Low Cost Rate Sensor for Automotive Applications – The Fabless Strategy

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1. Introduction

During the past 10 years, the use of MEMS or MST in automotive applications has increased steadily; in 1999 over 40 million accelerometer and manifold absolute pressure devices are used (Reference 1). Accelerometers represent a major portion of the MEMS parts required by the automotive industry. Yet, with the high volume of accelerometers being shipped, many observers have noted that profitability for the MEMS producers is taking far longer time than expected (Reference 2). Rapid price degradation due to competition, long development cycles, and large capital investments are the primary reasons. The experience that MEMS producers have encountered in fabricating airbag accelerometers demands that producers (and investors) closely watch the commercial reality of MEMS and MST industry.

To leverage their investments, MEMS producers must profitably develop new products, especially those with potential for high volumes and attractive margins. MEMS angular sensor, or micro gyro, is one such device (Reference 1). All major MEMS producers have programs aimed at developing low cost MEMS sensors for automotive applications. To date however, the producers have encountered significant development challenges that delay product introduction. After years of investment, only one company has introduced a high-end MEMS gyro, with many companies still working to produce low cost gyros for automotive applications (Reference 4).

The focus of this paper is to illustrate some of the issues inherent in the MEMS development process that lead to long design cycles and high costs. We will discuss an alternate approach to developing new MEMS products, using the micro gyro as an example. The approach is one of focusing on designing and characterizing the product, and using entirely external processing and manufacturing infrastructure. Through our own experience, this up-front focus on design and testing is crucial to completely validate any MEMS concept before making a commitment for production. By separating the design from process development, this approach greatly emphasizes designing to specifications, and statistical understanding of process variations. The approach is ideally suited for small companies with design expertise but lack in-house processing capabilities. For the larger companies, the ideas of establishing external design groups can also prove valuable to reducing product development costs. Most importantly, this approach can in a relatively short time validate not just the technical viability of the new design, but also the producibility of a new product, hence provide a realistic assessment of the development time and cost.

2. MEMS Gyro for Automotive Applications

Like accelerometers, gyros are motion detection devices. While accelerometers produce a signal relative to linear motion, gyros produce signals relative to rotational motion. The first use of the rotational sensors in automobiles is for traction control (Reference 2). In this application, the function of the gyro is to provide the vehicle rate of rotation while moving along a curved road. By comparing the angle of turn from the steering wheel, and the actual vehicle's rotation obtained from the gyro, the control system can determine if the vehicle is experiencing loss of road traction. When unsafe conditions are detected, the system initiates commands to the Anti-Lock Breaking System to provide counter torque to prevent the vehicle from spinning out of control.

Other automotive applications in development include using gyros to detect vehicle roll over condition, vehicle dynamics control, and navi gation. For each application, the specification may differ significantly. Each car in the future could potentially require three gyros. With current automotive forecast of 45 million units per year, this represents a significant opportunity for MEMS developers. The estimated price for the gyros ranges from near $10 for less demanding applications to $25 for applications requiring a higher degree of accuracy.

3. Conventional MEMS versus Semiconductor Fabrication Approaches

3.1 Concurrent Process and Design Development

Many MEMS sense elements and actuator elements are developed with the product and processes being developed concurrently. In MEMS for a long time, this approach has been a necessity due to small number of standardized processes and lack of contract manufacturers. The immaturity of the MEMS field means applications are identified daily, so naturally the best products and therefore the best processes have yet to be developed.

A good case study for the current MEMS development practices is the development of airbag accelerometers. The airbag accelerometer market has been dominated by several primary suppliers. Interestingly enough, although each of the suppliers has produced products for nearly the same systems, each has taken a significantly different approach to process implementation. Specifically, some have emphasized lowering the cost of packaging while others have emphasized reduction of cost through sense element and IC integration.

Each of these suppliers has utilized a concurrent process and product development of the sense element and package. Likewise, package development also requires process development depending on the design and application.

Concurrent product and process development of the sense element has followed this basic approach:

- Determine basic sense element structure shape and interface
- Determine basic process flow to implement structure
- Develop process
- Compare sense element to specification
- Integrate until process meets design requirements

3.2 Issues with concurrent process and design development

When the sense element processes and products are developed simultaneously, several issues arise which may compromise the resulting device design and performance and ultimately manufacturing costs. When the process is developed around the sense element structure, the resulting process development is optimized to the current device rather than determining a process which might suit the needs of several products. Many times the initial design of the structure is largely conceived by those with strong process backgrounds. This generally leads to an well-optimized process, but may cause the sub-optimization of design elements, which might greatly improve device performance.

