DEVELOPMENT OF HIGH-PERFORMANCE, HIGH-VOLUME CONSUMER MEMS GYROSCOPES

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ABSTRACT
This paper discusses the challenges and success factors for creating the world's first integrated MEMS gyroscopes for the consumer electronics market. A disruptive MEMS processing platform called Nasiri-Fabrication is described which has enabled Motion Processing applications, creating the largest and fastest growing MEMS sensors market segment. The paper also presents the design challenges and methodology behind the creation of the world's smallest and best performing consumer grade gyroscope.

INTRODUCTION
InvenSense was founded in April 2003 by Steve Nasiri, a seasoned MEMS veteran, with a unique combination of entrepreneurial success and MEMS sensor manufacturing expertise. The company was started on the principle that commercialization of silicon gyros requires a thorough understanding of all aspects of sensor production including MEMS fabrication, design, backend operations, and high volume production. Moreover these critical aspects must be mutually optimized to be universally adopted in the cost sensitive, high volume, consumer electronics market.

During the first year, the company was self funded by Steve Nasiri and employed a series of consultants to help develop its business plan and core intellectual property (IP). InvenSense cemented its disruptive fabrication platform recognizing that it has inherent cost, size, and performance advantages that can revolutionize the way MEMS products are manufactured. This technology was deeply rooted in the founder's past activities and his general expertise in volume production and MEMS fabrication. The fabrication platform is now known as Nasiri-Fabrication.

MEMS gyroscopes were identified as a product with huge potential in both automotive and consumer markets. InvenSense focused on consumer electronics (CE) because the market requires small size and low-cost which Nasiri-Fabrication can inherently address. Initially, the company targeted image stabilization for digital still cameras. This feature was becoming increasingly important as the resolution of the digital cameras steadily grew and the camera size was reduced requiring single handed operation. InvenSense succeeded in filing four of its core patents, fine tuning its business plan, and creating the blueprint of its first dual-axis gyroscope. The focus on the consumer market resonated with the VC community and InvenSense received its first funding of $8M in April of 2004, while operating from the founder's kitchen table.

From the inception, the market strategy, design, and fabrication converged to develop an extremely low cost and highly manufacturable gyro satisfying the CE market requirements. The first generation dual-axis MEMS gyroscope started production in 2006 and shipped to several Japanese DSC camera makers. The second generation gyroscope went into production in 2008, and largely due to the success of the Nintendo Wii Motion Plus, over 50 million units were shipped. In early 2010, InvenSense announced the world's first Motion Processing Unit™ (MPU), featuring the industry's first 3-axis gyroscope with embedded Digital Motion Processor™ (DMP) hardware accelerator for 6-axis sensor fusion.

Today the consumer market is the single largest market for MEMS sensors. Every portable consumer electronics device is moving toward the integration of Motion Processing™ technology. InvenSense, as reported by iSuppli, is now recognized as the number one supplier of gyroscopes for the CE market and as the innovation leader in MEMS.

At the time InvenSense was founded, there were several companies either developing or already producing gyroscopes for the automotive and consumer markets. Some used MEMS, while others used quartz or piezoceramics. InvenSense not only has been able to enter the market but has validated motion processing capability by addressing the key challenges of developing a gyroscope for the consumer market: low cost, high reliability, high performance, and fast time-to-market. Meeting these challenges required an experienced leadership team with knowledge spanning the core fabrication and design IP, as well as operations, test, packaging, applications and marketing. This paper presents the InvenSense core technical IP including Nasiri-Fabrication and MEMS design.

NASIRI-FABRICATION
The foundation for building the InvenSense line of inertial sensors is the Nasiri-Fabrication platform. It is a unique platform that is ideal for developing a low-cost gyroscope and other MEMS devices. It addresses the components that influence cost, size, and performance. The key attributes of the Nasiri-Fabrication are the use of single crystal silicon, wafer level integration with CMOS electronics, and a cost effective wafer level packaging technique.

The process flow is described in Figure 1. Only six masks are required to produce the integrated and hermetically sealed gyroscope. The device mask, which defines the MEMS structure, is the only critically dimensioned mask. Eutectic bonding between a germanium layer deposited on the MEMS and the top aluminum layer on the CMOS simultaneously creates multiple interconnects and a hermetic seal for thousands of devices per wafer. This one simple step addresses both the electrical integration and the packaging of thousands of sensors and is the cornerstone of Nasiri-Fabrication. The manufacturing uses commercially available equipment with standard off-the-shelf processes making the process easily scalable and portable to multiple foundries.

