MICRO-ELECTROMECHANICAL INSTRUMENT AND SYSTEMS DEVELOPMENT AT THE CHARLES STARK DRAPER LABORATORY

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Abstract

Draper Laboratory has been developing miniature micromechanical instruments for over 10 years, using and maturing silicon microfabrication techniques to achieve high yields in this batch processing environment. During this time, we have made considerable progress in the development and fabrication of micromechanical gyroscopes, accelerometers, and acoustic sensors. We have fabricated gyroscopes and accelerometers with dynamic ranges from 50 to 500 deg/s and 10 to 100,000 g, respectively. Bias stability of 33 deg/h and 0.55 mg has been demonstrated over a wide range of thermal and environmental conditions. In recent room temperature tests, 1°/h performance over a 0.1 Hz bandwidth, corresponding to 24°/h performance over 60 Hz, has been achieved. Our continuing development activities are expected to yield over an order of magnitude in performance enhancement. Draper builds its micromechanical instruments using a silicon wafer process that results in crystal silicon structures that are anodically bonded on a Pyrex (glass) substrate that contains sensing and control electrodes. This silicon-on-glass configuration has low stray capacitance, and is ideally suited for hybrid or flip-chip bonding technology.

Several generations of micromechanical gyros and accelerometers have been developed at Draper. Current design effort centers on tuning-fork gyro design and pendulous accelerometer configuration. Over 200 gyros of different generations have been packaged and tested. These units have successfully performed across a temperature range of -40 to 85°C, and have survived 30,000-g shock tests along all axes. Draper is currently under contract to develop an integrated Micromechanical Inertial Sensor Assembly (MMISA) and Global Positioning System (GPS) receiver configuration. Ultimate projections of size, weight, and power for an MMISA (after electronic design of the application-specific integrated circuit (ASIC) is completed) are 2 x 2 x 0.5 cm, 5 gm, and less than 1 W, respectively. This paper describes Draper's fabrication process, the current gyro and accelerometer designs, and system configurations.

Introduction

Draper has been developing miniature micromachined instruments for over 10 years, using and contributing to the maturation of silicon microfabrication technology. During this time, we have made extensive progress in the development and fabrication of micromechanical gyros, accelerometers, microphones, and hydrophones. In this context, we have fabricated gyros and accelerometers with dynamic ranges from 50 to 500 deg/s and 10 to 100,000 g, respectively. Performance resolution of 33 deg/h and 0.55 mg have been demonstrated over a wide range of thermal and environmental tests. Our continuing development activities are expected to yield an order of magnitude in performance improvement. Our acoustic sensors have demonstrated sensitivities that are significantly higher than comparably sized commercial units.

Consistent with the goal of transitioning technology to industry, Draper has entered into an alliance with the Rockwell International Corporation (RI). In 1993, the Draper/Rockwell alliance was consummated for the purpose of transitioning Draper-developed inertial micromechanical technology for production and commercialization. The proven performance and high-volume, low-cost manufacturability achievements have demonstrated commercial viability, and Rockwell has established a manufacturing capability.

Initial RI products are targeted for automotive applications. Extensive investments have already been made in the development of this technology and its preparation for production. While RI's current primary emphasis is oriented toward large-volume applications, Draper remains committed to enhancing the performance of these designs and extending our micromachining capabilities to other instruments and applications. We currently provide, and will continue to seek, additional opportunities to apply our micromechanical development expertise to meet the unique needs of DoD and NASA. Toward this end, we believe our current instruments can be tailored to address miniature spacecraft objectives for GN&C and robotics. These capabilities can also be applied to a host of integrated payload instrumentation suites, as well as vehicle health monitoring systems.

