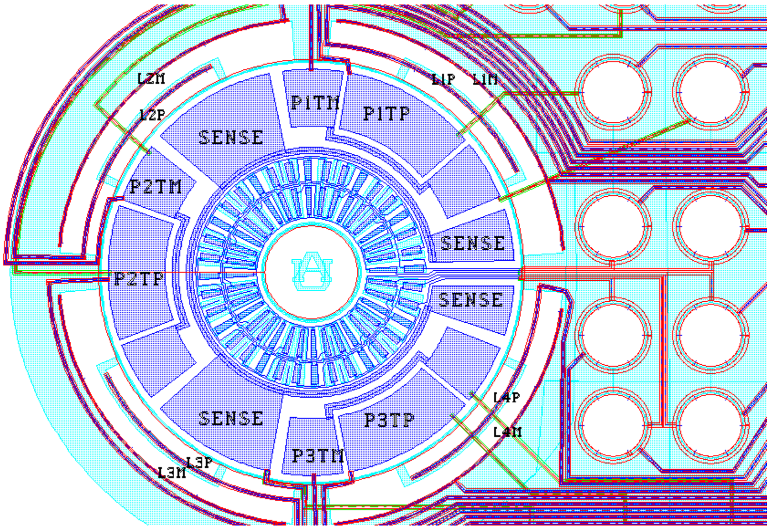

Figure 16. Lift pad and sensor pad lables (Bottom electrodes not shown). P1TP means Pad set 1 Top Positive (M would be minus), P1BP would be the bottom set. PIBP would be Pad set 1 Bottom Positive.

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