An Inertial-Grade, Micromachined Vibrating Beam Accelerometer

Terry V. Roszhart and Constant de Cotiis—Kearfott Guidance and Navagation, Little Falls, NJ
Hal Jerman and Joe Drake—IC Sensors, Milpitas, CA

SUMMARY

The Micromachined Vibrating Beam Accelerometer (MVBA) is a high performance, silicon micromachined sensor with a single-crystal silicon resonator. Its performance is capable of satisfying the demanding requirements of inertial guidance and navigation, including measured sensitivity of 1 μg with a full scale of 40 g, bias stability as low as 2 μg (1 sigma) over several days of continuous operation, and residual thermal errors of 50 μg over a temperature range of –50°C to +95°C.

SENSOR DESIGN

The sensor consists of a batch-fabricated, micromachined silicon chip and a pair of glass caps, as shown in Figure 1. The silicon chip contains an inertial proof mass, two flexural hinges, a motion sensing resonator, and a frame.[1] The glass caps contain electrodes for sensing the resonance of the vibrating beam. The silicon and glass wafers are anodically bonded at the wafer level and sawn into individual devices.

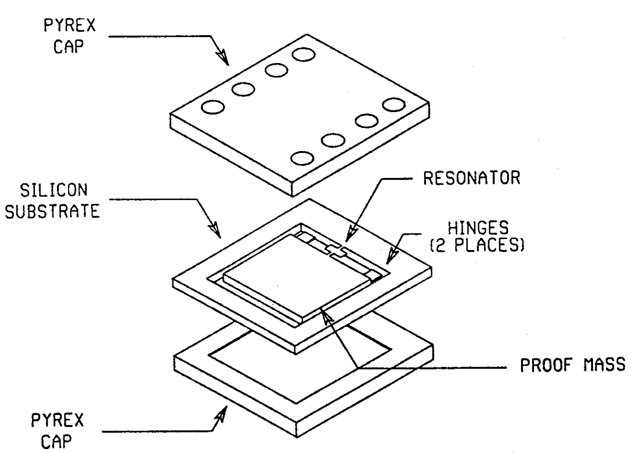

Figure 1. Exploded schematic view of MVBA sensor chip.

The operation of the sensor is shown schematically in Figure 2. When the MVBA is subjected to an acceleration, the proof mass responds by rotating about the axis of the flexure hinges. This rotation applies a force to the silicon resonator which, in turn, changes its resonant frequency according to the direction and magnitude of the acceleration. The changes in resonant frequency are monitored by the electrodes that are supported above the resonator, which both drive and sense the resonance. Since frequency can be measured with high precision over a wide dynamic range, resonant detection is advantageous for this type of inertial-grade accelerometer. A fundamental difference in the operation of this sensor over other high-performance designs is that this device operates open-loop, that is, it is not force balanced.[2,3,4] This results in simpler drive electronics and removes some concerns about added noise from the rebalance circuitry.

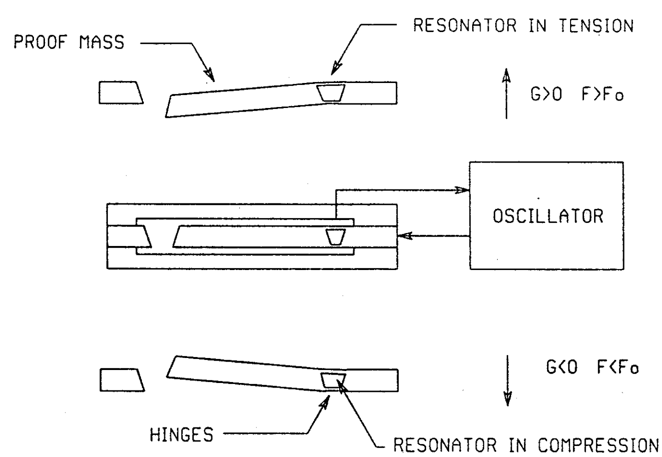

Figure 2. Principles of operation of the MVBA sensor chip.