This paper specifically details Draper's micromechanical silicon dissolved wafer fabrication process and describes and illustrates the current gyro and accelerometer development and fabrication status. Draper's achievements in micromechanical inertial systems technology has demonstrated a level of performance and manufacturability that warrants its consideration in Space and DoD applications. We are prepared to provide gyros, accelerometers, and inertial system development and fabrication activities that could result in near-term deliveries of components and systems for ground test and space flight demonstration. For example, under U.S. NAVY-NAVSEA sponsorship, Draper is developing an MMISA of three gyros and accelerometers, and is integrating it with a miniature GPS receiver for an Extended-Range Guided Munitions Demonstration Program (ERGM). We are interfacing these units with a TMS320C31 processor, and implementing software to perform attitude determination, instrument calibration, receiver aiding, and navigation, with an initial delivery scheduled for February 1996.

Fabrication Process

Draper builds its micromechanical instruments using a dissolved silicon wafer process that results in crystal silicon structures anodically bonded on a Pyrex (glass) substrate that contains the electrodes. Compared to conducting substrates, this silicon-on-glass configuration has low stray capacitance. Although on-chip electronics are not yet possible with P+ silicon on glass, this configuration is ideal for hybrid or flip-chip bonding technology.

The micromechanical instrument dissolved wafer fabrication process is illustrated in Figure 1. Reaction ion etching (RIE) and boron diffusion are used to define the final structure. As shown, the process starts with a silicon wafer of moderate doping. In the Mask 1 step, recesses are etched into the silicon using KOH. These recesses define the height of the silicon above the glass to allow gap spacing for the capacitive sensing plates and metal runs. A boron diffusion step follows, which defines the thickness of the structure. The structure's features (patterns) are then defined (Mask 2) and micromachined using RIE by etching past the diffused boron layers. This etching process results in straight side walls and high aspect ratios.

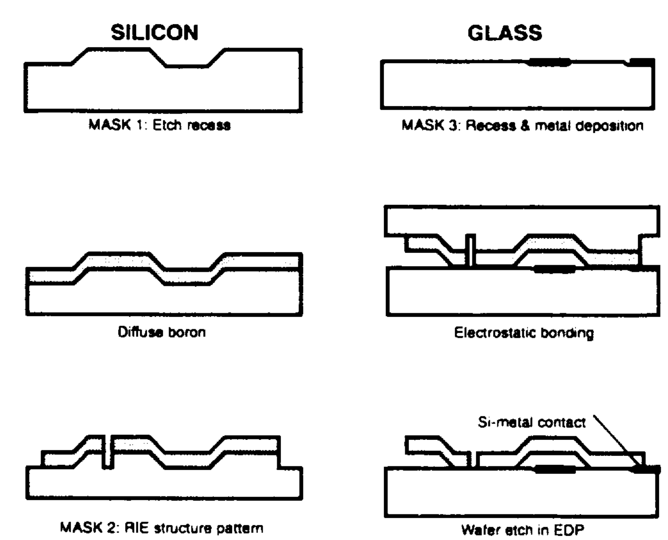

Figure 1. Dissolved wafer, silicon-on-glass process.

The glass processing (Mask 3) recesses the glass and then deposits and subsequently lifts off a multimetal system on a glass wafer. This results in a planar structure with metal electrodes and runs protruding only slightly above the glass surface. The metal forms the sense and drive plates of capacitor transducers and their output leads. The silicon and glass are then electrostatically bonded together. This electrostatic bonding process draws the silicon and glass tightly together to ensure a low-resistance contact. The final step corresponds to a selective etch in ethylene diamine pyrocatechol (EDP), which dissolves the undoped silicon and stops at the heavily boron diffused layers. This overall fabrication sequence requires only single-sided processing with 3 masking steps. Figure 2 illustrates the quality of the straight wall etching process.

Draper has achieved high yields using this batch processing technique. Hundreds of gyros are made on single wafer. Figure 3 (courtesy of RI) illustrates a tuning-fork gyro (TFG) wafer under probe test. Under Internal Research and Development (IR&D), Draper continues efforts to perfect these processing techniques to enable fabrication of higher performance instruments. Our fabrication capabilities will address and assess the future potential of micromechanical fabrication for a large variety of instrument applications.

