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# Vacuum Packaging for High-Performance Low Cost MEMS Gyro Used in 6 Degree of Freedom Inertial Navigation System (DOF INS)

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## Abstract

*Sensors in Motion Inc. is developing a navigation grade 6 DOF MEMS INS using its proprietary and patented technologies. The military is investing in INS and IMU technology which can answer its needs as well as provide the baseline for hundreds of other DOD and commercial applications which need a C-swap sensitive utility. SIM's technology for MEMS gyros was conceived to address past problems associated with MEMS gyroscopes while leveraging the C-swap benefits of high volume, high yield batch fabrication, automated packaging, self-calibration, and thermal compensation. A key requirement for the MEMS Gyroscope is controlled vacuum-levels to obtain high Q devices. Gyro die are packaged using a multilayer package and getter system, which provides and maintains sealed vacuum cavities. Die are assembled into the LCC package using conventional assembly techniques and the package cavity is sealed using an SST 3150 high-vacuum sealing system. The SST system is used to activate a thin-film getter layer on the package lid before reflow of the solder seal. Resulting pressure levels have been determined by characterizing packaged but unlidded sensor die in a vacuum chamber. The package material, process flow and test results are summarized and reviewed. Tooling, process parameters, and test techniques are explained.*

Key Words: MEMS, gyroscope, vacuum packaging, getter, inertial sensors, inertial navigation, inertial measurement unit, navigation grade gyro, Q, damping

## Introduction

Sensors in Motion, Inc. is developing a six degree-of-freedom (DOF), micro-electromechanical system (MEMS), internal navigation system (INS) using its proprietary MEMS Gyroscope structure. The INS technology will provide the baseline for hundreds of department of defense (DOD) and commercial applications which require a C-swap (Cost, size, weight and power) sensitive utility. The MEMS Gyroscope has been developed to greatly improve the performance of sense element and integrated sensor system. Silicon MEMS provides the C-swap benefits of high volume, high yield batch fabrication, automated packaging, self-calibration, and thermal compensation.

Sensors in Motion has been developing packaging approaches using commercial practices to meet required specifications. A key requirement for the MEMS Gyroscope is controlled vacuum-levels to obtain high Q devices. This paper discusses the prototype package configuration and process which meets milliTorr level requirements. The prototype gyro element configuration is a silicon transducer die packaged using a multilayer package and getter system. The prototype package process provides a vacuum seal using an SST 3150.

## Package Requirements

MEMS packaging must be tailored to the requirements of the sensor system. For example, some devices require coupling to environment; others do not. Generally, mechanical properties of the package affect mechanical performance of the system. In many MEMS sensor applications it is difficult to test the sensor performance unless sense element die are packaged. For Sensors in Motion, development of the prototype package configuration has accommodated bench top electronics development eliminating the need for earlier bell-jar functional characterization.

Packaging has been an integral consideration from the beginning of development. The Sensors in Motion MEMS Gyroscope is a patented silicon disc structure with capacitive drive and sense electrodes.

The resonator resides on a central node mounting post which minimizes anchor losses and thermal saturation. The configuration provides a very high signal to noise ratio with limited sensitivity to shock and temperature. Considerations undertaken for the functions of the MEMS Gyroscope package include: mechanical support, environmental protection, electrical connection, EMI coupling, parasitics, thermal matching, contamination, system partition, shock, vibration, vacuum and cost.

### *Configuration Selection*

Basic requirements for the MEMS Gyroscope package are vacuum level, pin-out and size (see Table 1). Vacuum characterization and design analysis has shown that a vacuum level under 10mT can provide the required gyro performance. The package must accommodate the die volume. The die has multiple pins in the form of bond pad connections.