Generally, the process is developed relative to the device performance not to a more general process specification. The sense element may itself not be a good amplifier for many critical process parameters. Thus significant process variation may be overlooked during the early stages of development which may have been determined using other process parametric measurements or process capability structures. If the sense element itself is used as a measure of process variation and capability the actual levels maybe obscured by the insensitivity designed into the structure.

Often the characterization and testing of the sense element takes a back seat to the process development. The resulting test capability and data flow that would dictate a better process or structural approach are available too late in the development to adjust the design or process.

Finally, one of the greatest concerns of this approach is cost. Many times the primary cost drivers of the product and process are not identified up front and the entire design/process approach is not optimized to produce lowest possible cost. The likely iterations required to achieve a suitable product outcome usually will not meet the required cost and schedule goals.

3.3 Fabless Approach

MEMS close relationship to the semiconductor industry clearly means most benefits will come from using the semiconductor infrastructure. Therefore, MEMS can easily follow the semiconductor development models. For example, MEMS leverages semiconductor batch processing to increase throughput and reduce manufacturing costs. One primary development in the semiconductor industry has been the implementation of fabless integrated circuit design.

The basic flow of fabless design and process development is as follows:

- Process conception
- Process development
- Process evaluation/qualification
- Design specification and design
- Design evaluation/qualification

Figure 3_1 shows a schematic of the two different approaches. It is clear that the fabless approach significantly reduces the number of potential iterations. This is made possible simply because of designing to matured and proven processes. Likewise, the designers are required to adhere to established design rules, much like the integrated circuit designers must strictly following the design rules for CMOS or Bipolar processes, so that structural integrity can be assured.

Figure 3_1: Concurrent versus Fabless MEMS development approach.

Applying a fabless approach to developing MEMS products has not been viable until recently. Today more MEMS processing foundries are offering their wafer processing services. Although there is still a lack of process standardization across the MEMS industry, a few processes are now widely used enough to becoming "de-facto" standards. Even with limited choices, it is possible for companies to find the process that is most suitable to their design. By eliminating expensive and time consuming process development, fabless companies can complete product development in less time and lower cost than companies with concurrent process development.

4. Fabless Approach Example: MEMS Gyro

In this section, we will discuss the specific example of applying the fabless approach to developing a MEMS gyro. We will highlight the essential aspects involved in planning, design specification, cost tradeoff, and the results of our development.

4.1 Planning for MEMS Gyro Development

Detailed planning for a fabless approach to MEMS development is essential. The major steps involved are:

- Survey and identify qualified fabricators
- Validate concept with selected fabricators
- Prepare system specification and flow-down
- Design sense element/ Characterize using statistics
- Design ASIC/ Characterize using statistics
- Design packaging/ Characterize using statistics
- Design test procedure/ Validate
- Statistical Evaluation/ Production readiness

Figure 4_1 illustrates the development phases for micro gyros. In this approach, there is greater emphasis on evaluating external fabricators, specifications, design tradeoff, and characterization than concurrent MEMS development approach. Because the design is based on proven production process, the characterization tests yield uniquely the design's sensitivity to the process. In contrast, under concurrent process and design development, often information relating to the effect of process variation does not flow directly back to the designers because of continuous process changes and optimization. A great deal of discipline and organizational structure is required to make the concurrent development work as effectively effectively as in a fabless approach.

Figure 4_1: Development phases for a micro gyro using a fabless strategy.

With each major design step, the emphasis on characterization forces the designer to realistically assess the producibility of the design. Statistical data allows the designers to compare real data against specifications. Only when the statistical data falls within the allowable range does the design (not the process) become "qualified". At the completion of the design, a final specification and a manufacturing plan are prepared.

4.2 Cost Elements and Tradeoff

Product development requires continuous up-to-date information relative to price points, volume, and schedule. This information forms the basis for a number of tradeoffs that will guide development decisions. Figure 4_2 shows a price and volume forecast for different levels of gyro performance. A clear target for the planned development using the latest information is important. The automotive segment with its large volume, though competitive pricing, attracts new MEMS gyro producers.

With target price and volume requirements, producers can now conduct tradeoffs to evaluate the cost of the sensor. Figure 4_2 shows key cost elements of MEMS gyros. The percentages of each element will vary depending on the process selected, and the intended application. The sense element and ASIC unit costs are typically lower than packaging and testing because of the batch fabrication process. To achieve comparable costs goals, packaging must be done using standardized plastic packages. To reduce testing costs, MEMS testing must be fully automated. Most importantly from this tradeoff, the producers can make intelligent choices regarding the use of their resources. Essentially, the key to reducing cost is by leveraging the existing semiconductor infrastructure and their mature processes. Custom development of specialized process and handling equipment will inevitably add significant costs.

Figure 4_2: Major cost elements of a MEMS gyro.