The sensor is fabricated using bulk micromachining techniques. After a heavy p-type diffusion later used as a substrate contact, a deep anisotropic etch from the backside is used to set the resonator thickness. A second anisotropic silicon etch from the resonator side is used to largely free the proof mass from the frame, except for thin regions used as

1. Roszhart, T.V., U.S. Patent #4,945,756, Aug. 7, 1990.
2. Rudolf, F., Alain, J., and Bencze, P., Fourth Int. Conf. on Solid-State Sensors and Actuators, Tokyo, 1987, pp. 395-398.
3. Warren, K., Navigation, V. 38, N. 1, (1991) pp. 91-99.
4. Rockstad, H.K., Kenny, T.W., Reynolds, J.K., and Kaiser, W.J., Sensors and Actuators A, V. 43 (1994), pp. 107-114.

latches. Isotropic plasma etches are then used to form the resonator and hinge shapes from the diaphragm regions formed during the anisotropic etches. A top view of a completed silicon sensor chip is shown in Figure 3.

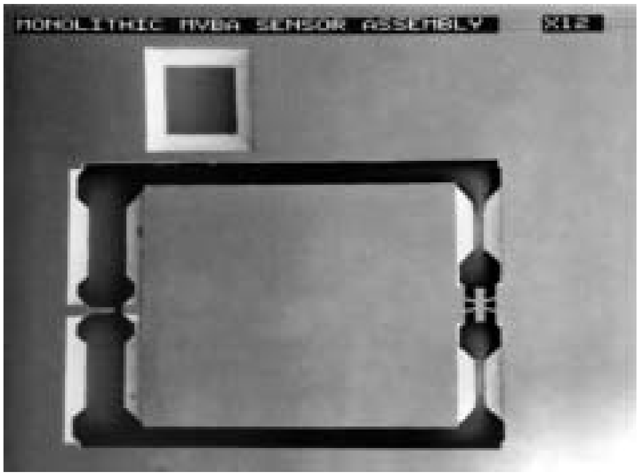

Figure 3. SEM of completed silicon MVBA chip

Recesses are formed in the glass caps using hydrofluoric acid, and gold electrodes are sputtered, patterned and etched. The caps are anodically bonded and the devices sawn apart. The metallization forms the substrate contacts during anodic bonding. Since the metal traces run entirely on the glass surface, the stray capacitances between traces and to the substrate are minimized. The current chip size is quite large, about 10.2 mm by 8.3 mm. The proof mass on the current device is also large, however the current chip has not been optimized for minimum possible size or cost.

A fully assembled MVBA consists of two of these sensor chips mounted in a modified electronic hybrid. Two sensors are used in this “dual-stage” configuration so that many of the measurement errors that would be produced in a single stage accelerometer are eliminated. The sensors are mounted in opposite directions so that one sensor increases frequency with positive acceleration while the other decreases. The hybrid contains the electronics needed to drive the sensor chips and provide the frequency output.

The thermal response of the MVBA is determined primarily by the thermal coefficients of elasticity and expansion which, in bulk silicon, are highly linear. This means that the temperature coefficients in each stage of the MVBA are also very linear, which permits accurate thermal compensation when a dual-stage configuration is used. It also reduces the amount of calibration testing that is needed to determine temperature correction constants and reduces the computational processing needed for temperature compensation. The use of bulk, single-crystal silicon is also a factor in the long term stability of the MVBA. The resonant frequency of a vibrating beam is controlled by the elastic modulus and the density of the material from which it is made, which appear to be exceptionally stable in single crystal material.

