# International
# Technology Roadmap
# for
# Semiconductors

## 2013 Edition

# Micro-Electro-Mechanical Systems
# (MEMS)

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## MICRO-ELECTRO-MECHANICAL SYSTEMS (MEMS)

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# MICROELECTROMECHANICAL SYSTEMS (MEMS)

"*One of the indispensable tools for all of the doctors in the Star Trek universe is the tricorder - a handheld device equipped with sensors that allowed Doctors to noninvasively scan their patients, providing instant results on blood characteristics, vital signs, and other tests that can take hours or days today. This enables Starfleet medical personnel to develop diagnoses and cures as quickly as the plot will allow.*"

-- *X PRIZE and Qualcomm Announce $10 Million Tricorder Prize*

## 1 SCOPE

Micro-Electro-Mechanical Systems (MEMS) are mechanical sensors and actuators that are fabricated using techniques similar to those used for integrated circuits [1]. They are micrometer-sized mechanical structures, such as cantilevers, combs, membranes, and channels that are often integrated with logic circuitry. MEMS can act as sensors, receiving information from their environment, or as actuators, responding to a decision from the control system to change the environment.

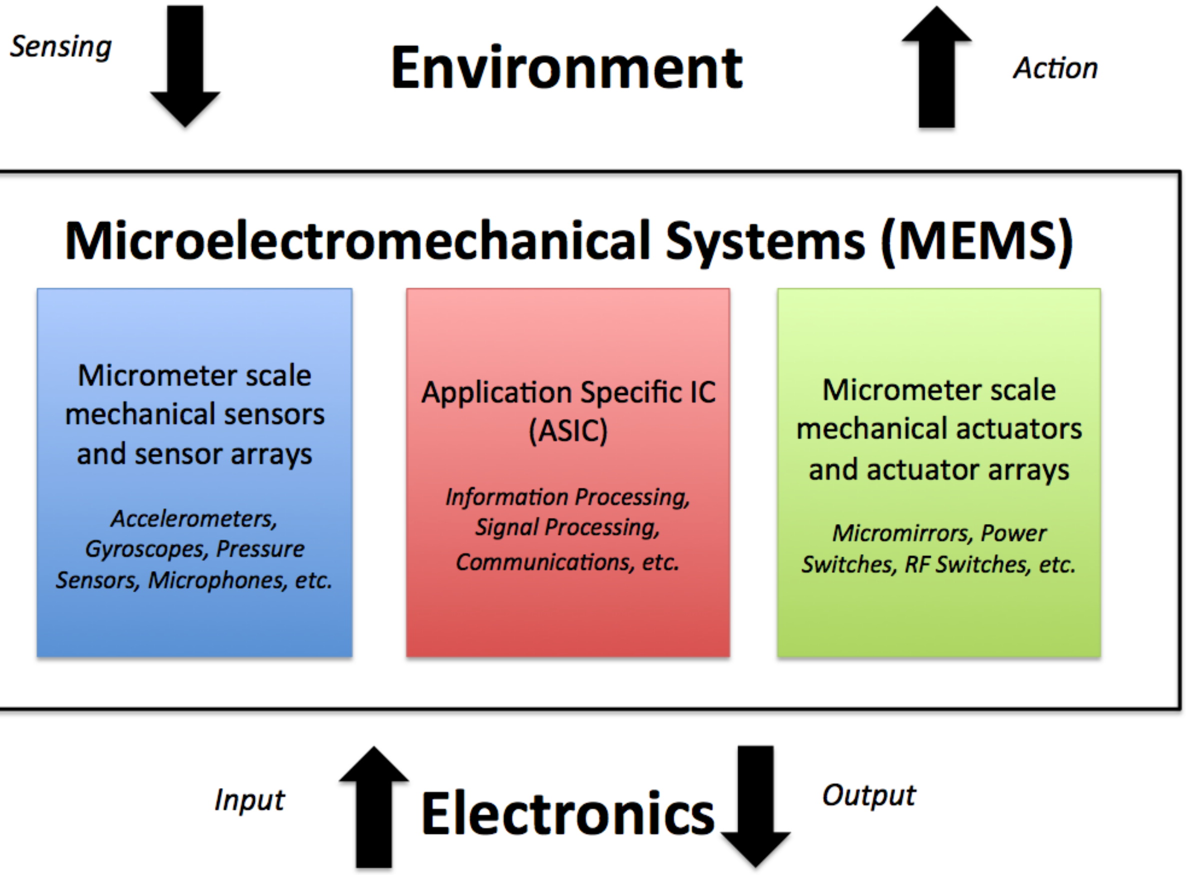


*Figure MEMS1 Diagram of the functionality of a MEMS device.*

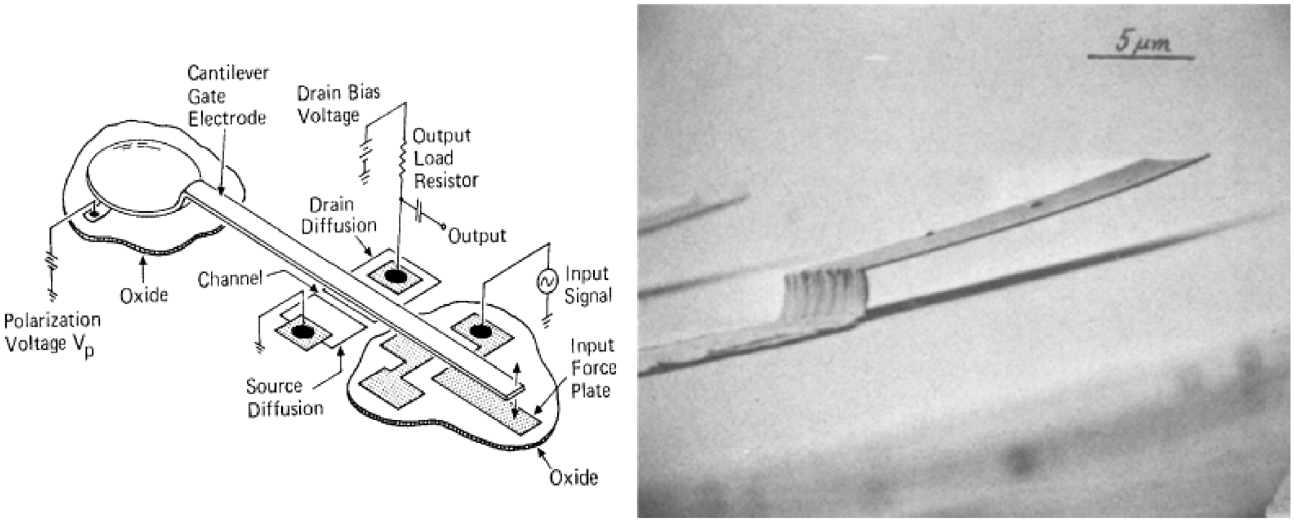


*Figure MEMS2 The resonant gate transistor reported by Nathanson et. al. in 1964 [6] (left) and the polysilicon cantilever reported by Howe and Muller in 1993 [7] (right).*

A MEMS device typically contains a microelectromechanical sensor or actuator element packaged together with an integrated circuit (IC). The IC provides an electrical interface to the sensor or actuator, signal processing / compensation, and an analog or digital output. The microelectromechanical sensor or actuator can be integrated monolithically or co-integrated with the IC. Monolithic integration refers to a MEMS device that is integrated on the IC chip, while co-integration refers to a MEMS device that is on a separate chip and packaged with the IC.

