Wafer-Scale Packaging and Integration Are Credited for New Generation of Low-Cost MEMS Motion Sensor Products

Steven Nasiri, Founder and CEO
InvenSense Inc.
Santa Clara, Ca 95054

INTRODUCTION

Motion sensing is quickly becoming the next technology to enable a host of innovative products and solutions for all types of mobile consumer applications. Most manufacturers are demanding lower cost and smaller size solutions they can integrate into their products to bring new generation of applications to market. These new opportunities range from image stabilization to advance motion sense-enabled game consoles, gesture recognition and intuitive user interfaces, GPS-assist for personal navigation devices (PND), and the location-based services (LBS) for the cellphones.

While discrete motion-sensing devices have existed in the market for some times, the current solutions are not suitable for many of the latest consumer electronic products due to their large size, expensive cost, and high power consumptions. The multi-component architecture is a barrier to entry for many of new generation, feature-rich products and applications. What is required is integrated multi-axis motion sensing products that are affordable, low power, and require very little real estate in the design.

The primary challenge in providing a viable solution has been the availability of low cost, multi-axis, integrated gyroscopes, which are the required component of any motion sensing solution for all of the applications mentioned. Development of low-cost and high performance MEMS gyroscopes have been very slow and incomplete. While the performance of MEMS gyroscopes have improved by a factor of ten every two to four years, reduced size and unit costs have failed to reach an acceptable levels to meet the needs of mainstream consumer applications.

This paper will describe a new approach coming to the market that will break the barrier to creating the ideal in motion sensors with the promise to meet market needs in size, performance, and cost.

This unique new approach comes from the patented MEMS fabrication process with vertical integration of MEMS with CMOS electronics that achieves wafer-scale packaging to enable a generation of motion sensing products that meet market demand. This new disruptive technology is called Nasiri-Fabrication and its benefits and features will be discussed and compared with the traditional sensor packaging in today's products.

OVERVIEW

The variables and degree of complexity that are involved in designing and fabricating a high-performance, reliable and low-cost MEMS gyroscope have been the major obstacle to success for many of existing MEMS manufacturers and new companies that desire to service this fast growing market. The learning curve has been long – 17 years – a lifetime in Silicon Valley terms. Yet MEMS gyros are still a high-cost, low-volume business, serving limited high-end applications. This is expected to change rapidly, however, in large part thanks to the latest innovations in wafer-scale-integration and wafer-scale packaging.

Some of the difficulties have been due in part to the fact that gyroscopes are much more challenging sensor products to design and fabricate than any other high volume MEMS products such as accelerometers or pressure sensors. MEMS gyros operate on the principal of vibrating masses and hence are equivalent to manufacturing two high-performing MEMS devices into one single unit - a self-tuned resonator for creating the sensing force (Coriolis), and a micro-g accelerometer for sensing this force which is proportional to the rate of rotation. Both have to work in tandem to produce the precise results.

The absolute magnitude of the Coriolis force sensed (which arises in a rotating reference frame and is proportional to the angular rate of rotation) is orders of magnitude lower than any high-volume production MEMS accelerometer. Capacitive sensors generally must be used for measuring these minute changes of capacitance. Gyroscope performance is very sensitive to any potential manufacturing variations, packaging stresses, linear acceleration and changes in ambient temperature. In order to achieve high performance and low cost, great care must be taken during initial design to achieve a solution that is inherently less sensitive to such potential variations.

CHALLENGES IN MAKING LOW-COST MEMS SENSOR PRODUCTS

The term MEMS originated during the advent of surface micromachining where polysilicon was used as a mechanical element and a conductive electrode to sense or actuate the mechanical element. The term generally refers to a mechanical element forged by semiconductor processing techniques, and has only recently encompassed the integration of electronics with the mechanical element. The terms "smart" or "intelligent" MEMS are now used to signify sophisticated circuitry integrated with MEMS. For high volume products where yield is a critical factor for success, the burden on the electronics is to compensate for production imperfections inherent in MEMS manufacturing and subsequent packaging.