The functionality of the chips can be evaluated, in part, by measuring the Q of the micro machined resonator. Resonator Q is related to the resonator's damping and is an important factor controlling the frequency stability of the sensor chip. The distribution of resonator Q’s that were measured on one wafer are shown in Figure 4. Most of these resonators have Q’s above 60,000 and some exhibit Q’s as high as 140,000. Studying the relationship between resonator Q and resonator design has shown that thermoelastic internal friction is the major mechanism of damping in these types of resonators.[5] These high Q’s are maintained after the chips are assembled into MVBA sensor assemblies, demonstrating good isolation of the chip from the effects of mounting stress.

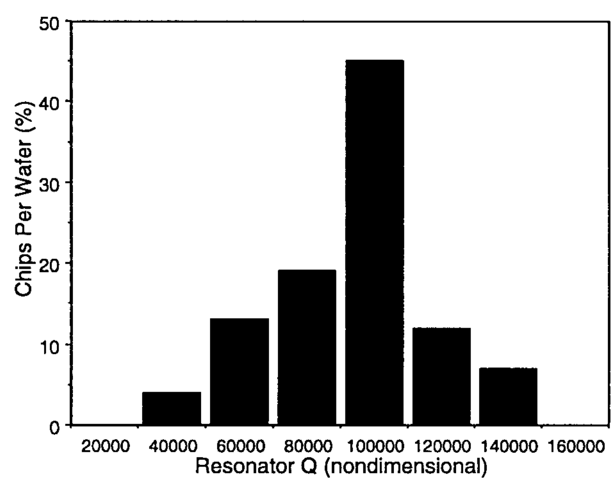

Figure 4. Histogram of Q values for one wafer.

PERFORMANCE TESTING

While the initial intent of the MVBA development was to produce a tactical-grade accelerometer, initial test results revealed that the basic design was capable of achieving

5. Rozhart, T. V., IEEE Solid-State Sensor and Actuator Workshop Digest, Hilton Head, NC, June, 1990, pp. 13-16.

accuracies consistent with medium inertial grade requirements. Thus development is focused on achieving performance of 50 μg, 50 ppm, and 25 μrad for bias, scale factor, and alignment, respectively. All data for stability, range, and thermal residuals are obtained by processing the output frequencies of a dual-stage unit in accordance with an equation which models the acceleration in terms of the sum and difference frequencies of the two sensors in the unit. The acceleration is closely proportional to the change in frequency difference between the two sensors and temperature is closely proportional to the sum of output frequencies of the sensors, thus the corrected acceleration signal can be extracted from the frequency signals without an additional, error-prone measurement of temperature.

The stability of the devices has been measured over short (9-hour) and long (6 day) periods at constant temperature. Short term stability (1 sigma) values of 1.1 μg, 1.4 ppm, and 2.8 μrad were seen for an example device. The graph of bias stability of this part is shown in Figure 5.

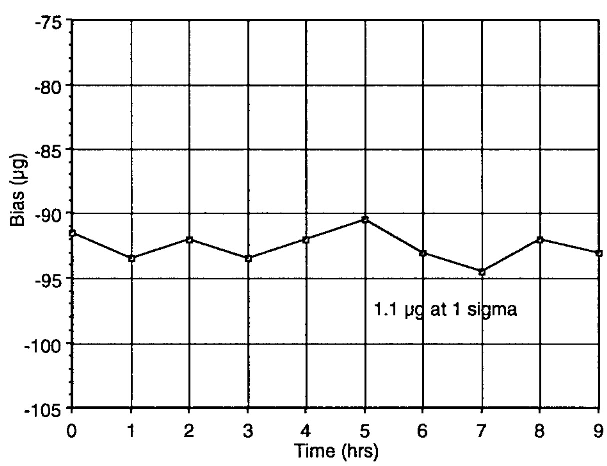

Figure 5. Short term bias stability of device SN 9.

Over a six day period this same device showed a standard deviation of 7 μg, of which about 5 μg is attributed to bias variation. From this test an estimated value of 40 μg for the one year stability can be predicted using a square root of time approach. A series of five multi-position tests was run over a five-day period with turn-ons. Each test was conducted after the turn-on transient was complete. The one-sigma performance under these conditions were 16 μg and 17 ppm.