4.3 Sense Element Specification

A comprehensive specification of the gyro is essential to work effectively in the fabless approach to developing MEMS products. This systematic method of specifying requirements involves flowing down the end-user specification to detailed component and sub-component specifications.

Several conditions are needed to develop a meaningful specification and its flow down. First, the designers need to have sufficient understanding of the interaction of the sense element and signal conditioning methodology. In a gyro, a thorough understanding of the interaction between the rate signal, quadrature, feedthrough, and noise is crucial. Much of the understanding comes from system level modeling, and first hand experience. A strong technical team containing specialists in systems, manufacturing, mechanical, electronics, and integrated circuit engineering is essential.

Second, a detailed understanding of the interaction between physical parameters and major performance parameters is critical. For example, one of the essential performance parameters is Scale Factor Sensitivity. A contributor to this sensitivity is the resonant frequency separation. Figure 4_3 shows a flow down specification for scale factor sensitivity. To establish a flow down as shown, the designer needs to evaluate by simulation the effect of process variations. Tools necessary include behavioral and finite element modeling software. Although tedious and time consuming, establishing detailed specifications will logically set the allowable process variations. It then becomes a relatively simple task to evaluate candidate processes offered by external foundries.

Figure 4_3: Specification details for Scale Factor Sensitivity.

In summary, the procedure of establishing detailed specifications requires the designers to face the reality of processing variations early on. Potential problems are identified quickly, and verified later by comprehensive characterization tests.

4.4 Packaging and Testing Tradeoff

As indicated in previous section, packaging and testing comprise the major cost elements of the sensor system. For gyros, a vacuum environment is required to enhance the rate signal. The method of gyro actuation (electrostatic or magnetic) will affect the price of the packages. Most importantly, if a custom package is selected, and it involves using expensive materials such as multi-layered ceramic the price of the package quickly increases. Even in cases where vacuum is not utilized, the use of a magnetic drive alters the package design significantly such that standardized packages cannot be used.

One advantage of utilizing vacuum environment that is often overlooked is the resulting product offers clear failure indicators. Whenever the vacuum seal is broken, the device will abruptly stop working. Devices that do not rely on vacuum will likely experience a slow degradation of performance due to intrusion of moisture or contaminants. For safety critical applications, abrupt failures are required.

The drawback to using vacuum is the cost of the package and the vacuum sealing process. Alternatively, sealing can be done at the wafer level, but at lower vacuum levels. Figure 4_4 shows a tradeoff of the packaging costs versus performance and vacuum level. For the target performance (0.5 deg/sec), it clearly shows that the best option is to operate the device at near 1 Torr in order to achieve the lowest package cost.

Figure 4_4: A tradeoff between Package costs, Performance and Vacuum Level

Testing tradeoff involves using infrastructure already available in the semiconductor industry. Unlike conventional IC testing, MEMS device testing requires mechanical stimuli such as acceleration or angular velocity. These unconventional requirements mean that custom equipment must be fabricated to significant capital expenditures, to meet automotive testing requirements. In addition, testing at temperature, vibration, and shock all contribute to increased costs. Automated MEMS testing is an important area where innovation or elimination will drive down product costs.

4.5 Gyro Development Results

The Fabless approach described in this paper has been used to develop a MEMS gyro. Figure 4_5 shows the gyro sense element, capacitive readout ASIC, and a mock up of the finished plastic part that will be utilized in production. The fabrication of the sense element and the ASIC are both done by external foundries.

Figure 4_5: MEMS gyro sense element, capacitive test IC, and anticipated plastic package

The gyro has been tested using board electronics that includes drive and capacitive sensing circuits. Some of the test results are shown in Figure 4_6 and Figure 4_7. Figure 4_6 shows the linearity of the gyro output versus angular rate. The measured results yielded linearity of less than 0.4%. Figure 4_7 shows gyro's response to incremental rate tests in the range of 50 to 200 deg/sec steps. Future work will focus on shrinking the PCB electronics into a final ASIC.

Figure 4_6: MEMS gyro response to angular rate input. Linearity is better than 0.4%

Figure 4_7: MEMS gyro response to step rate input from 50 to 200 degrees/sec. Scale factor is 8 mV/deg/second.

5. Conclusions

A method of developing MEMS products using a fabless strategy has been discussed. A complex device such as micro gyro has been designed, prototyped, and tested using external fabrication infrastructure. Final work is now in progress to reduce the board electronics into an IC. Although there remains a number of steps before production can begin, we have demonstrated that by focusing on design and characterization, it is possible to quickly arrive at a viable design. We have made numerous design changes to improve the gyro performance while staying within the process design rules. By separating the design and processing, we have reduced the development time significantly. We have also discovered that an important outcome of the fabless approach is that a wealth of intellectual property has been generated due to focusing on product design. In summary, we believe that through a partnership between design and processing companies new MEMS products can reach the market sooner and at lower costs than the concurrent MEMS development approach commonly practiced today.