Table 1 Mininum Requirements

| **Parameter** | **Minimum Requirement** | **Unit** |
|---|---|---|
| Vacuum Level | 10 | mT |
| Cavity Volume | Accommodate Die | N/A |
| Pin count | Accommodate Die | N/A |

### *Vacuum Requirements*

Performance of the MEMS Gyroscope is increased by observing that the output signal of any resonant, vibratory sensor is proportional to $2\pi Q/\omega^2$, where Q = quality factor for the resonator, and $\omega$ = resonant (angular) frequency of the sense mode of the system. Thus, increasing Q will boost the sensitivity of the device by increasing the amplitude of the output signal. The physics of damping mechanisms as a function of pressure has been studied and is fairly well understood[1]. Damping decreases as vacuum pressure decreases, with oscillator performance being dominated by different loss mechanisms. It is known that the relationship of Q to pressure follows a curve shown in the graph below (see Fig. 1). Damping is dominated by viscous damping at high pressures. At low pressures, damping is no longer a function of pressure and is dominated by intrinsic damping mechanisms in the mechanical microstructure. In between viscous and intrinsic regions, damping is dominated by momentum losses due to collisions with trapped molecules.

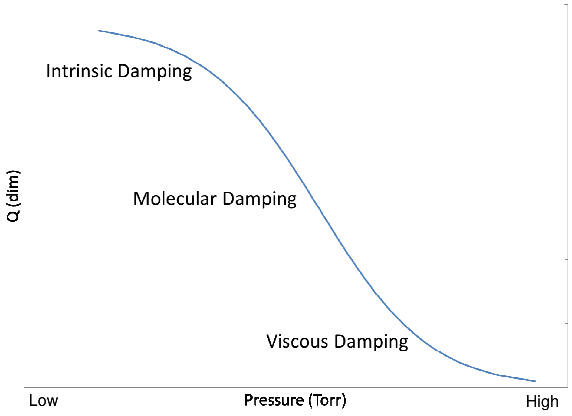

Fig. 1. Relationship between Pressure and Resonant Quality Factor for Typical Microstructure

The overall damping of the system can be represented by the inverse of the sum of the inverse of each component as described above. Thus, the intrinsic damping can only dominate at sufficiently low pressures where viscous and molecular damping mechanisms are no longer present.

$$Q = \left[ \frac{1}{Q_{Intrinic}} + \frac{1}{Q_{Molecular}} + \frac{1}{Q_{Viscous}} \right]^{-1}$$

Fig. 2. Total Damping Relationship

The theoretical maximum quality factor for a given resonator, or intrinsic Q, is determined by geometric factors, the properties of the resonator material and the vacuum level under which the device operates (see Fig. 3).

$$Q_{TE} = Q_o \left[ \overbrace{\frac{1+(\omega\tau)^2}{2(\omega\tau)}}^{\text{Geometry dependent}} \right]$$

$$\left. Q_o = \frac{2C_v}{E\alpha^2 T_o} \right\} \boxed{\text{Material and temperature dependent}}$$

$C_v$ = Specific heat capacity
$E$ = Young's modulus
$\alpha$ = Coefficient of thermal expansion
$T_o$ = nominal resonator temperature
$\tau$ = thermal relaxation time
$\omega$ = 2π*(frequency of oscillation)

Fig. 3. Intrisic Damping Relationship

This theory of thermoelastic damping effects was originally developed by Zener[2] and refined by Lifshitz and Roukes[3] and Houston et al[4]. Thermoelastic damping has been verified empirically as a major energy loss mechanism in MEMS structures by Duwel et al[5].For a given resonator, the minimum thermoelastic quality factor, $Q_{TE}$, arises when the thermal relaxation time constant for the resonator is equal to the reciprocal of the vibration frequency[6], this corresponds to maximum heat flow due to acoustic mode coupling to the strain field. The thermal elastic limit for $Q_{TE}$ can be increased either through material selection or by geometric optimization. The factor $Q_o$ is dependent upon the absolute temperature and upon intrinsic material properties of the resonator. For silicon, with its high intrinsic thermal conductivity and low thermal relaxation time, Q can be increased through operation at high resonant frequencies.

