The MEMS Motion Sensor Perspectives

- Case Studies of the Technology and Business of MEMS Motion Sensors

A companion study guide for Foundations of MEMS textbook.
By Chang Liu
MEMS Central

The MEMS technology and motion sensors market is growing rapidly. Motion sensors are fueling the growth of new consumer electronics devices, which in turn helps the growth of the MEMS industry. This article provides a review of the technology and business of MEMS motion sensors – accelerometer and gyroscopes. The article provides an inside view of the technology/business evolution and device at world's major companies in this space – Analog Devices, MEMSIC, InvenSense, and STMicroelectronics. This document attempts to chronicle major development history of MEMS motion sensors up to 2010.

This article provides the following parts.

Part 1: Overview
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Section 1: Overview

Motion sensing refers to measuring the spatial bearing, linear motion, and rotational movement. Here are a few examples:

- A motion sensor in the Nintendo Wii controller (called Wii mote) can detect the movement of hand and allows a game player to play simulated games of tennis, golf, boxing, etc.
- Motion sensors in smart phones such as iPhone can detect the orientation of the phone with respect to gravity and change the format of display (landscape vs. portrait) when a user holds the phone differently.
- Gyros in iPhones measures the rotation speed, allowing users to play interactive games such as simulated car driving – a user simply rotate the device to simulate the action of turning steering wheels.

Today (2010), there are two major classes of motion sensors: **accelerometers** which measure linear acceleration, and **gyros** which measure rotation speed. The technologies for these two are deeply related but of course not exactly the same. In this article, we discuss them interchangably.

Figure 1: Gyros (rotation speed sensors) allows an iPhone app JetCar to simulate driving a car by using the phone itself as a steering wheel.

A review paper by Prof. Walters provides a very detailed account of the development of accelerometer. (Citation provided at the end of this section. Do a web search with the terms "history of accelerometer walters" to find the article). It is believed that the first accelerometer was made in 1920. The first devices were based on resistance-bridge of carbon resistors. This device weighted a pound. Later, around 1938-1941, bonded metal resistance strain gauges are developed. However, such devices suffer from signal-to-noise ratio issues. Later, piezoelectric accelerometers were developed. Such devices were used in vibration monitoring for space and air force programs. Around 1960 Walter Kistler established Kistler Instrument Company to commercialize piezoelectric sensors. Endevco was formed in 1947 in Pasadena, California and commercialized accelerometer in 1951. Endevco focused on microminiature, high shock, high temperature accelerometers. It also pioneered diffused semiconductor strain gauge in 1967.

Around 1960-1975, a number of companies start to take advantage of diffused silicon resistors for acceleration sensing. These include Fairchild, IC Transducers, Kulite, and National Semiconductors. Kulite was founded in 1959 as the first commercial source of bare silicon strain gages. National Semiconductor was founded in 1959 by Dr. Bernard J Rothlein after leaving the Rand Corporation (which is founded in 1910 as the **Sperry Gyroscope Company** by Elmer Ambrose Sperry). In 1982, National Semiconductors exited the sensors business. Around 1983, a new group of sensor companies were formed, after the bulk silicon micromachining process development. These companies include IC Sensors (1983) and Nova Sensors (1985).

Before 2006, MEMS motion sensors were exclusively developed for the automotive market (crash sensor). The typical volume demand is on the order of tens of millions per year. In 2006, the five major suppliers of accelerometers are Freescale, Analog Devices, Bosch, VTI, and Denso. The leader of automotive MEMS is Bosch, with overall revenue of $457M (M means million) in 2007 and $429M in 2008.

The MEMS sensors business was already a business in 2006. However, it is about to get bigger. In fact, it is predicted to grow so fast that it will overtake the current MEMS revenue leaders – Texas Instrument DLP and Hewlett Packard ink jet printer heads. Why?

In 2006, three things happened:

- Low cost of MEMS: the MEMS field, after over 15 years of active research and production, is finally able to make motion sensors for less than $1 each;
- Growing consumer electronics (CE) market: the CE market exploded, with innovative products such as gaming, smart phones, etc. This is the result of multiple factors, including consumer habit. The Internet infrastructure is fully innovated and people's use of Internet starts to change (Web 2.0), making portable CE devices highly practical and desirable. Consumers appetite for new electronics gadgets increased dramatically.
- CE and gaming manufacturers seek differentiation and growth. The CE devices need new human-computer interface (HCI) devices because of their small sizes. Traditional mouse and keyboard are no longer suitable for such platforms. Traditional gaming companies also enter stagnant growth and wants to have new game titles in their business pipelines.