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Acknowledgement

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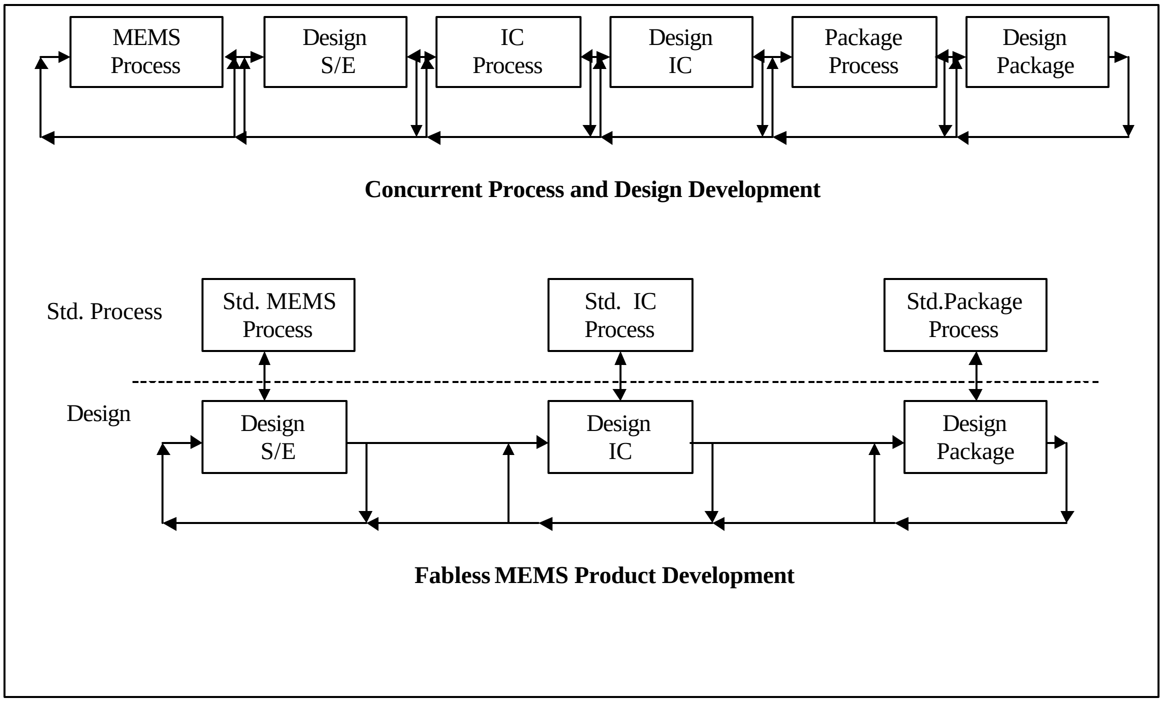

Figure 3_1: Concurrent versus Fabless MEMS product development. Each arrow represents a possible iteration path. A fabless approach allows significantly reduced number of possible iterations by strictly adhering to standard process design rules.