It is an accepted rule-of-thumb in the MEMS industry that more than 80% of the cost of a MEMS sensor product is in its packaging and testing. Therefore, to produce low cost MEMS products one must address the packaging and testing issues at the front end of the product conception phase with a high-level understanding of manufacturing and testing requirements for the final product. The challenge for MEMS packaging is that in most cases MEMS devices include moving structures that must be protected from the environment and hermetically sealed. Additionally, to test the MEMS device, the drive electronics and/or the sensing electronics must be previously integrated or assembled into the finished product.

To address these challenges, a solution is needed that provides a highly cost-effective integration of the electronics and packaging requirements while meeting the hermeticity of the MEMS structures. In recent years there have been developments involving capping methodologies at the wafer level that allow for low cost plastic packaging, generally applying silicon or Pyrex caps over the MEMS using glass frits or anodic bonding. However, electronic integration has been neglected and is still a packaging issue that is only addressed by die stacking or side-by-side multi-chip module approaches. One problem with the latter is the inability to properly test the MEMS devices prior to its final packaging. Significant costs are incurred prior to any level of testing.

Another issue is the extra cost associated with the additional interconnects between the MEMS and the electronics. MEMS structures by definition are very small and any transducer motion is proportionally small. Using traces and wire bond interconnects can add major sources of signal attenuation and noise due to parasitics and the environment. This can drive the solution to be housed in a more expensive metal can, or force the design of the structure to be much larger in order to achieve a better signal-to-noise ratio.

CURRENT STATE OF MEMS PACKAGING FOR MOTION SENSORS

Current MEMS gyros are based on evolutionary technology that were used to fabricate other sensors, such as, accelerometers and pressure sensors, and primarily targeting higher end applications for military and automotive. Many of the early generation gyro designs utilized electromagnetic drives with electromagnetic sensing or capacitive sensing at a cost per axis in excess of $50 for the final packaged solutions that were measured in cubic centimeters.

Figure 1. First generation electromagnetic MEMS vibrating ring yaw sensor by Silicon Sensing System

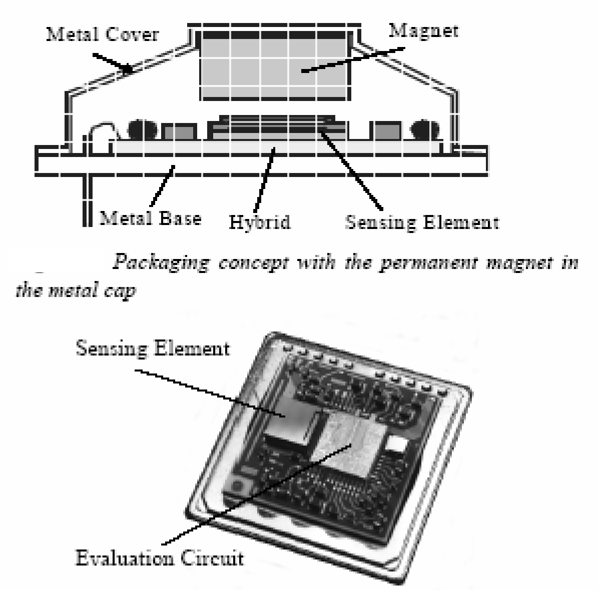

Figure 2. Bosch automotive yaw rate sensor showing sensing element and electronics.

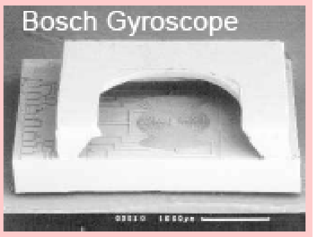

Figure 3. Bosch latest generation of single axis in-plane gyro sensor using wafer bonded cover with frit glass seal, compensating electronics not shown, (approximate size 3x3 mm).