2006-2008 was a turning point for MEMS industry, because of the booming of smart consumer electronics and mobile electronics, which themselves are contributed by the maturation of microelectronics industry (CPU, hard drives, memory, display). The success of motion-based products – Nintendo Wii (released Nov 19, 2006), Apple iPhone (January 9, 2007), and Google Android based smart phones (released Nov 5, 2007), changed the landscape of MEMS motion sensors. (In fact, these phones changed the landscapes of MANY industries). Apple iPod becomes the first smart phone product to use gyros. However, the iPod only opens up people's mind about the potential market. Android phones and future generation of smart phones have much bigger consumer followings. As the price of some MEMS sensors dips below a dollar, every smartphone vendor is scrambling to match Apple's sensor complement.

Even in a generally favorable climate, it still takes tremendous vision, technical skills and courage to succeed. Companies that took advantage of the CE market boom, innovate boldly in time, and bet heavy on the trend, starts to become leaders. For example, in 2008, STMicroelectronics, a company that only started to make accelerometers in 2006, takes a lead in accelerometers for consumer electronics market. By September 2010, ST has made over 850 million accelerometers and gyroscopes!

2008 is also the same year that sales from CE outpaced automotive applications. The sales are now driven by smart phones. Automotive applications account for 40% of global accelerometer revenue in 2008, down from 78% in 2006. In the same period, the revenue from CE applications of accelerometer rise from 22% to 58%.

The growth of CE will lift revenue of MEMS field in general. Global revenue for MEMS devices in cell phones will increase to $1.3b by 2012, up from projected $1 b in 2011, $ 821 m in 2010 and $299m in 2007. The MEMS-for-cell phone market is expected to be $2 b in 2015.

Compared to accelerometers, gyroscope is a new entry. The gyroscope market is growing fast in a number of application segments. In addition to automotive electronic stability systems and GPS receivers, MEMS gyroscopes took off in the consumer segment around 2007, including computer game controllers (e.g. Nintendo Wii), motion-user interfaces in portable communication devices and image stabilizers in camcorders and digital cameras. Analysts expect the total available market for MEMS gyroscopes to grow from $400 million in 2006 to more than $1.2 billion in 2012.

The price drop is significant, and the application volume increased. A major catalyst for the rise in accelerometer sales is pricing. The price of accelerometers goes below $1 in 2008, making it attractive for a large number of products. Pricing and volume is a chicken-egg problem. **Pricing and volume, which is the chicken and which is the egg?**

A happy marriage between MEMS and CE goes like this: because MEMS is cheap enough, CE vendors starts to incorporate them in units – the units are large volume demand, very well suited for the MEMS industry. In fact, MEMS has a difficult time dealing with small volume and high cost – high volume CE application seems to be a natural fit. The large demand drives down the price, which further make MEMS more suitable, and make more CE vendors and consumer want more MEMS products. On paper, having pressure for unit pricing is not good economics for the MEMS industry. Many MEMS companies would secretly admit they love to make more money per unit. However, the price drop opens new, often unexpected market and in turn grows the field in previously unestablished new application arena.

It is fair to say that the MEMS field and the consumer electronics field is symbiotic – mutually beneficial and growing together.

The dynamics between MEMS chip manufacturers, chip packaging factories, and system manufacturers are blurring. The line between electronics and MEMS is blurring.

Sensors that draw low power and have built-in intelligence will be major trends in future. MEMS Chips are becoming more circuit and computing oriented, whereas IC chips and computers are increasingly becoming MEMS-augmented. In the next five years, the following trends will fully play out:

- MEMS foundries will mature and able to handle large volume production of complex products;

- MEMS will become more intelligent by incorporating growing degree of circuit sophistication;
- On the other hand, integrated circuit companies will start to innovate in the MEMS space.