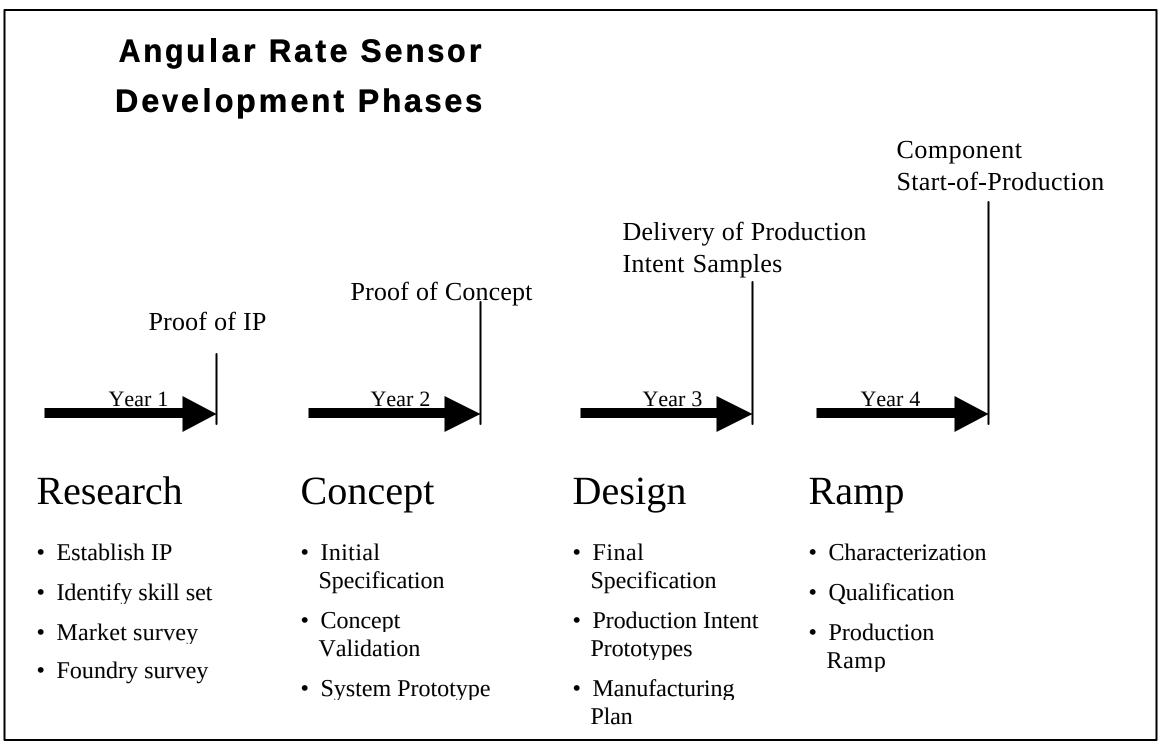

Figure 4_1: Development phases for a MEMS angular rate sensor. Emphasis is on specification, design, and characterization to determine the producibility of the design.

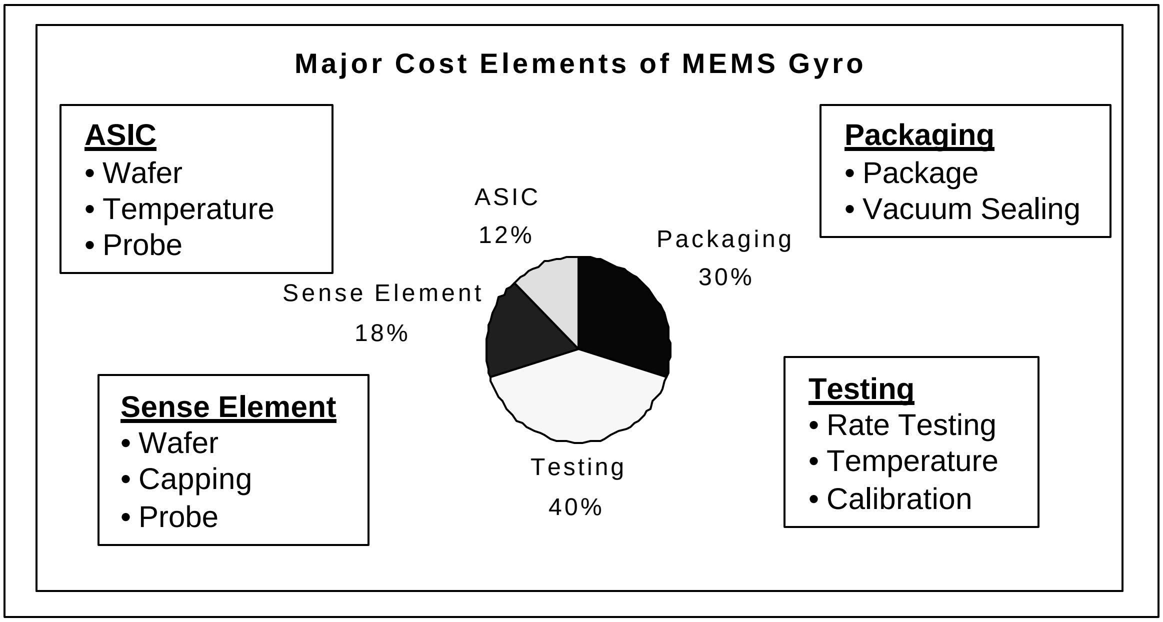

Figure 4_2: Major cost elements of MEMS gyro. A fabless approach allows the producer choice to focus their resources on the element with largest cost impact, rather than on the fabrication processes developed in-house.