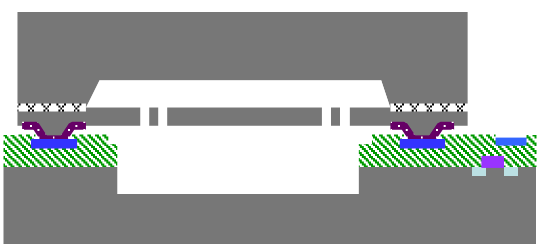
The process seamlessly integrates MEMS and CMOS and avoids the complex process interdependencies of other integrated platforms. This allows the IC design to use the best CMOS technology nodes to add features and to lower costs as needed. The process also allows circuits under the MEMS outside the small cavity areas. This maximizes the available CMOS area and minimizes the wiring parasitics between the MEMS structure and interface circuits. The top layer of CMOS aluminum provides electrodes for actuation and sensing of the MEMS structure. Unlike two-chip MEMS platforms, in which the routing to the sensor uses the MEMS layers, all signal routing in Nasiri-Fabrication is done using the CMOS substrate, leveraging the low resistance, compact metal routing capability of the multi-metal CMOS process. Electronic shielding is enabled, routing congestion is reduced, and signal fidelity is preserved. The AlGe contacts between the MEMS and CMOS support differential capacitive sense structures due to the compact size of the contacts and its demonstrated reliability. InvenSense has leveraged this capability to make over 100 contacts to capacitance sensing comb structures per chip.

The all-silicon construction avoids problems caused by thermal mismatch of materials. Using a bulk silicon device layer allows for thicker MEMS structures (20-100µm) which provides inherently better noise and sensitivity due to larger masses, larger capacitances, and higher frequencies for operation outside of the audio range. MEMS designers have the flexibility of choosing the thickness for optimal performance, which is not easily achieved in a surface micromachining processes.

(a) The engineered silicon on insulator (ESOI) wafer is formed starting with a standard silicon handle wafer etched with simple targets for backside alignment (mask 1); followed by oxidation and cavity etch (mask 2). A second wafer is fusion bonded to the handle wafer and subsequently thinned to define the device layer thickness.

(b) The MEMS wafer is completed by etching the device layer to form standoffs (mask 3) that define the seal ring, the electrical contacts to CMOS, and the vertical gap between the CMOS and MEMS; depositing and patterning a germanium layer (mask 4) over standoffs; and patterning (mask 5) and deep reactive ion etching the device layer to form the mechanical structure.

(c) A standard CMOS wafer is fabricated by an independent foundry, and cavities (mask 6) can be etched into the CMOS wafer, if needed for larger clearance under moving MEMS structures.



(d) The MEMS wafer is bonded to the CMOS wafer using AlGe eutectic bonding between the Al on the CMOS and the Ge on the MEMS wafer. After bonding, a portion of the MEMS wafer is removed by conventional dicing saw cuts to expose the CMOS wire bond pads.

Figure 1: Simple six mask Nasiri-Fabrication process flow.

The resonating MEMS device is encapsulated and hermetically sealed in a vacuum environment. The vacuum level is controlled during the bonding process. Getters are not required to maintain the vacuum because the seal is hermetic and the materials used in the process do not outgas. This point is actually more important than first may be realized. Damping is one of the key functional parameters that affects the proof-mass velocity and gyro bias. Achieving a stable and constant damping factor, which is a direct function of the vacuum, is critical. Adding getters to maintain a vacuum over the product lifetime does not guarantee a constant vacuum or hermeticity, and hence builds in a reliability problem, particularly in humid environments.

Wafer level integration of MEMS, electronics and micro packaging addresses the widely recognized high cost of package and test associated with MEMS devices. Each die is fully encapsulated and is packaged using standard, low-cost QFN packages, as shown in Figure 2. Furthermore, the bonded wafer has full functionality, allowing each die to be tested at wafer probe. Wafer level testing provides mapping information for timely feedback to the foundries for improved process control, and provides device level traceability. Use of conventional high speed testers at the wafer probing level reduces the test costs associated with custom testers needed for sensitivity calibration of packaged parts.

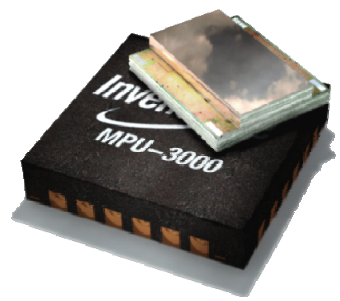


Figure 2: Fully functional, hermetically sealed, 3-axis gyroscope and standard QFN package.