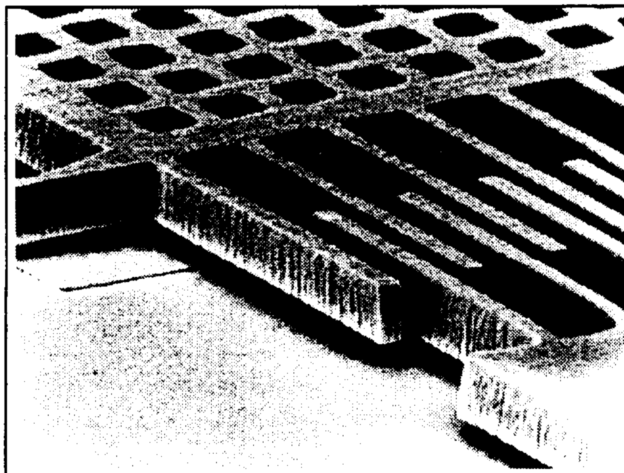

Figure 2. The comb structure on a TFG.

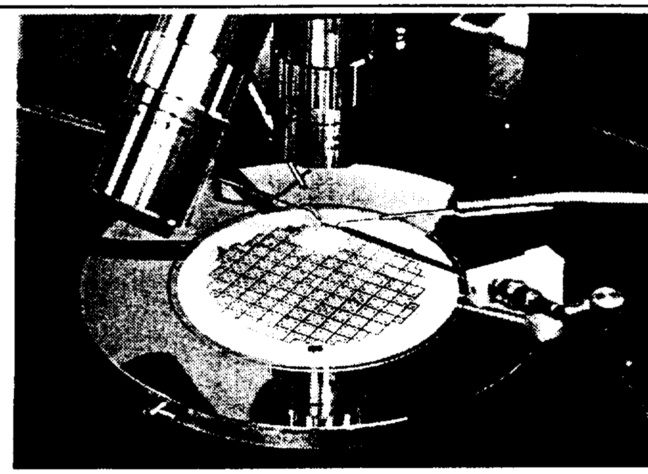

Figure 3. TFG wafer under test probe.

Micromechanical Inertial Sensors

Draper has developed several generations of micromechanical gyros and accelerometers. The current build process is described in the Fabrications section of this paper. This section describes our current micromechanical TFG and pendulous mass accelerometer designs.

Tuning Fork Gyro

The TFG's principle of operation and construction features are illustrated in the mechanical schematic shown in Figure 4. Both an in-plane (top view) and a cross-sectional (side view) are shown. The top view shows two vibrating mass members suspended by sets of flexural (struts) supports. The proof masses are vibrated in the plane of the structure by the operation of electrostatic forces applied through the interaction of the motor drive comb structures. An AC excitation is applied to the comb drives to sustain a lateral oscillation of the proof mass members. The resulting oscillation yields an in-plane peak velocity, V, that is a function of the drive frequency (f) and the peak amplitude of the vibration displacement (Y_A).

$$V = 2\pi f Y_A \quad (1)$$

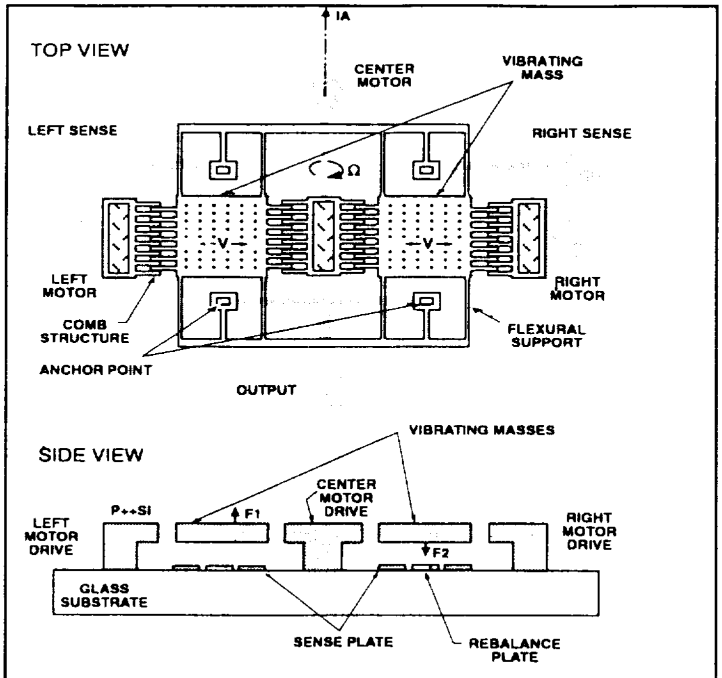

Figure 4. Micromechanical yaw rate sensor configuration.