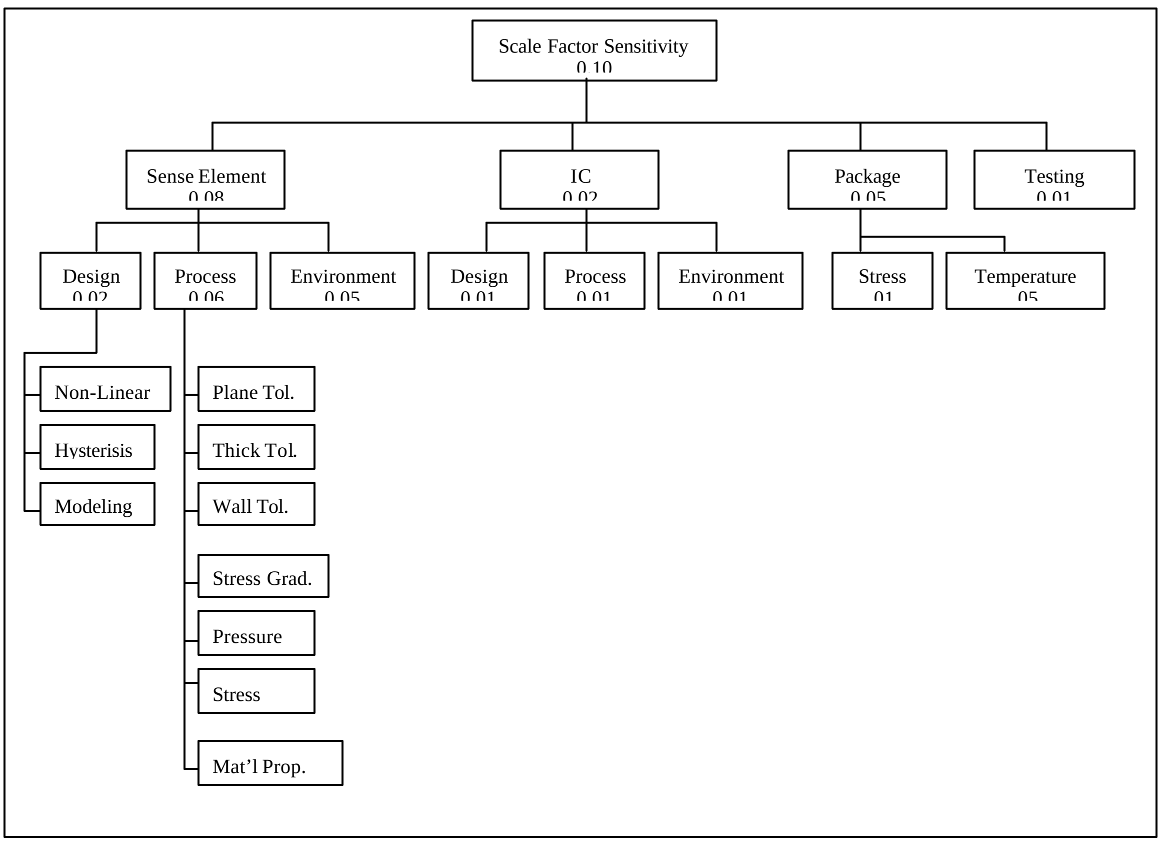

Figure 4_3: Factors that affect Scale Factor Sensitivity. Both system level and detailed Finite Element modeling is required to capture the effects of influencing parameters.

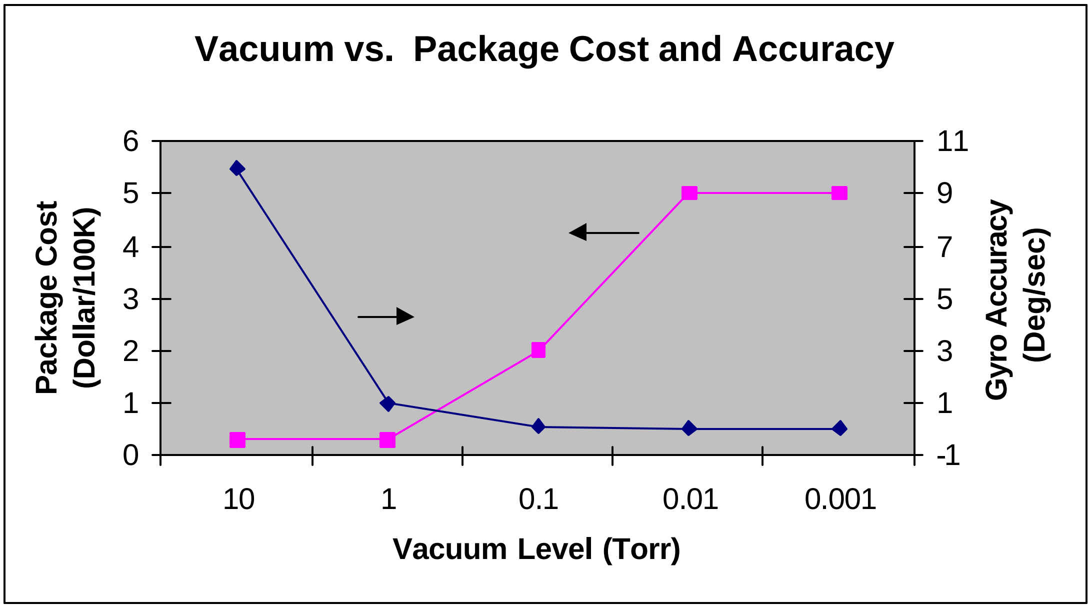

Figure 4_4: A tradeoff between vacuum level, package cost, and gyro performance. The package cost is minimized when plastic packages are used. Higher level vacuum requires ceramic packages and specialized “getters” to maintain vacuum.