GYROSCOPE DESIGN

Nasiri-Fabrication provides a platform well-suited for gyroscope design. The process provides controlled vacuum, thick structures, low parasitics, and built-in reliability. Nonetheless, the gyroscope design challenges are formidable. The design must work within the process: it must be robust against inherent process variations and against the package stresses brought on by low-cost packaging. The design must meet the consumer market demands of cost, size, performance, and reliability and the design cycle must meet the rapid development time required to be the first in the market. The key to meeting these challenges has been to comprehend the fundamental issues in gyroscopes and properly design the integrated system to compensate for the error sources. This was achieved by developing good simulation capabilities and structured design flows. While this already existed for the IC industry, this was relatively new for the MEMS industry.

Mechanical Architecture

MEMS vibratory gyroscopes measure rotation rate by vibrating a proof-mass and sensing the Coriolis force caused by angular velocity. Beyond the goal of making a vibrating structure that gives rise to a Coriolis force, the true goals of the gyro transducer are to minimize the error sources that corrupt the Coriolis signal and to simplify the IC architecture. The former is achieved by a design that minimizes Brownian noise, rejects external vibrations, survives shock, rejects package stresses, and minimizes cross-axis sensitivity. The latter is achieved by a design that has high transducer sensitivity, minimal quadrature, carefully designed resonant modes, and minimal parasitic capacitance.

All InvenSense X- and Y-axis gyroscopes are based on coupled dual-mass (tuning fork) proof-masses that are driven out-of-plane and generate Coriolis forces in-plane, as shown in Figure 3. The vibration mode consists of a five-mass system. The two proof-masses translate out-of-plane coupled together through lever arms connected to three separate torsion plates. The torsion plates are mounted on springs that act as pivot points, which is the key to achieve vertical motion using thick silicon. Aluminum electrodes on the IC are located under the torsion plates forming parallel-plate electrodes that can exert torque on the torsion plates for actuation and detect the torsion plate angle for feedback to resonate and provide amplitude control.

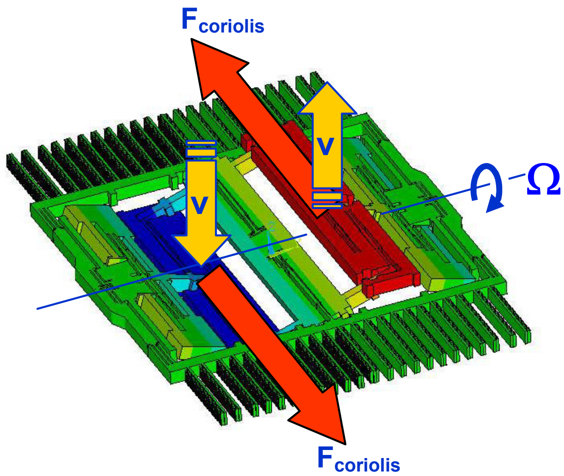


Figure 3: X-axis gyroscope driven mode

The coupled mass system is essential for rejecting external vibrations because the design is fully balanced and therefore does not move in response to linear acceleration. However, the first generation gyroscopes, which operated in the 12 kHz to 15 kHz range, were found to respond to acoustic interference. Later generation gyros were designed to operate in the 25 kHz to 30 kHz range to avoid interference from sound and other ambient sources of noise found in consumer applications.

The key to reducing size has been to improve the Coriolis sensing system. In the first generation sensors, the three torsion plates were connected to a sensing frame. The sensing frame was suspended such that it could only rotate. The Coriolis forces from the proof-masses created a torque that rotated the ring in plane. Motion of the ring was detected by capacitive combs. The full scale angular rate in image stabilization generated merely ~1Å of mechanical deflection of the sensing frame. Sensing the deflection required lots of capacitive combs and low-noise electronics.

In the next generation InvenSense introduced patented "dual-mode sensing," in-which the two outer torsion plates are anchored to the substrate, and the center torsion plate is flexibly connected to the sense frame. By flexibly connecting the drive system and sense system, two resonant modes are created, and the drive resonant frequency is in the middle. This introduced several benefits including lower sensitivity variation as well as 2x higher mechanical sensitivity. The design improvement resulted in smaller MEMS that met the same performance with higher resonant frequency to avoid the audio range. In the third and current generation, the sense frame was further optimized into a four-bar linkage. The Coriolis torque moves the four-bar linkage which is sensed in-plane using capacitive electrodes, as shown in Figure 4. The four-bar linkage has lower inertia than the corresponding rigid frame structure of the past. This generation also anchors the structure at two points which minimizes sensitivity to any stress associated with conventional QFN plastic packages.