Section 2: How it works technically

The general idea for a motion sensor is as follows: acceleration or motion create forces, such forces causes displacements of or internal stress concentration in the mechanical structure, and the displacement and/or stress are turned into electrical signals. There are various ways to accomplish the last-stage transduction. However, the need to have three-axis sensors places limitations on candidate transduction methods. (Some techniques that are good for making one axis sensor may not be able to make three axis sensors).

Today, the vast majority of MEMS sensor is based on capacitive sensing – a three dimensional microstructure, consisting of a moving mass suspended by springs, moves under applied acceleration or force. The springs are made of three dimensional beams – precisely defined by photolithography, carved by plasma etching, and released by sacrificial etching.

The microstructure is conductive – it forms capacitors with its neighboring surfaces. Hence when the microstructure structures, the capacitance values change. The changes in capacitance can be measured by electronics circuitry, yielding either analog or digital output values.

The leading companies – Analog Devices, InvenSense, and STMicroelectronics, use different designs and materials for the moving pass and springs. Their methods result in different thickness, geometries, material stress levels, and uniformity.

Below is a comparison of gyro principles and designs for three major companies in this space: STMicroelectronics, InvenSense, and Analog Devices.

Table: Comparison of chip technologies of major MEMS motion sensor companies, as of 2010.

	Analog Devices	STMicroelectronics	InvenSense
Transduction principle	Capacitive sensing	Capacitive sensing	Capacitive sensing
Circuit-MEMS integration	Monolithic integration	Circuit and MEMS on separate chips; Side-by-side packaging	Circuit and MEMS on separate chips; Side-by-side packaging
Proof mass layer material	LPCVD grown polysilicon film	Single crystal silicon	Epitaxial grown silicon
Thickness of mass layer	1-5 micrometer	20 to several hundred micrometer	50 to 30 micrometer

The above description pertains to how the device work. The following discussion is about how the device is made and manufactured. There are three general steps to turn a piece of silicon into a chip that gets soldered on an iPhone board:

- first: on chip processing must be done to make the device on silicon;
- second: the device must be separated, packaged, and encapsulated to form a chip;
- third: the chip must be sent to iPhone manufacturers and gets attached to circuit boards.

MEMS moving mass and springs are made on a silicon wafer. After processing, the wafer must be diced and mounted on an electrical wire frame. Wire leads are formed by bonding – between the chip and the electric wire frame. The prevailing method of packaging involves casting the entire device in a polymer matrix and then cutting the slab of cured polymer into individual chips. Such chips are directly mounted on circuit boards using surface mount techniques.

The moving parts must be protected and encapsulated in a stable environment. The MEMS moving parts must be protected from particles and environmental elements, during dicing, handling, and packaging. The environment typically involves low level vacuum.

The encapsulation is a process that Integrated Circuit manufacturers don't need to be concerned about, since circuits do not contain moving parts and won't be affected by particles, polymer cast, or packaging materials. Circuits are also not vulnerable to pressure and humidity, whereas MEMS devices are. As a result, MEMS packaging and testing often constitute between 30-70% of the overall cost.

Section 3: Analog Devices

Analog Devices was started by Ray Stata in 1965. From 1965 to 1990, the company has been built into a strong business of semiconductor design and manufacturing. The company enjoyed double digit growth. The company was listed in the US stock exchange (Symbol=ADI). However, in 1990, the growth starts to slow, dropping to 10%. ADI, with its specialty in analog devices, was not in the computer chip segment.

In 1987, Analog Devices began to develop a plan for accelerometers. Richie Payne, then working for Analog Devices, starts to develop new business in new areas. They experimented in MEMS technology and began to see its business potentials. Initially, they focus on acceleration sensors for airbag triggering. The then commercial standard is ball-in-a-tube design. A MEMS option could promise reduce the size, reduce the cost, and increase reliability.

The company developed the MEMS technology with a lot of internal resources. Even though the MEMS technology and business model is similar to electronics circuits, the fabrication process is not entirely compatible. Both doing research and fabricating MEMS devices would take up resources the company has for making semiconductor circuits. Besides, there are a lot of uncertainties, including:

- the automotive market is unfamiliar customer for ADI;
- the business model require ADI to mass produce a lot of sensors with small variety;
- manufacturing and quality control present significant challenges.