Most of today's applications of MEMS are found in automobiles, video projectors, and in the rapidly growing portable consumer electronics market. The consumers' desire for higher functionality has increased demand from electronic systems integrators for MEMS devices with higher performance, lower cost, new functions, and integration of multiple sensor functions. The MEMS device manufacturers are responding to this demand by integrating tri-axis accelerometers with gyroscopes and magnetometers (electronic compass), developing new device technologies, and advancing signal processing and communications interfaces.

## 1.1 HISTORY

Microelectromechanical Systems (MEMS) technology is often said to have been inspired by Richard Feynman. In his 1959 lecture entitled "There's plenty of room at the bottom" [2], Feynman spoke of the great opportunity of "manipulating and controlling things on a small scale." Later, Feynman also spoke on the topic of "Infinitesimal Machinery" [3] and using "evaporation" and photolithographic processes for making tiny machines. His vision and foresight was an inspiration to developers in the field.

The miniaturization of electromechanical devices composed of suspended membranes and movable structures appeared in the 60's [4] and further developed in the 70's [5] based on the "bulk" micromachining method, which released the elements by chemically etching the silicon substrate material.

In 1964, Harvey Nathanson from Westinghouse developed what most consider as the first batch fabricated surface micromachined MEMS device, called the resonant gate transistor [6] (see Figure MEMS2). It consisted of a metal cantilever used as a MOS transistor gate whose gap could be varied by an input signal. The material of choice for surface micromachined MEMS, demonstrated by Howe and Muller in the early 80's [7], became polysilicon. Surface micromachining consists of depositing a sacrificial layer of material on top of a substrate, followed by depositing and patterning a structural layer over it. The last step of the process is chemically etching (removing) the sacrificial layer away to leave a freestanding structural layer. This technique is one that is used predominately for commercial MEMS fabrication.

In 1982, Kurt E. Petersen published a landmark paper in the field entitled: Silicon as a Mechanical Material [8] where he foresaw a very promising future for silicon as a structural material for the fabrication of microelectromechanical systems.