*Getter Selection*

The use of a getter is required to achieve low milliTorr vacuum levels. Getters provide chemical sorption of active gases, including $H_2O$, $O_2$, CO, $CO_2$, $N_2$ and $H_2$. Getters cannot however remove noble gases such as Ar. Noble gases must be removed from the package materials and avoided during the seal process to assure low vacuum levels. The getter is activated before sealing and captures gases freed during the seal processing but more importantly continues to capture active gases as they outgas during the life of the product. Getter sorption capacity for active gases is a function of getter fire temperature and is much higher than its capacity at room temperature. Higher temperature promotes the diffusion of the absorbed gases on the surface of the bulk getter film. Capacity must be designed to assure the getter can not only provide sorption of large quantities of gases desorbed during high-temperature bonding processes but allow additional capture of outgassed active gasses over product life.

Three basic getter configurations: thin-film, thick-film and leaded were considered for this product (see Table 2). Thin-film getters are deposited directly onto the package structure surface and have been developed primarily to accommodate wafer level packaging. Thick film getters are screened and sintered onto nichrome carriers and typically welded to the package. Leaded getters are generally welded to package pins and can be procured with internal nichrome heating elements to fire the getter using current.

Table 2 Getter Configurations

| **Getter Type** | Thin Film | Thick Film | Leaded |
|---|---|---|---|
| **Application** | Kovar lids for multilayer ceramic packages,<br>Wafer Level Packaging | Kovar lids Header-type package | Header-type packages |
| **Attachment** | Deposited onto package surfaces – lid or wafer | Welded to package surface | Welded to package pins or surface |
| **Seal Options** | Vacuum heaters | Vacuum heaters | Fire/pinch<br>Vacuum heaters |

SAES Getters' Page film[7] was selected for this product for process compatibility and high pumping capacity. The Page film has good adhesion properties, fully complying with the adhesion test method ATSM D 3359-02, the semiconductor industry tape test. Page film is also mechanically stable with respect to temperature cycles used in automotive applications (tested up to 500 temperature cycles from - 40 up to + 150 °C). Activation requires a minimum of 15 minutes at 300°C. A relative of increase of 2.5 times getter capacity can be achieved by firing the getter at 450°C for 30 minutes.

*Package and Seal Selection*

Metal packages, ceramic packages, and wafer scale vacuum packaging were considered. The associated seal types are summarized briefly (see Table 3). Eutectic seals are common on multilayer ceramic packages and this configuration is still commonly used for high-reliability, hermetic packaging. Header-type, metal packages are used with Cu pinch tubes to provide high-vacuum sealing of bolometers and IR sensors. This configuration is effective but suffers from larger, customized packages and does not scale well for higher volumes. Wafer level packaging (WLP) is employed to seal each die at the wafer level using eutectic seals or low temperature glasses[8]. This configuration is desirable for volume, low-cost packaging but requires a high level of customization to the wafer structure and tooling. Another approach to vacuum sealing (not shown in table) is e-beam weld closure of a small opening in the package placed under vacuum. This approach has some merit but requires sophistication in the getter fire process. Plastic cavity-type packages as well as epoxy bonding were considered but immediately ruled out due to hermeticity concerns, out-gassing and getter fire temperature compatibility. Additional exploration of Cu cold-welded seal rings and wafer level external packages is in progress. At this time, multilayer ceramic chip-carrier packages and wafer scale vacuum processing were identified as the most viable candidates.