The next generation of gyros developed in the late nineties, were able to achieve smaller sizes compared to the earlier versions that were using magnetic drives by moving to electrostatic actuation and capacitive sensing technologies. However, integration of the CMOS electronics was performed by using multichip packaging solutions. Separating the sense elements and the signal processing electronics has major performance drawbacks due mostly to routing of very low-level output signals from the capacitance pickup (ranges in Attofarads) of the sensors to the compensating amplifiers in the companion silicon. To overcome the signal-to-noise issues, the MEMS element must be large in size to generate a higher level of output signal. *Figure 3* shows one example of such solution by Bosch, using surface micromachined MEMS and wafer scale silicon covers using frit glass; this is only the sensing element without the compensating electronic and is measured approximately 3x3mm. *Figure 4* shows an example of packaging of the MEMS sensors with the companion CMOS using multichip technology.

Figure 4. Example of using the MEMS sensing elements and the companion CMOS

Another example of the present generation of MEMS sensor packaging is shown in *Figure 5* below. This is a cross-sectional x-ray view of a three-axis accelerometer MEMS sensor element stacked on top of the companion CMOS chip. This approach is a lower cost than the alternative hermetic seal used in a ceramic package, shown in *Figure 6*. However, it still adds cost associated with the silicon cover, wafer thinning, and enlargement of the silicon MEMS and silicon IC due to the wire bond interconnects. Furthermore, performance of the device is degraded due to the additional parasitics that results from routing of low-level sensor signals to the CMOS compensating electronics.

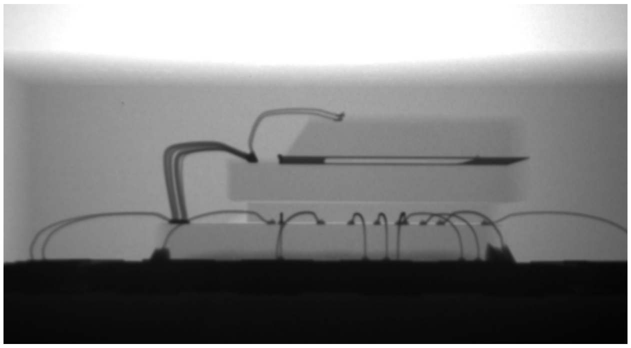

Figure 5. Cross-sectional X-ray of a commercially available 3-axis accelerometer using chip stacking technology and wire bond interconnects.

Although the existing generation of MEMS gyros were able to reduce unit prices to a lower benchmark than earlier generation products, they are still priced over $10 per axis and unable to address any of the high volume consumer applications due primarily to cost and size.

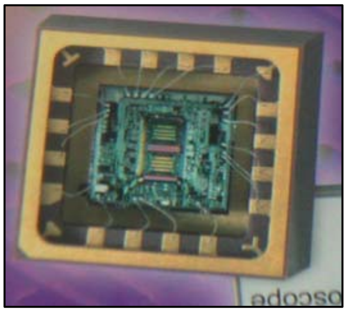

Figure 6. Single axis MEMS yaw-rate sensor using Surface micromachining technology in a BGA ceramic package of approximately 7x7x2 mm.

NASIRI-FABRICATION PROCESS

Nasiri-Fabrication developed by InvenSense Inc. overcomes many of the noted issues with today’s state-of-the-art sensor packaging and fabrication. Nasiri-Fabrication is all new and patented fabrication technology, which is a simple five mask, MEMS-specific fabrication process that is CMOS compatible. Its patented wafer-to-wafer bonding process allows for direct integration of the fabricated MEMS wafers to any off-the-shelf CMOS wafers at wafer level.

Although the wafer bonding process uses off-the-shelf wafer bonding equipments, the bonding process itself is InvenSense’s proprietary process that allows for a eutectic bonding of the MEMS wafers directly to the aluminum layer on the CMOS wafer, without addition of any other material layers on top of the aluminum. In one bonding step, Nasiri-Fabrication provide for a wafer-scale integration, by making electrical interconnects between the MEMS and CMOS, and wafer-scale packaging by providing a fully hermetic sealing of the sensitive MEMS structures at the same time.