The mass members are excited so that their velocities are 180 deg out of phase with respect to each other.

When an angular rate (Ω) is applied about the input axis (IA), one of the vibrating masses will lift up out of the plane and the other will move down due to Coriolis forces F_1 and F_2 (side view), respectively.

$$F = 2\Omega Vm \tag{2}$$

where m is the integrated mass of the vibrating member.

The capacitor electrodes (sense plates) below these proof masses sense this motion. Feedback through a control loop can apply voltages to the rebalance plate electrodes to provide nulling electrostatic forces. For lower cost and performance applications, open-loop operation is adequate.

A scanning electron microscope (SEM) photo of the TFG is shown in Figure 5. Figure 6 shows the device next to an ant for size comparison. The unit shown corresponds to the product of many design and test iterations. Over 200 gyros of different generations have been packaged and tested. Steady performance improvement has been achieved. These units have survived 30,000-g shock and centrifuge tests along all axes.

In open-loop, low-bandwidth tests, compensated bias stability of 33 deg/h has been demonstrated over a temperature range of -40 to +85°C. Figure 7 illustrates the open-loop voltage output of the TFG across a ±100 deg/s input angular rate. Scale-factor (SF) repeatability of better than 0.1% has

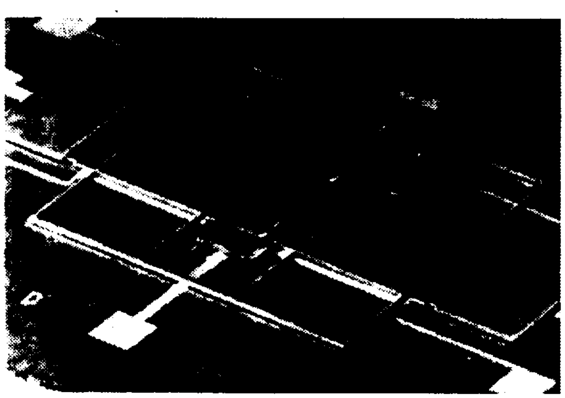

Figure 5. Micromachined comb drive TFG.

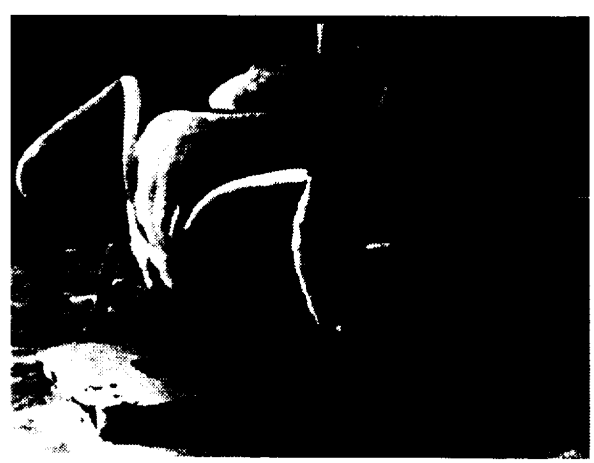

Figure 6. Silicon micromechanical gyro size comparison

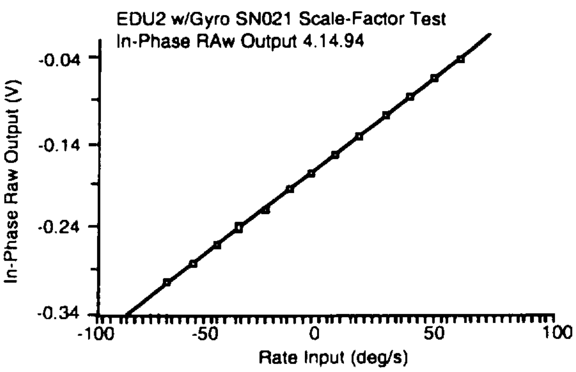

Figure 7. Gyro SF test.