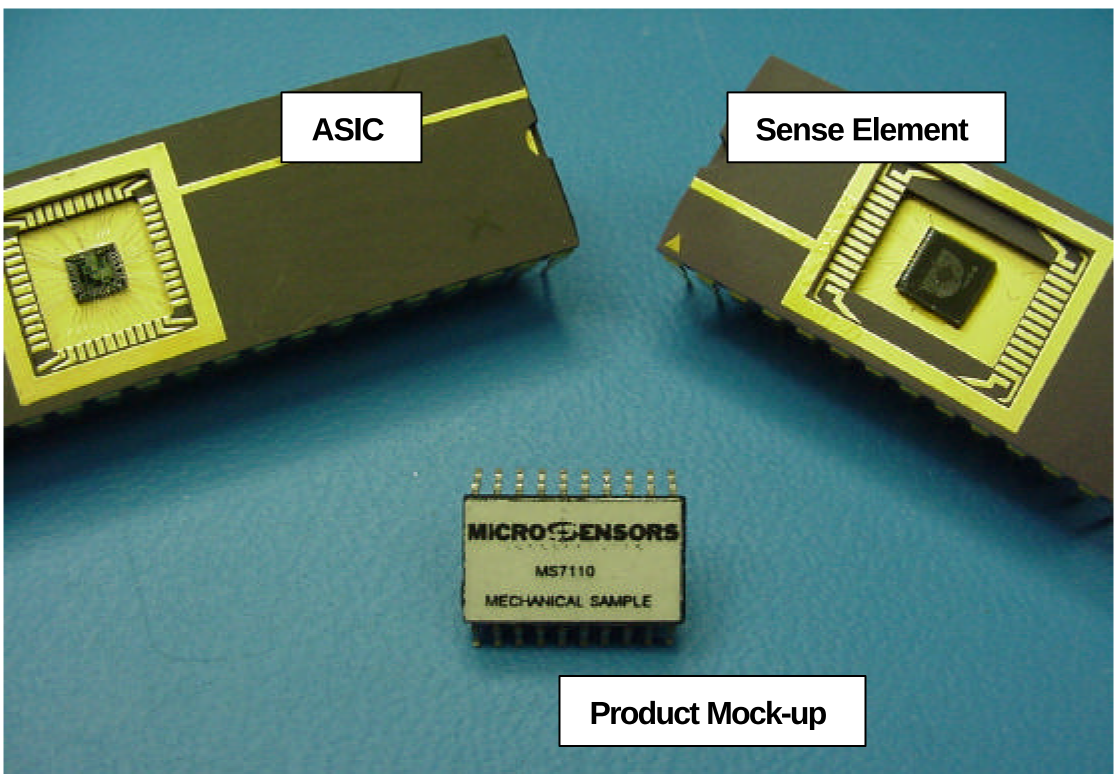

Figure 4_5: MEMS gyro sense element, capacitive readout test IC, and anticipated finish package.