The modeled thermal residual bias errors for devices SN 9 and SN 11 are shown in Figure 6. over the range of –55 to +70°C. Other data to 95°C shows a similar result. The corresponding scale factor residuals for SN 9 were 40 ppm and for SN 11 only 3.5 ppm at 1 sigma, while the alignment residuals were 13.6 μR and 8.4 μR, respectively.

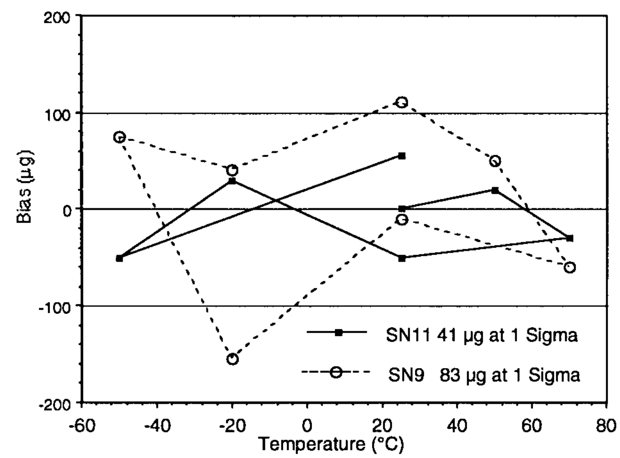

Figure 6. Thermal bias residuals for devices SN 9 and SN 11.

A centrifuge test program was conducted to determine the operating range and linearity characteristics of the MVBA using a precision air bearing centrifuge. Fig 7 shows the performance of an early unit over a 20g range in terms of nonlinearities and residual errors. The second order error term is –20 $\mu g/g^2$ and the cubic term is 0.4 $\mu m/g^3$. The residual error is 56 μg at 1 sigma.

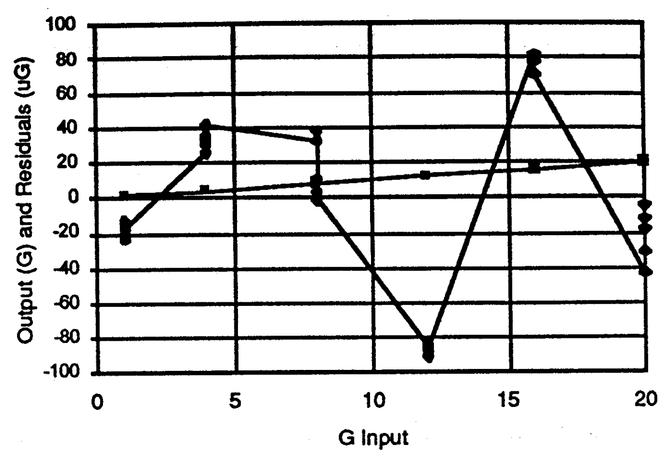

Figure 7. Linearity and residuals of sample device

The random walk coefficient is essentially the randomness of the DC component of the signal. The coefficient describes an envelope which increases with time. Statistically, the envelope increases proportionally with the square root of time and places upper and lower bounds on the DC level of the signal at any point in time. The coefficient can be determined from the power spectral density of the signal by extrapolation to zero frequency. Values of about –100 dB below 40g have been found which correspond to 10^{-5} $gs^{0.5}$, or in terms of random walk units, 0.006 m/s-$h^{0.5}$.

CONCLUSIONS

The development of this device is focused on achieving performance suitable for inertial guidance requirements, which requires performance of 50 μg, 50 ppm, and 25 μrad for bias, scale factor, and alignment accuracy. The measured performance has been seen to be suitable for the stringent requirements of defense-related inertial navigation, while the relatively low costs due to batch fabrication may allow the use of this device in commercial applications.