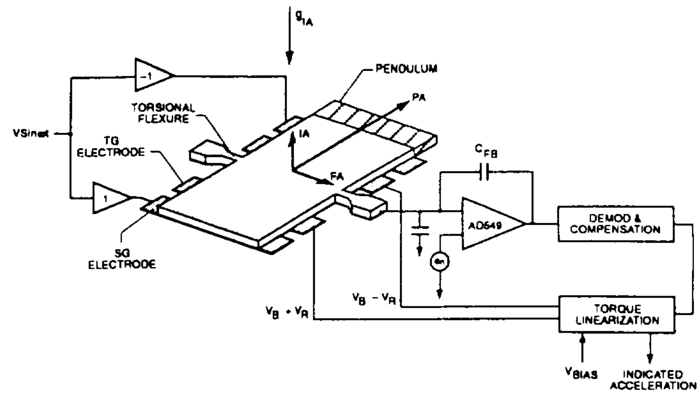

Figure 8. 100-g accelerometer schematic.

been achieved in testing across numerous temperature cycles and shutdowns. Continued TFG development and design enhancement is planned, and a long-term performance goal of 1 to 10 deg/h over -40 to +85°C is projected. Draper has made steady progress in the evolution of the micromechanical gyro with continuing improvements in performance. In recent room temperature tests, 1°/h performance over a 0.1 Hz bandwidth, corresponding to 24°/h performance over 60 Hz, has been achieved. Table 1 illustrates the performance progress that has been achieved from 1993 to date. A projected 1996 performance target of 0.25°/h is shown. Fabrication of a larger unit and improved sense electrode preamplifier is expected to provide significant performance enhancements.

Table 1. Micromechanical gyro performance history*.

DATE/STATUS		RMS DRIFT (deg/h, 0.1-60 Hz)	ARW (deg/√h)	DRIFT (0.1 Hz)	SF STABILITY (ppm)
5/93	Measured	1000	1.52	40.8	~150
6/94	Measured	500	0.76	20.4	<100
8/95	Measured	200	0.3	8.17	—
10/95	Measured	24	0.037	0.98	~50
11/96	Projected	6	0.009	0.25	~10
* Room temperature tests					

Pendulous Accelerometer

A schematic of the accelerometer is shown in Figure 8. A simple mechanical design is employed. The acceleration-sensitive element corresponds to a single thickness proof mass that is suspended on a pair of micromachined torsional flexures. The pendulous effect is achieved by mounting the structure off center (one side is longer than the other). A pair of electrodes lies below the proof mass structure. Capacitive changes occur when the proof mass rotates about the flexure axis (FA) in response to acceleration inputs along the unit's input axis (IA). The gaps between the proof mass structure and the SG electrodes change (one gap opens while the other closes). The resultant capacitive changes are proportional to the input acceleration, and a net current flows out of the proof mass flexure into the low-noise preamplifier. The flexure and proof mass structures are scaled to accommodate the desired g range . Units may be operated in an open- or closed-loop torque-to-balance mode. Closed-loop operation is achieved by electrostatic forces resulting from feedback voltages applied to the torque generator (TG) electrodes. Selection of open- or closed-loop operation is a function of cost considerations and accuracy requirements. Draper has configured units with three design ranges: 100,000, 100, and 10 g. For the 100,000-g unit, open-loop operation has been more than adequate. The high-g range development activity has been under U.S. Army sponsorship for kinetic energy projectile tests.