The automotive market is also very cost and safety conscious. Products that get sold into the automotive market must perform extraordinarily well for very low price. The MEMS fabrication is, on the other hand, capital intensive and costly. Therefore, only a market with large volume can satisfy the business model. However, it is difficult to navigate the growth period. It was difficult to borrow funds and facilities. It was difficult to convince auto makers to bet on a brand new technology. It was not sure how cheaply the company can eventually make it. Therefore, the picture of profitability is not clear at the beginning.

Between 1991-1994, the company sold first batch of sensors to Saab. Richie Payne and team has to propose to the auto makers an aggressively low per-unit price to start. ADI does not make money on the deal. This kind of deal would naturally cause concerns internally in the company, as MEMS division has to compete for resources from other larger, more profitable divisions. In the end, ADI did not make profits until at least 1998.

Despite all the difficulties, ADI should be thankful of its involvement with MEMS technology. Between 2004-2007, ADI posted a 1% compounded annual growth rate in revenues, because its core business (handset baseband, modems inside phone) was becoming a commodity product. In 2008, ADI sold the PC power-management business to **ON Semiconductor** (nasdaq: ONNN - news - people) for $185 million, and the handset baseband business to MediaTek for $350 million. After this reshuffling, ADI is 90% analog circuitry and 10% MEMS. Now ADI looks set to deliver double-digit growth of 13% five-year CAGR.

ADI banked on the surface micromachining technology invented at UC Berkeley (by Roger Howe and Ph.D. advisor Richard Muller). The device is based on surface micromachining process using LPCVD polycrystal silicon as a structural layer and LPCVD oxide as a sacrificial layer. Both materials are commonly used in the semiconductor industry. The polysilicon surface micromachining process allows MEMS parts to be built on top of circuitry (although with a lot of detailed recipe adjustment).

The company had to solve many tough technical issues, including film stress, damping, and control algorithms.

Section 4: The transition era

The growing market of MEMS motion sensors started way before 2006. In fact, transition occurs after 1993. The transition happens mainly as the market shifts from automotive applications to consumer applications (consumer electronics, or CE). For example, laptop computers are subject to fall and potential damages to hard drives – hence accelerometers were capable of detecting an impending fall and stop the spinning hard disks, minimizing damages to the hard drive surfaces and thereby preserving data.

(Interestingly, around 2010, as solid-state drives, SSD, start to become cheaper and bigger in capacity, traditional spinning-disk hard drives are phasing out. As a result, motion sensors for hard drive protection starts to decline.)

A second area of shift is the way MEMS are manufactured. In the past, MEMS manufacturing is done by dedicated manufacturing facilities. For example, Analog Devices use internal resources and facilities to handle manufacturing. However, as the needs to reduce price keeps on mounting for consumer electronics devices, the custom foundry option proves to be increasingly difficult. The semiconductor foundries, lead by the fabless fabrication model, proves to be a great success for reducing the cost of semiconductor electronics. Although the foundry model was never new, the success of TSMC (Taiwan Semiconductor Manufacturing Corp) proved the business model. (TSMC was founded in 1985 by Morris Chang, a 25 year veteran of TI, 1958-85). Naturally, MEMS companies seek to explore compatible fabrication processes with such foundries.

One of the companies that took advantage of this trend is MEMSIC. The company is founded by Dr. Yang Zhao, a veteran of ADI, along with four partners. Yang Zhao and ADI purchased a patent for building accelerometers without moving parts – the acceleration sensing is done with the movement of a heated air pocket. The concept is extremely matched to the foundry model – the entire chip is made just like a circuit. As a result, MEMSIC enjoyed large growth because of its ability to offer low cost products. The failure rate of the device is low, at less than 2 PPM (two per million) device. The company is located both in the US (Andover, MA) and in Wuxi, China. Since Yang Zhao founded the company in November 1999, the company enjoyed rapid growth. Between 2004-2007, the company enjoyed 77% annual growth The company was listed in the US stock market in December 2007. At the time, the company has revenue of 150 million Chinese yuan and profit of 30 million Chinese yuan.

However, such products have much lower frequency response compared with devices with moving mass. It is also difficult to make multi-axis accelerometers using this technology. Although designs are possible, the process is not compatible with the foundry process and, as a result, would not enjoy as much financial advantage.