InvenSense introduced a Z-axis gyroscope in 2009. It consists of two proof-masses that are resonated in-plane as shown in Figure 5. The proof-masses are flexibly coupled and resonate in a differential mode. The proof-masses can move in two directions but the actuation structures are constrained to move only in the drive direction. The Z-axis gyroscope also uses dual-mode sensing. The proof-masses are flexibly coupled to the sense frame and the resulting Coriolis torque moves the sense frame similar to the X and Y gyroscopes. In this manner, the Z-axis gyroscope is able to leverage the entire sense-system mechanics and electronics developed for the X-and-Y sensor. In fact, the first generation Z-gyro simply replaced the Y-gyro drive masses with proof-masses that are driven in-plane, enabling rapid development.

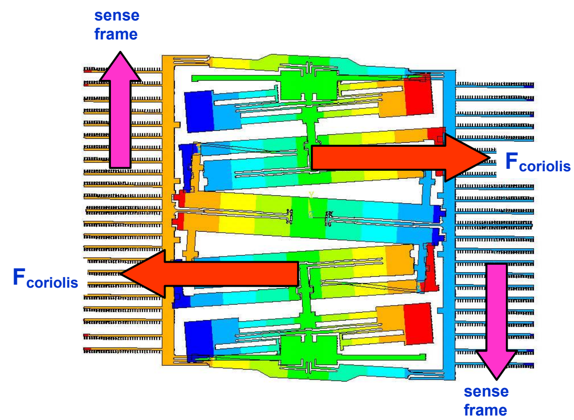


Figure 4: X-axis gyroscope sense frame first resonant mode

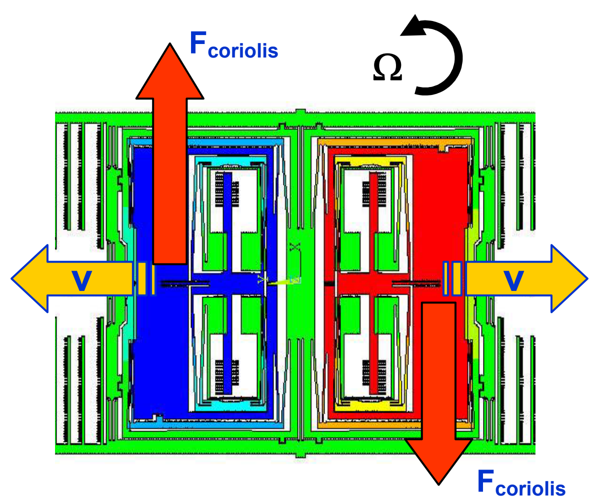


Figure 5: Z-axis gyroscope driven mode

IC Architecture

The gyro signal path is the core of the MPU-3000. Shown in Figure 6, it includes a drive-loop that vibrates the structure at resonance, a sense path that detects the motion caused by Coriolis acceleration, a synchronous demodulator that recovers the rotation signal, and an ADC that provides digital output to the motion processor.

The IC architecture was chosen for the balance of noise, power, and size to meet the market requirements. The chargepump provides high signal gain for the low-noise, continuous time signal path. The drive-loop consists of a capacitive position sensing stage followed by a simple 90º phase shift to oscillate the MEMS structure at resonance.

The IC also compensates for transducer variation and imperfections. For example, the trans-capacitance value in the drive-loop and sense path amplifiers are programmable and can be written to on-chip, non-volatile memory during factory trim to compensate for both etching and vertical gap variations. The patented feedthrough (FT) cancellation block, is a programmable capacitor that is used to reduce the undesired quadrature signal. Amplitude control circuitry maintains constant vibration amplitude as the damping varies due to process and temperature variation. The digital signal path provides means for offset temperature compensation that can be factory programmed.

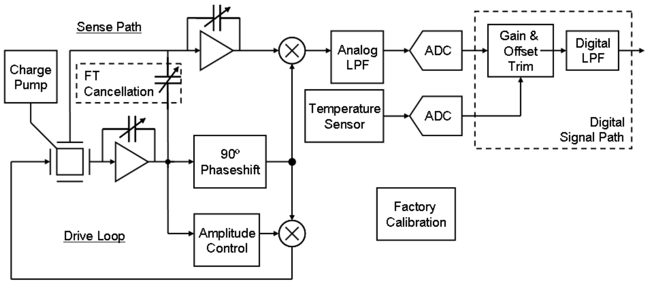


Figure 6: Single-axis gyroscope signal path electronics

RESULTS

InvenSense has met the challenges of the consumer market, introducing the world's first dual-axis gyroscope in 2006 and new generations of smaller size products at lower cost regularly ever since, as shown in Table 1. The commercialization of multiple products with millions of gyros ships are a testament of successful integration of the core IP of Nasiri-Fabrication and design.