Table 3 Package and Seal Configurations

| **Package** | Wafer | Multilayer ceramic | Header-type |
|---|---|---|---|
| **Seal type** | Eutectic | Eutectic | Cold Weld |
| **Package Material** | Silicon | High fire ceramic | Au plated Kovar |
| **Seal material** | Au/In<br>Au/Sn | Au/Sn | Cu |
| **Seal configuration** | Au evaporated seal ring | Au plated seal ring | Tube or seal ring |
| **Customization** | Fully custom | Modified standard package | Custom packages |
| **Product Cost** | Low | Moderate | High |
| **Development Cost** | High | Low | Moderate |

Based on the selection considerations above, a leadless chip-carrier (LCC) multi-layer ceramic package has been selected (see Fig. 4). The package is configured with a Au-plated kovar lid that has a thin-film gettering material applied to the inside surface. Gettering materials are provided by SAES. The element die is attached to the package using a solder disk preform to minimize outgassing of the die attach materials. The die is wired bonded using Au wire and standard ball bonding techniques.

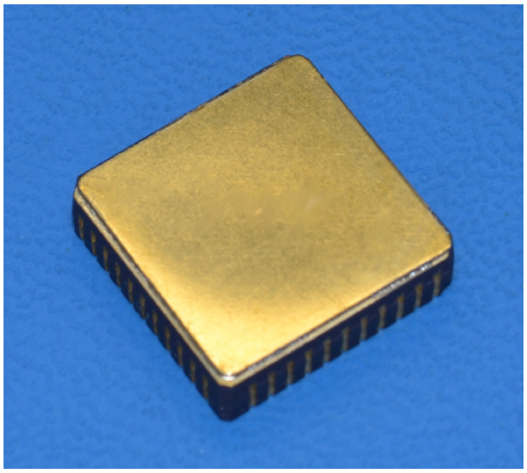

Fig. 4. Sealed LCC Package

## Seal Process

The gyro package assembly is sealed using an SST International 3150 machine (see Fig. 5). The base SST machine is the 3130 that has been used regularly in assembly labs for over 40 years. The 3150 machine was developed specifically for vacuum sealing multi-layer ceramic packages in a high-vacuum, micro-Torr environment with a heat-fired getter. The machine has since been adapted to a large range of additional package configurations and seal processes. The SST 3150 has a high-vacuum capable vacuum system using a water-cooled, turbo pump and a stainless steel, water-cooled vacuum chamber. Bake-out, getter-fire and reflow are achieved using a graphite heater plate. The graphite plate is connected directly to a transformer providing up to 1000 amperes of current. Thermocouples are attached to the heater plate and the heat current is controlled using PID controllers. The temperature ramp and soak can be closely controlled and the parameters and sequence are monitored using a personal computer.

Fig. 5. SST 3150 Sealing Machine

The SST sealing chamber is shown for process description purposes (see Fig. 6). Cu electrodes on the left and right connect to the fixture to provide the heating current. The upper fixture is lifted from below; using the 'X' shaped actuator, which presses on the 'legs' of the upper fixture (see fixture description below). A shutter mechanism rotates metal plates between the fixture plates to prevent radiation heating of the upper fixture during getter fire. A stainless-steel jacketed thermocouple is inserted into the lower fixture to control the temperature. The chamber lid (not shown) is water-cooled and attached to the vacuum chamber to allow O-ring seal.

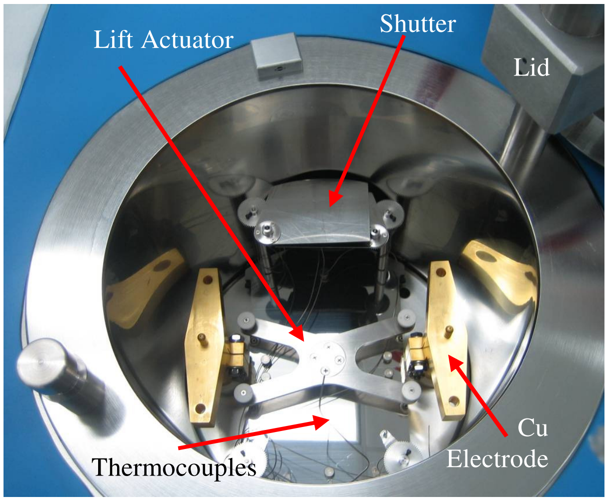

Fig. 6. SST 3150 Sealing Chamber

Package parts are held in a custom, two-tier graphite fixture (see Fig. 7 and Fig. 8). The fixture is built in two interlocking pieces, with the lower fixture assembly attached to the machine by way of the Au-plated, Cu electrodes. The upper fixture is allowed to move upward when pressure is applied from the lifting mechanism below. The lid is held getter-up in the lower fixture (see Fig. 7).