Section 5: The InvenSense Story

InvenSense is a company based on the vision of one person – Steven Nasiri, a veteran of the MEMS industry. He came to the United States from Iran in 1974 and completed a BS degree from UC Berkeley. He has been involved with many MEMS sensors companies as cofounders or executives, including SenSym (Honeywell), NovaSensor (GE), Integrated Sensor Solutions (TI), and ISS Nagano. He was hired by Nova Sensors, founded by Kurt Petersen, Janusz Bredzyk and Joseph Lemon (a veteran of Kulite), to manage the manufacturing process. He also held key management and operations positions at several semiconductor companies, including National Semiconductor, Fairchild Semiconductor and Maxim Integrated Products.

Mr. Nasiri founded InvenSense from his home in early 2003 and received the company's first funding in April of 2004. It is said that he spent close to one year focused on the unique MEMS fabrication platform and its gyroscope feasibility study. 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.

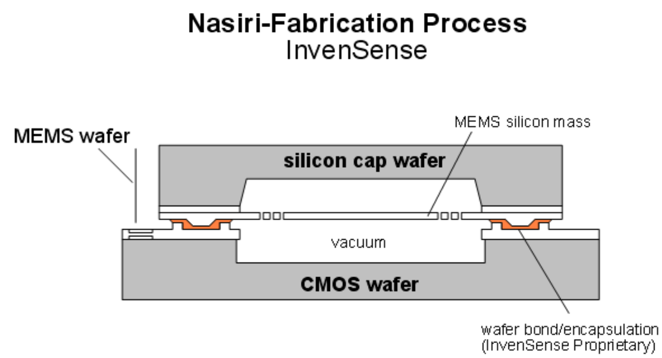


Figure 2: The Nasiri-Fabrication Process for InvenSense Gyroscope.

Nasiri's philosophy is to only start something if it has the potential to be the first of its kind in the world. Nasiri's deep entrepreneurial spirit drives him to be both strategic and hands-on. He takes the time to understand the details of a problem and remains in the trenches to help work toward the optimal resolution. He won the Ernst & Young Entrepreneur of the Year 2010 Award Recipient in Northern California

Section 6. Sensor Fusion

Nintendo Wii is the first to use motion processing seriously in games. Since the beginning, a 1:1 motion control was not possible with accelerometer sensors only. Nintendo thought to a combination between tri-axial accelerometer and multi-axis gyroscope for the wiimote in order to improve playability. Indeed, sensor fusion is the preferred solution for increasing accuracy. Such a use of gyroscope and accelerometer sensors became obvious for Nintendo's engineers. The Wii MotionPlus accessory is based on IDG 600(Invensense) dual axis gyroscope sensor and X3500W (EPSON) single-axis gyroscope sensor.

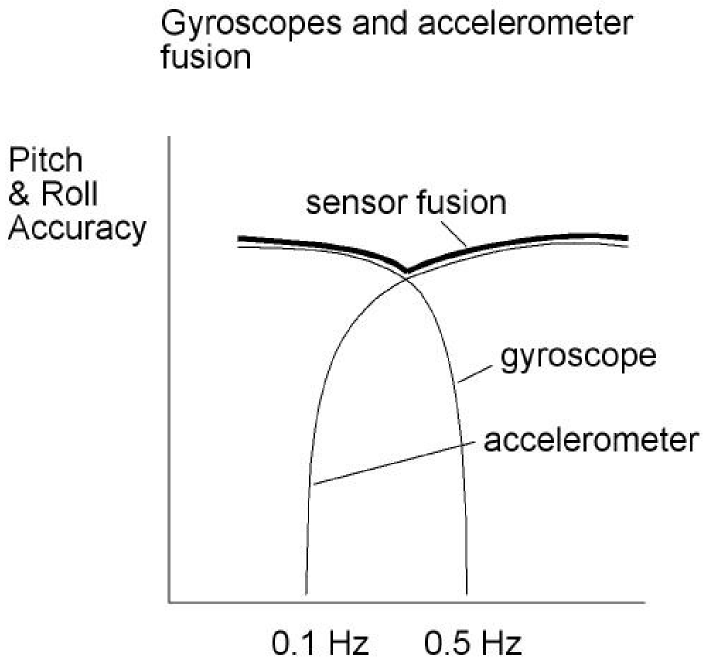


Figure 3: Pitch and roll accuracy with different types of motion sensors. (Source)

The Apple iPhone is said to use nine axis motion sensing. In the future, more axis of sensors may be integrated closely together to satisfy form factor and pricing targets.