In the current generation gyroscope, the MPU-3000 shown in Figure 7, the MEMS size per axis is one-half the size of the first generation; the CMOS area per axis is one-third of the first generation. The process has migrated from 0.5µm CMOS to 0.18µm and is being built on a 200 mm line.

Characterization of this product shows that the goals of small-size and high performance have been achieved in a standard plastic package. The sensitivity variation is better than 4% over a temperature span of 145ºC as shown in Figure 8. The Allan variance plot in Figure 9 indicates an angle random walk of 0.016deg/√s and a bias instability of better than 0.01º/s at 10s.

CONCLUSION

InvenSense entered the consumer market for gyroscopes in 2006 based on Nasiri-Fabrication and novel dual-axis gyroscope design. The fabrication platform has been proven to be reliable, low-cost, and suited for high volume production. The gyroscope design has met the market needs for size, cost and performance culminating with nearly 100 million units shipped. Continuing design innovation to reduce size, improve performance, and integrate additional sensors has earned InvenSense the technological leadership. InvenSense has enabled the motion processing market, with expected demand to reach over one billion units annually by 2015. InvenSense is preparing to meet this exciting demand by increasing capacity and to continually introduce high value products.

Table 1: InvenSense gyroscope product history

Product	**IDG-1000**	**IDG-600**	**IXZ-600**	**MPU-3000**	
MP Date	2006	2008	2009	2010	
Gyro Axes	X/Y	X/Y	X/Z	X/Y/Z	
Package	6x6x1.4 QFN	5x4x1.2 QFN	5x4x1.2 QFN	4x4x0.9 QFN	mm^3
Die Size	12.2	7.4	7.4	6.7	mm^2
MEMS Area	4.1	2.8	2.8	2.9	mm^2
CMOS technology	0.5um	0.35um	0.35um	0.18um	
Output	Analog	Analog	Analog	Digital	

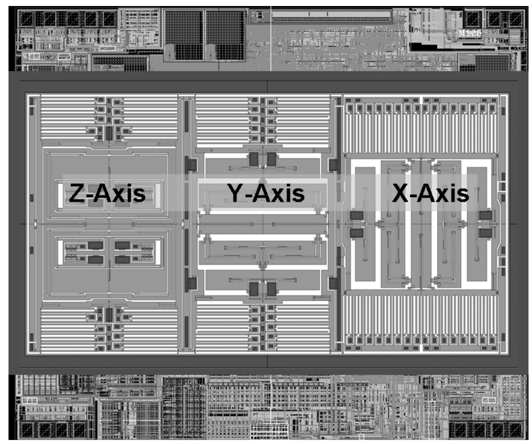


Figure 7: MPU-3000, 3-Axis gyroscope in 2.8mm x 2.4mm

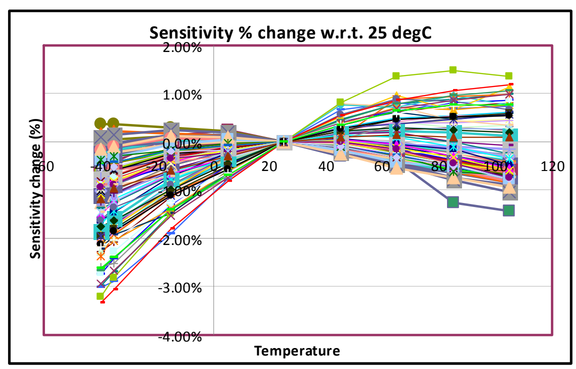


Figure 8: MPU-3000, sensitivity variation of 30 units (90 axes) from -40ºC to 105ºC.

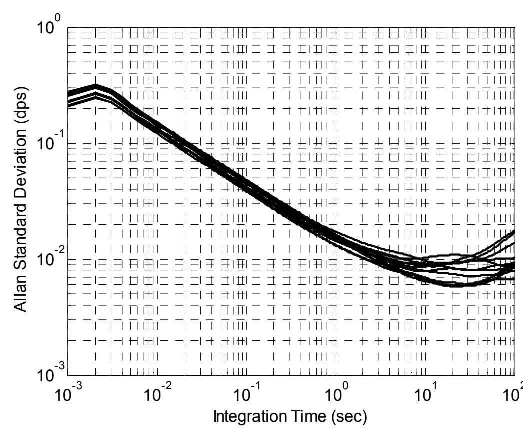


Figure 9: MPU-3000, Allan deviation for 4 units (12 axes)