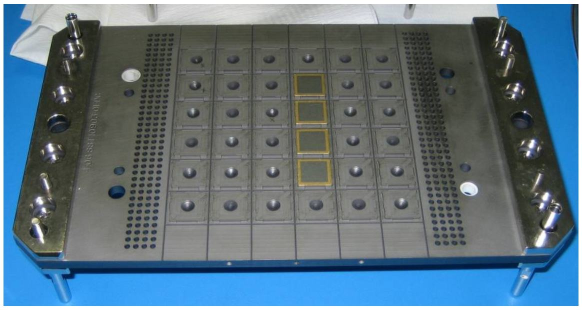

Fig. 7. Two-Tier Package Assembly Fixture, Lower Fixture w/ Lid getter-side-up

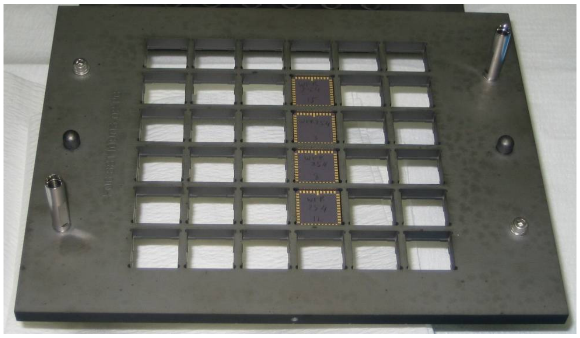

Fig. 8. Two-Tier Package Assembly Fixture, Upper Fixture, open face of package facing down

A cross-sectional diagram fixture with preseal assembly is shown below (see Fig. 9). The preseal assembly is held die-facing-down by small tabs in the fixture that interlock with recesses machined into the lid holding pedestal.

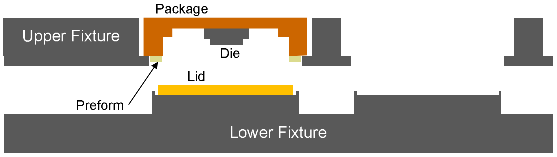

Fig. 9. Schematic Cross-Section of Fixture and Package Assembly

During getter fire, the upper fixture is lifted into the highest position away from the lid, shutters are folded between the upper and lower fixtures, and current is run through the lower fixture heating the lid. Shutters provide additional thermal isolation from radiation heating during getter firing of the lid. After the getter has been fired, the temperature is reduced below the reflow temperature, the shutters are removed, and the lift actuator is lowered. This brings the upper and lower fixtures in contact and allows the preseal assembly to contact with the lid. Stainless steel weight cylinders are held in an additional fixture assembly (not shown) and hold the preseal assembly in contact with the lid. The temperature is then raised to the reflow temperature and the lid preform forms a eutectic bond.

### *Assembly Process*

Gyro sense element die are assembled into the LCC package using conventional micro-assembly techniques. Lids are sent to SAES for standard getter deposition. Packages are baked before die assembly to degas hydrogen trapped in the plating layers[9], degas noble gases to avoid outgassing during seal and as a cleaning mechanism. Die are eutectic attached using solder preforms in a nitrogen-filled, glove-box with a hot plate. Wirebonding is completed using a standard Au-wire, ball-bonding process. Parts are marked with the lot and serial number of the preseal assembly lots using a pencil before seal to maintain die and process traceability. A key distinction in the process from a standard ambient pressure seal is that the preform must be attached to the package to allow getter firing of the lid. Seal preform attach is accomplished using a soldering iron and a hot plate.