Section 7: The STMicroelectronics Story

ST Microelectronics is an Italian-French company based on the 1987 merger between two companies: SGS Microelettronica of Italy and Thomson Semiconducteurs of France. ST Microelectronics is the fifth largest semiconductor company in the world, with MEMS revenue of approximately $450m in 2008 (accelerometers, pressure sensors, ink jet printer heads). In 2008, accelerometers account for $220M, eclipsing its own accelerometer revenue of $27M in 2007. This helps STMicroelectronics gain a market share of 20% in 2008, up from 4% in 2006.

The company has many product lines, including Integrated circuits for specific applications, Memories (flash, EEPROM), Microcontrollers, smartcards, analog circuits power ICs. The company's revenue in 2009 is $8.51B (billion). In 2005, it earns revenue of $8.87B with profit of $ 266M.

The company's stock is trades at the New York Stock Exchange, Euronext, and the Italian stock exchange Borca Italiana (BIT) under symbol STM. The company owns a network of design centers, front end processing (wafer), and back end processing (assembly). The Agrate facility near Milan, Italy has 8 inch fab facility, whereas the Grenoble, France site has up to 12 inch facilty.

STMicro is a relative late coming in the field of motion sensors. It entered the MEMS market in 2001. By 2005, the company was earning $3M in MEMS business annually. In November 2006, STMicroelectronics inaugurated a new state-of-the-art 200mm (8-inch) semiconductor wafer fabrication line at Agrate, in the Milan area, dedicated to MEMS devices. This is a bold move, requiring investment on the order of $50M. Benedetto Vigna, General manager of MEMS and Sensors division at STM, made a huge bet. He even invested his own money to convince the STM management to agree with his vision. This bold move allows STM to be prepared for the revolution of CE sensors before other rivals. In doing so, Mr. Vigna made two important decisions: (1) not to "wait and see"; (2) not to outsource fabrication to foundries in the famous Fabless model.

The STMicro company entered the Gyro market in June 2008 to target the growing consumer electronics (CE) market. The company has been on a rapid pace – it announced single-axis gyro in 2008, two axis gyro in June 2009, and three axis digital gyro (L32G4200D) on February 15, 2010. The L32G4200D is a revolutionary device. It provides angular rate measurement in three axis, using a *single sensing element*. The entire chip, including both MEMS and ASIC, is housed in a package of 4 mm by 4 mm by 2 mm. ST's 3-axis digital gyroscope offers a wide set of user-programmable full-scale ranges from ±250 dps up to ±2000 dps, with the low full-scale values for high accuracy of slow-motion sensing and the high range to detect and measure very fast gestures and movements. The device provides a 16-bit data output, together with additional embedded digital features, such as configurable low- and high-pass filters, and boasts excellent output stability over time and temperature.

The L3G4200D 3-axis MEMS gyroscope with digital output has been designed and produced using the same manufacturing-process technology that ST has already successfully applied to more than 600 million motion sensors sold in the market. Volume production began in Q2 2010 and the unit price is $2.9 in quantities greater than 200,000 pieces.