A SEM photo of the 100-g accelerometer is shown in Figure 9. As in the case of the gyro, the proof mass structure is perforated. These devices have undergone vibration and shock tests, and centrifuge testing has been performed to set the unit's SF and determine its linearity. Figure 10 shows a centrifuge test run on a 100-g accelerometer stack (with electronics) with a 100-Hz control loop. Due to centrifuge limitations, the SF test was constrained to a 22-g input. A 0.57% SF linearity was measured. Bias stability on the order of 0.55 mg, have been demonstrated in tests on the 100-g accelerometer.

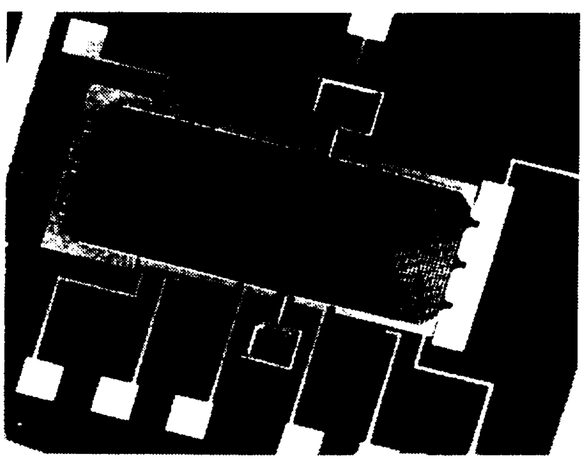

Figure 9. 100-g accelerometer.

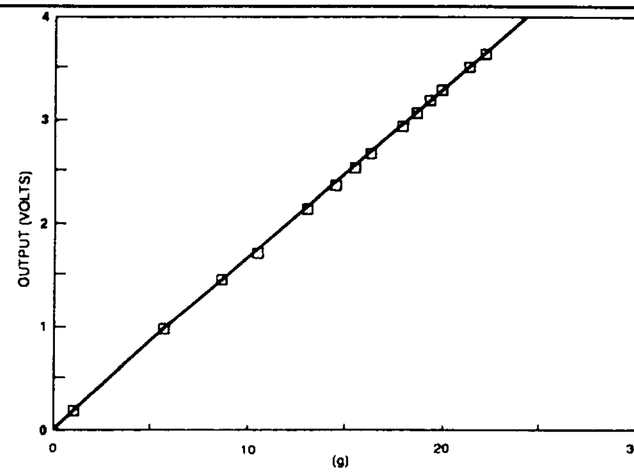

Figure 10. 100-g accelerometer stack output voltage vs acceleration input.

System and Device Development

As noted in the introductory section, Draper is currently developing an integrated MMISA/GPS for the ERGM Demonstration Program. Draper has also configured a number of single-axis gyro packages with hybrid electronics, and configured TFG units with RI-fabricated ASICs for test evaluation, and has delivered accelerometer units for high-g applications.

Representative sensor packages are shown in Figures 11 and 12. Figure 11 is a magnified photo of a TFG installed in a 1-in x 1-in hybrid single-axis package, and Figure 12 is a photo of a triad of microaccelerometers in a 1-in x 1-in hybrid package with preamplifiers. Device development could be oriented to provide further device performance enhancements or to tailor devices for relevant payload applications. For example, TFG devices could complement camera imaging sensors by providing wide-band rate stabilization signals or be used in a structural array to provide sensing for flexural mode sensing and damping.

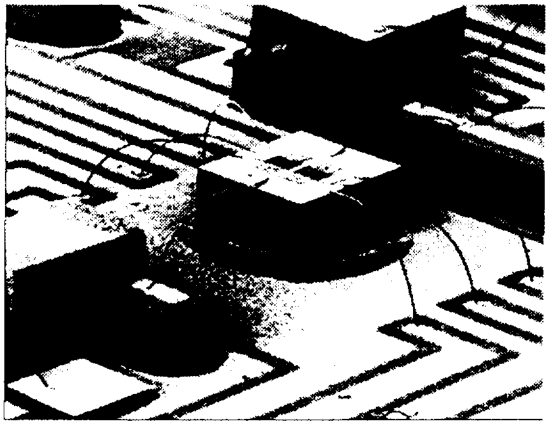

Figure 11. TFG in hybrid package.