Finished wafer then go through yet another patented and proprietary pad opening step that uses a standard sawing technique to remove unneeded MEMS silicon that covers electrical pads. Finished wafers are then tested on standard automated wafer probers. Due to its novel wafer-scale packaging, the subsequent packaging can readily be completed cost effectively in plastic packages at any industry standard contract assembly house, avoiding the need for more costly and customized ceramic and/or multichip packaging alternatives.

Nasiri-Fabrication allows for the use of bulk silicon fabrication process, which offers many other key advantages. It permits the design of much thicker (10-20X) proof masses, compared to surface micromachining, enabling a more sensitive and higher performing gyroscopes per square footprint.

The inherently superior mechanical properties of single-crystal silicon compared with deposited polysilicon films ensure more consistent, reliable and higher yielding devices. One of the key benefits of the Nasiri-Fabrication is its compatibility with any already fabricated 6” or 8”CMOS wafers. Figure 7, shows InvenSense’s dual-axis gyroscope wafer after wafer bonding and pad opening.

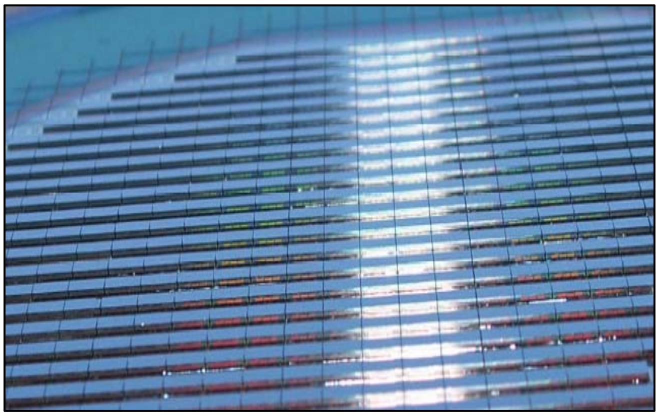

Figure 7. InvenSense’s complete MEMS gyro wafer with batch processed wafer-scale integration

Another key advantage of this fabrication process is the close proximity of the MEMS sensing element to its companion CMOS signal conditioning circuitry. This is an enabling feature that allows for an unprecedented level of shrinkage in the size of the sensing element that can enable processing of very small signals from the capacitive sensing elements. As an example, InvenSense dual-axis gyro, shown in Figure 8, has full scale output of ~100 atofarad, several orders of magnitude lower than many inertial sensors commercially produced presently, while maintaining the same or better overall performance.

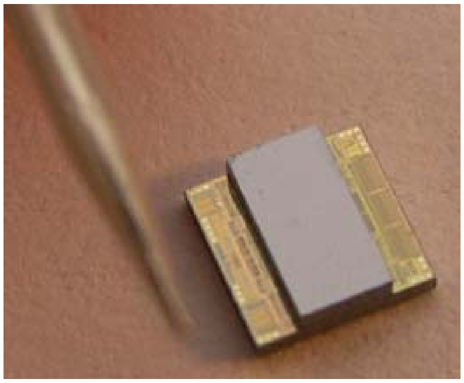

Figure 8. InvenSense’s dual-axis gyro die with MEMS integrated to the CMOS, die size 3x3mm

Yet, another major benefit of Nasiri-fabrication is its capability to form wafer-scale packaging by providing a complete hermetically sealed environment for the critical MEMS features, shown in Figure 9 below.

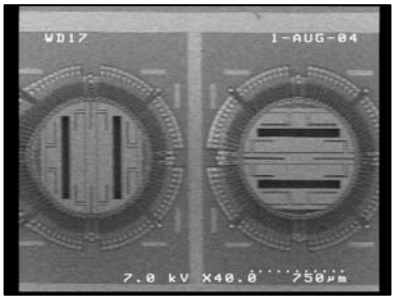

Figure 9. SEM picture of InvenSense’s IDG family of dual-axis gyros sensing features, shown is X and Y –Axis

In one processing step it can deliver complete electrical integration of the MEMS to the CMOS with a fully hermetic seal under a controlled atmosphere for all critical MEMS features, eliminating the need for any costly ceramic packaging or die stacking.