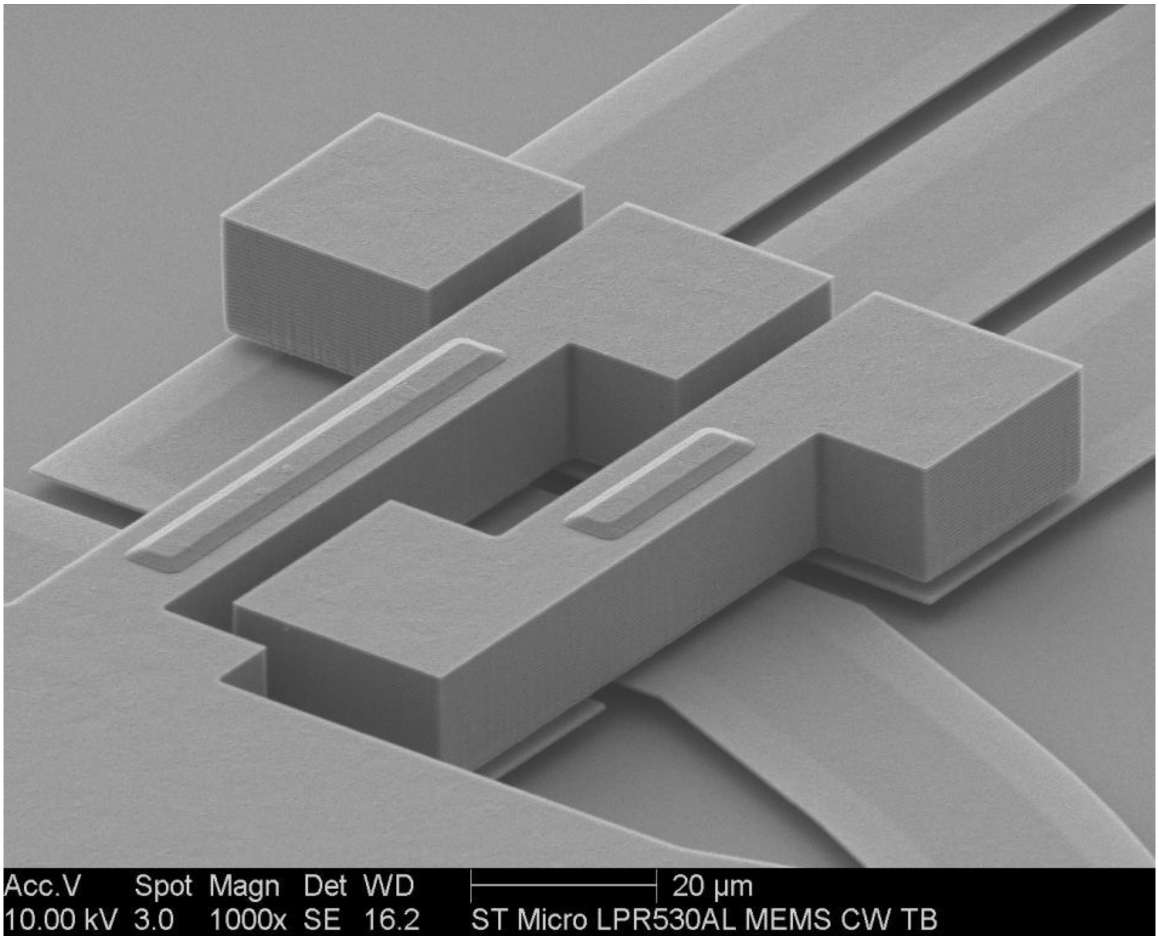
What contributed to STM's success include at least the following factors:

1. An earlier bold bet to invest in 8" wafer technology for MEMS, before market starts to establish. The 8" line allows STM to lower cost, good for CE applications.
2. The STM gyro is based on a novel design utilizing a single element, therefore reducing the dimensions of chips. Small form factor is really important for CE.

The STMicroelectronics company uses a process called THELMA: Thick Epi-Poly Layer for Microactuators and Accelerometers. A thick layer of polysilicon is grown on top of silicon oxide sacrificial layers. Since the thickness is large, it is etched using the deep reactive ion etching process (DRIE). The thickness allows the capacitors to have large values and hence greater sensitivity.

The device is encapsulated at a wafer level with frit glass seal. Since the gyros are vibratory devices that must operate near vacuum, remaining gas molecules are absorbed with a SAES Getter material (provided by SAES Getters Group).

Figure 4: SEM Micrograph of STMicroelectronics L3G4200D Gyroscope mechanical structure.



Summary

What do we learn from this?

- Industry evolve rapidly and it takes tremendous efforts and innovation to stay at the front;
- Technical superiority is not enough to make an innovation successful;
- The success of products are always behind visionary individuals and bold, persistent moves;
- The MEMS motion sensor business will continue to be exciting and competitive for a long future to come.

Reference:

Patrick L. Walter, "The History of the Accelerometer – 1920-1996", Sound and Vibration, www.SandV.com, 84-92, 2007. (PLW is a Professor with Texas Christian University, Ft. Worth, Texas). His email is p.walter@tcu.edu.