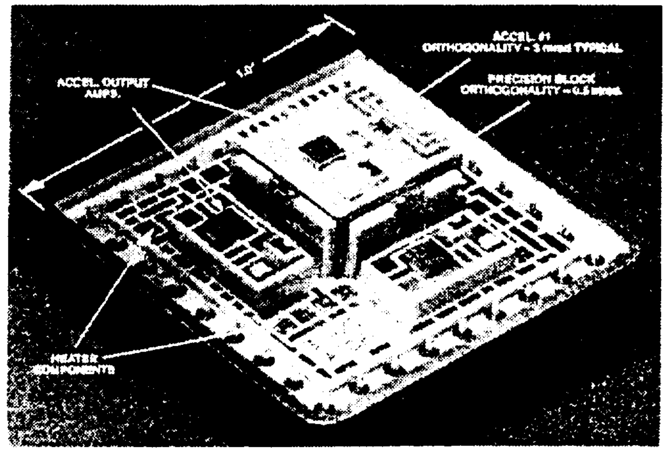

Figure 12. Three-axis 100-g accelerometer hybrid.

Conclusion

Draper Laboratory has made significant progress in the development of micromechanical instruments. Further design enhancements and high density packaging development are in process.

A gyro package with compensated performance on the order of 10 deg/h over -40 to +85°C with a ±100 deg/s dynamic range will be realized by early 1997.

ASIC technology design iterations and validations will be completed in mid-1996, and the goal of a fully miniaturized micromechanical inertial sensing system will be realized:

- Three axes of gyros and accelerometers.
- 2 x 2 x 0.5 cm package; 5-gm weight.
- Less than 1 W power.

Performance enhancements are expected as continued IR&D design improvements are realized. For example, currently, IR&D efforts have doubled the proof mass thickness and the drive amplitude. Improved fabrication techniques are also under evaluation.

- Gyro TFG performance goals:
  - ± 100 deg/s rate range.
  - 0.1% SF stability.
  - <1 deg/h drift stability.
- Accelerometer performance goals:
  - 100-g measurement range.
  - 0.05% SF stability.
  - 100-μg bias stability.

Micromechanical Development Facilities

Draper has a well-equipped 1200-ft^2 laboratory dedicated to micromechanical device fabrication. Diffusion, oxidation, photolithography, metallization, chemical vapor deposition (CVD), and plasma and wet etching are performed within the laboratory. Internal fabrication allows process optimization for our sensors and maintains proper control over the development. The processing staff are experienced in both bulk and surface micromachining.

Facilities now include: 11 diffusion/oxidation tubes for oxidation, including low-pressure chemical vapor deposition (LPCVD) tubes for the deposition of polysilicon, silicon nitride, silicon dioxide, and phosphoro silicate glass; and two contact mask aligners, including a Karl Suss with infrared capability, allowing front-to-back side alignment of silicon wafers. Reactive ion etch and plasma CVD equipment were recently added to the microfabrication resources. A plasma oxygen asher is used to remove trace organic residues and photoresist. A dc magnetron sputtering machine allows up to three metals to be deposited in one pump-down. In-house computer-aided design (CAD) facilities are used to design photomasks and to perform finite-element analysis on all designs prior to fabrication.

System and component packaging is performed at Draper. Conventional die mounting and wire bonding facilities, and a hybrid assembly facility are available. Custom ceramic substrates are fabricated, and chip components can be assembled, along with the sensors, preamplifier, and electronics in the sensor package.

Electronics packaging facilities at Draper include CAD design for printed circuit boards, ceramic wiring boards, and multichip module wiring. Fabrication facilities include an extensive printed circuit prototype facility and a ceramic wiring board facility that can produce screened multilayer ceramic boards and multilayer boards using green tape processing. Draper also maintains a multichip module rapid prototyping facility that is compatible with industry manufacturing "foundries." Draper ASIC electronic design capabilities are mature, and many Draper designs have been manufactured in quantities for fielded systems using qualified high-reliability foundries. These facilities will be available for development activities in support of small spacecraft initiatives.

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