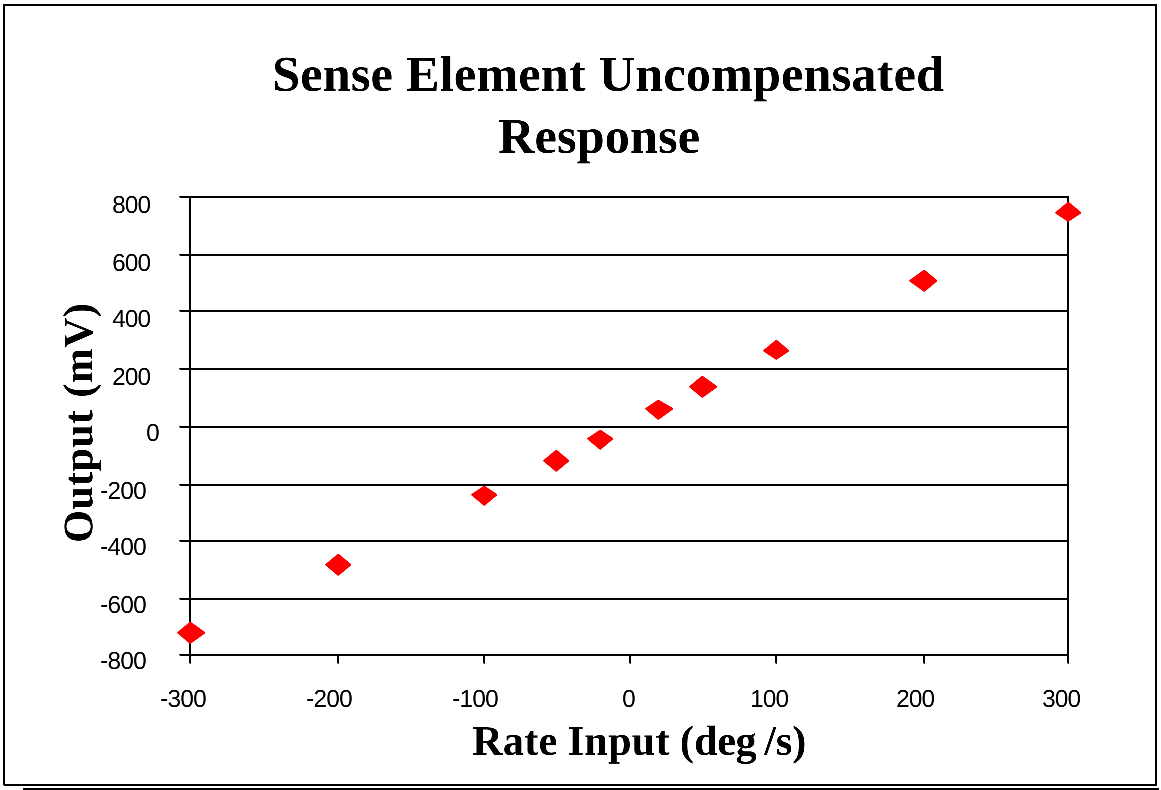

Figure 4_6: Response of a prototype MEMS gyro to angular rate input. Linearity of the response is better than 0.4%

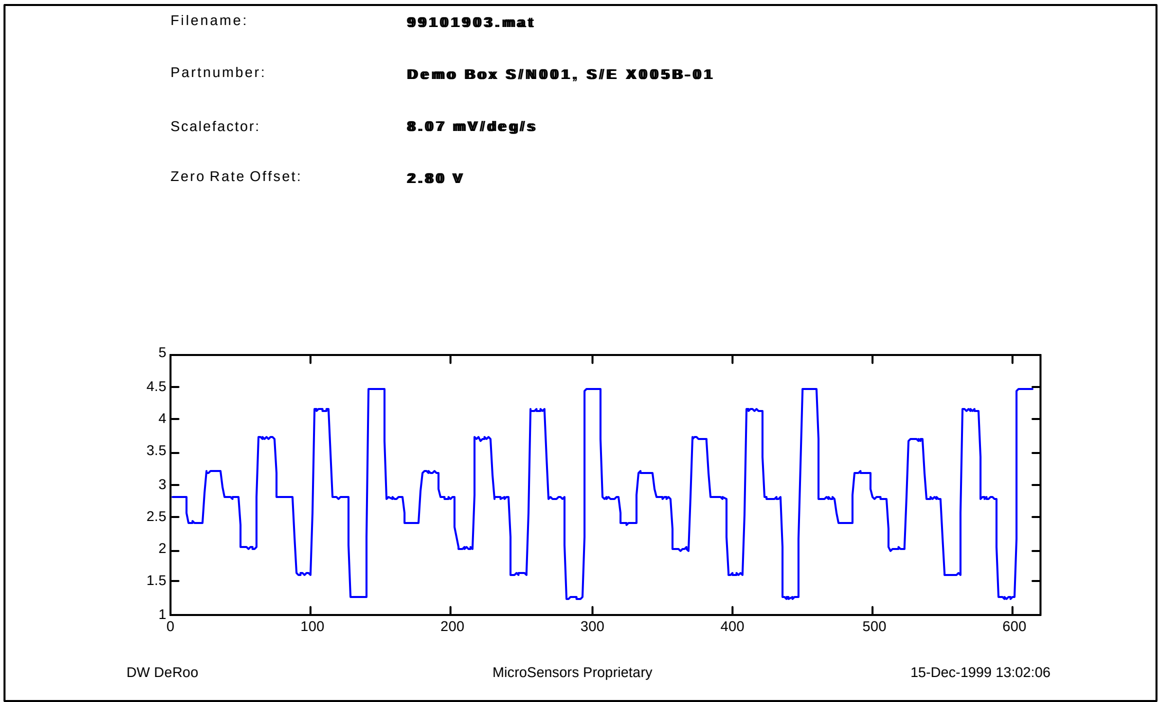

Figure 4_7: Response of prototype MEMS gyro to step rate inputs from 50 to 200 degrees/sec. Scale factor is 8 mV/deg/second.