For package sealing, the preseal assembly and the getter-coated lids in placed in the fixture inside the SST 3150[10][11]. The parts are then pumped down to micro-Torr levels and vacuum is maintained during the entire seal profile. At the beginning of the seal profile, the package and lid assemblies are vacuum baked with the fixture separated several millimeters. Then the fixture then separates up to 5cm and getter is then fired. After the getter fire step, the system is cooled below the lid seal reflow temperature and the die and preseal assembly is brought into contact with the lid. At this point the system is reheated to allow the reflow and sealing of the package assembly.

## Test

Sealed devices are tested using a custom spectrum analysis system that provides the frequency and Q values of the device. A computer is used to control and process the data. A custom amplifier board amplifies the output of the gyro element and buffers the drive input. Modes of interest are determined by sweeping the frequency range and measuring the response (see Fig. 10). Sealed parts show a strong modal peak with the modes of interest dominating the response.

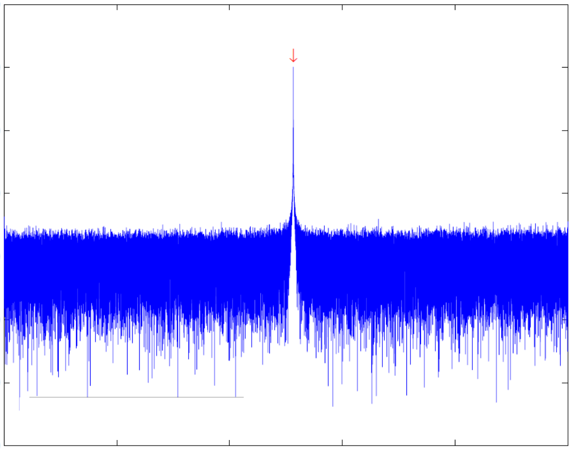

Fig. 10. Sweep of Sealed Part: Magnitude vs. Frequency

Once the peak frequencies are obtained, the device is driven at a peak frequency, the input is halted and the device is allowed to 'ring down'. The Q of the device is determined using the envelope of this ringdown (see Fig. 11).

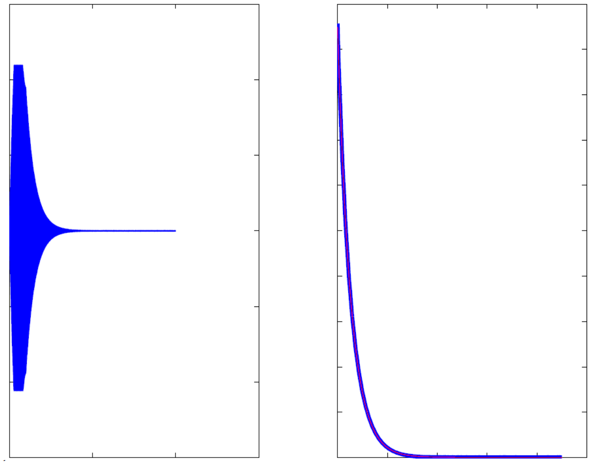

Fig. 11. Ringdown Script Plots: Magnitude vs. Time, Left and Magnitude Envelope, Right

### *Test Results*

Over 300 parts have been sealed as of the date of this report, representing a production intent process flow for various applications. These parts represent 23 separate seal runs, and were derived from 11 preseal lots (see Table 4). Seal yield has been evaluated and tracked for each seal lot.

Table 4 Analysis Summary

| **Item** | **Lot Qty** | **Parts Sealed** | **Result** |
|---|---|---|---|
| Seal Lots | 23 | 333 | Q > 1k |

Q (resonator) testing provides an effective test for sealing, with any parts that have a measureable peak deemed sealed (Q>1000). Data for all 333 parts has been collected and selected Q testing results are shown in the plot below. Recent results show high Q values meeting product requirements.