Furthermore, Nasiri-Fabrication provides for ease of fabrication and portability to many MEMS foundries. The MEMS fabrication portion is only a five-masking step and no active devices, using all off-the-shelf fabrication processes. This provides major benefits by shortening the development cycles and reducing the need for capital investments generally required for more specialized and customized processing steps.

Nasiri-Fabrication can be considered the latest evolution in the MEMS fabrication that has produced the new generation of motion sensing products at much lower cost points and at record development speed. The first product produced on Nasiri-Fabrication is an integrated MEMS dual-axis gyro called IDG (InvenSense Dual-Axis Gyro) shown in *Figure 10*, which is in high volume production with millions of units shipped world wide to major OEMs.

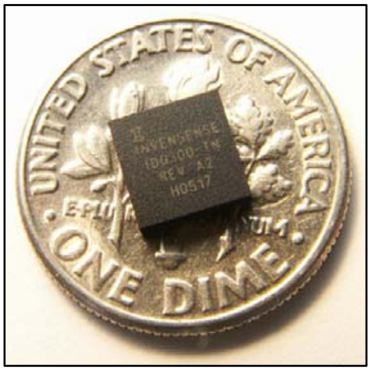

Figure 10. InvenSense dual-axis IDG product fully packaged in small 6x6 mm QFN package

The IDG product family is the first of its kind and the only fully integrated gyroscope in the world, brought to market in 2006. It is also the first MEMS gyroscope addressing high volume and low-cost consumer market. At price points of around $1 per axis it is an order of magnitude lower in cost than its closest MEMS gyro counter parts that are serving the automotive market. It’s the smallest solution available with two axis of sensing per package in 6x6 QFN.

Nasiri-Fabrication is capable of supporting a wide range of MEMS devices including gyroscopes, accelerometers, rotation sensors, actuators, and potentially many other MEMS devices. This process is particularly suitable for MEMS capacitive type sensing-detection devices and products requiring actuators and/or requiring very low-level signal detection.

Figure 11. InvenSense’s dual-axis gyro after dicing and pad

opening for access to the CMOS

APPLICATIONS IN CONSUMER ELECTRONICS

Development of low-cost motion sensor products has significant positive ramifications for the consumer electronics (CE) market. Owing to its cost, size and performance advantages, these motion sensors are well suited for use in every mobile consumer application, opening the door to a multitude of feature rich and user friendly consumer electronics products.

Image stabilization for video and still cameras. As the digital camera makers have already developed >8 mega pixel cameras with increased zoom levels, the need for image stabilization to improve image quality and correct for blurriness caused by hand jitter has been on the raise. Image stabilization used to be deployed only in more expensive cameras due to the size and costs associated primarily with required gyros. Today, such features are readily available in even the lower cost DSC cameras and have become a standard feature.

Motion Sensing Market. Motion sensors are starting to find their way into various consumer electronics applications, from game consoles to 3D-mouse, and remote controllers, to more advanced applications such as portable navigation systems and user interfaces for more feature rich devices. Gyroscopes are the essential element of a true motion sensing solution, where ultimately six degrees of freedom (3 axis of rotation and 3 axis of accelerations) will be required. MEMS technology is the only technology capable of providing multi-axis integrated solutions on a single piece of silicon while meeting the stringent cost, size, and performance requirements of the stated applications.

Motion Sensing for Mobile Phones. A MEMS-based motion sensor has the potential to drive next-generation mobile phone applications, such as smart phones, by enabling the development of tiny integrated multi-axis motion sensors. These sensors will add new dimensions in intelligence and user interface while enabling a variety of new applications such as gesture-recognition, menu navigation, image stabilization, and location-based services.