### *Characterization*

In order to understand the performance of the package it is necessary to determine Q values as a function of pressure. A vacuum test system was developed to allow unsealed devices to be tested under vacuum (see Fig. 12). The test provides a correlation of pressure to Q and facilitates the understanding and feasibility of further Q increases. The system consists of the same Q test system described above with the addition of an aluminum vacuum chamber, pirani gauge, valve, and turbo-pump system. The chamber provides a small area vacuum capability with rubber seal and two glass-sealed, DB15, vacuum connectors.

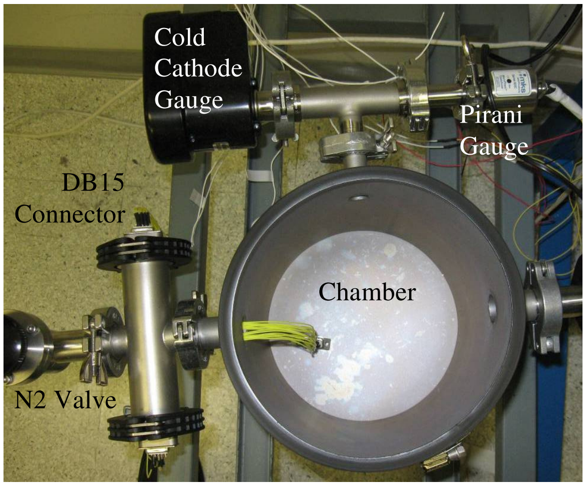

Fig. 12. Vacuum Q Evaluation System; Chamber (left), Pump (right)

The amplifier interface board is connected through the connectors to provide amplification and buffering for a packaged gyro without a lid (not shown) and connects to the Q test system. The valve to the left allows N2 to enter the system for pressure release after measurement. The system is capable of pumping below$10^{-5}$ Torr.

The plot below shows a Q measurement taken as a function of measured pressure using the characterization test system (see Fig. 13). The system is pumped down and allowed to leak upward after turning the pump off. The Q measurement during the leak up is shown as plus signs in green and the associated fit is the dashed line. The shape of the Q vs. P plot shows the expected response described earlier. Calculated pressures are shown for selected parts with the fit curve providing pressure values for sealed package devices.

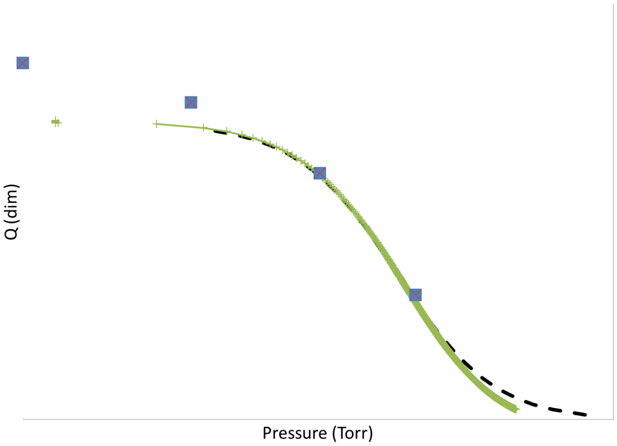

Fig. 13. Q vs. Pressure; vacuum chamber result for part L032-064 (small plus sign), QvsP fit (dashed line) and calculated pressure for selected parts (square)

## Conclusions

A viable prototype vacuum seal process has been demonstrated. Vacuum levels below 10mT have been consistently achieved, providing Q's ranging from 20k to 100k for the present MEMS Gyroscope device. This level is sufficient to provide the necessary gyro sensor performance well below the 1 degree/hour requirement. The LCC package and SST seal process provide a suitable configuration and cost point for mid-volume military and aerospace applications. Development of wafer level vacuum packaging is in progress and evaluation of alternate discrete package configurations continues.

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