CONCLUSION

The growing demand and high volume potential for MEMS inertial products has led to the development of a more cost effective MEMS fabrication process, called Nasiri-Fabrication. This development is expected to have significant positive ramifications for the MEMS industry by enabling more advanced MEMS products to enter the market at record speeds.

The Nasiri-Fabrication process has allowed creation of a new generation of inertial sensors. Providing the capability to integrate bulk silicon MEMS wafers directly with their integrated electronic circuits at the wafer level to produce a new price-performance benchmark that is more than 10x lower than its closest MEMS counterpart due to its patented wafer-scale packaging and direct wafer bonding capability to the CMOS.

The combination of its patented gyro microstructure design, simultaneous wafer-level integration and packaging, and built-in test and calibration, enables the technology to meet the all-important size and price points necessary for deployment in consumer devices. InvenSense’s new dual-axis sensor product line, IDG, is produced cost effectively on a single wafer using batch process fabrication to produce thousands of dual-axis gyros simultaneously. With the IDG family introduction in 2006, a short two years from the company’s funding, and with millions of units already shipped, this is by far one of the fastest MEMS development and high volume production ramps in recent MEMS market history.

ABOUT THE AUTHOR

Mr. Nasiri founded InvneSense from his home in early 2003 and received the company’s first funding in April of 2004. During this period, he developed the novel product concept of the MEMS gyroscope and the low-cost, high-volume fabrication process known as, “Nasiri-Fabrication”. These efforts have led to the filing of the four core patents for the company, including the dual-axis gyro design and the vertical MEMS fabrication process. These patents are now responsible for the development of world’s first integrated dual-axis gyroscopes which is the company’s flagship products and being shipped in millions of units to major OEM companies around the world.

Mr. Nasiri is a 28 years veteran of the MEMS industry with expertise in fabrication and packaging of various types of MEMS products. His extensive knowledge of MEMS fabrication technologies was instrumental in his ability to conceive the design of the "Nasiri-Platform" and creation of a novel mirror design for Transparent Networks, where Mr. Nasiri was a co-founder and served as the Vice President of Operations and MEMS Development.

Mr. Nasiri has been the co-founder and early stage executive at some of the leading MEMS companies in Silicon Valley including: SenSym (Honeywell), NovaSensor (GE), Integrated Sensor Solutions (TI), and ISS Nagano. He has been responsible for successful deployment of over 50 sensors and MEMS-based products with cumulative shipments in excess of 100M units.

Mr. Nasiri received his MBA from Santa Clara University, a MSME from San Jose State University and a BSME from the University of California, Berkeley. He has authored over 40 patents (issued and pending) and many articles in the MEMS field.

REFERENCES

[1] S. Nasiri, “Critical View of MEMS Gyroscope Technology and Commercialization Status,” 2003

[2] S. Nasiri et al, September 6, 2005, US Patent 6939473 Methods of Making an X-Y dual-axis , Dual-mass Tuning fork Gyroscope With Vertical Integration of Electronics and Wafer Scale Packaging

[3] S. Nasiri et al, September 12, 2006, US Patent 7,104,129 Vertically integrated MEMS structure with electronics in a hermetically sealed cavity

[4] S. Nasiri et al, May 17, 2005, US Patent 6,892,575, X-Y axis dual-mass tuning fork gyroscope with vertically integrated electronics and wafer-scale hermetic packaging

[5] S. Nasiri, Wafer Level Packaging of MOEMS Solves Manufacturability Challenges In Optical Cross Connect, 2003

[6] N. Yazdi, F. Ayazi, and K. Najafi. Aug. 1998. “Micromachined Inertial Sensors,” *Proc* IEEE, Vol. 86, No. 8

[7] S. Nasiri patent, MEMS Mirrors and MEMS arrays, Pat# 6,480,320

[8] Y. Gianchandani and K. Najafi. June 1992. “A bulk silicon dissolved wafer process for microelectromechanical systems,” *J Microelectromech Syst*:77-85