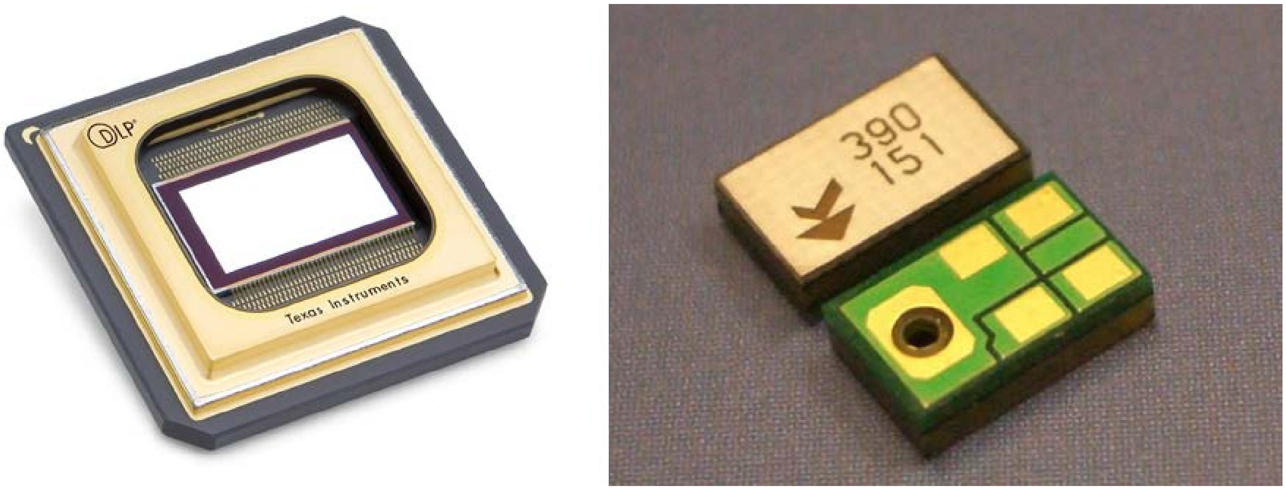


*Figure MEMS3 The digital light projector (DLP) by Texas Instruments used in video projectors (left) and the Knowles MEMS microphone used in smart phones and tablet computers (right).*

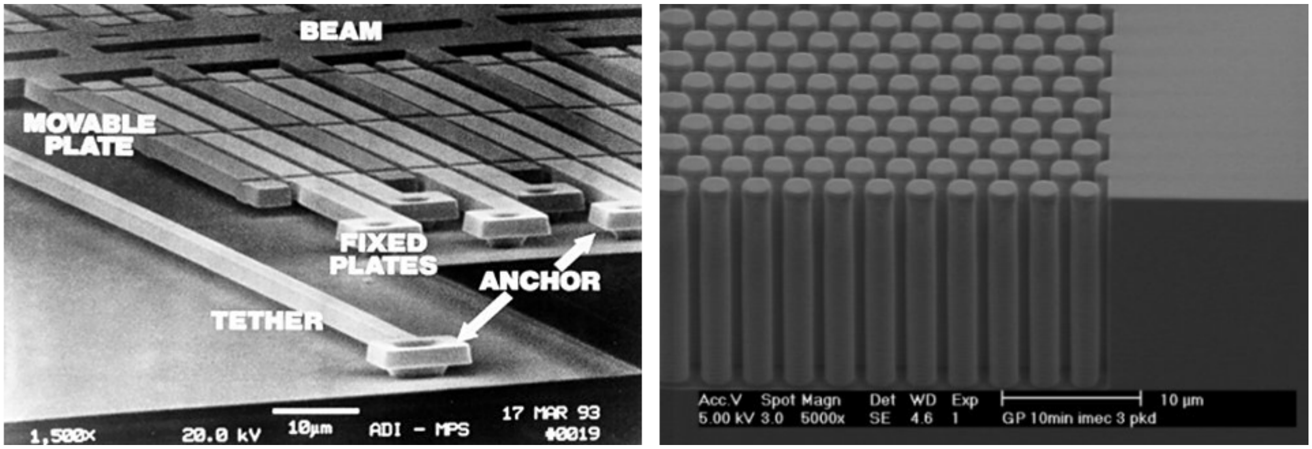


*Figure MEMS4 Analog Devices ADXL 50 from 1993 (left), fabricated by surface micromachining, and pillars in silicon for a micro fluidic device fabricated at IMEC using the deep reactive ion etch Bosch process (right).*

In 1993, Analog Devices was the first MEMS device manufacturer to produce a surface micromachined accelerometer in high volume (see Figure MEMS4a). The ADXL50 was used in automobiles for collision sensing and deployment of airbags. It sold for $5 at the time of its introduction, which was substantially less compared to the technology in use.

In 1994 Bosch patented the so-called “Bosch Process” for deep reactive ion etching of silicon (see Figure MEMS4b). This process is the predominate method for the fabrication MEMS with features thicker than a few micrometers, called high aspect ratio MEMS. This method is also ubiquitously used for MEMS manufacturing, and for fabrication of through silicon vias (TSVs) used for 3-D stacking of memory chips in semiconductor manufacturing.

The year 1998 marked the premiere of the movie Star Wars: Episode I - The Phantom Menace shown using the DLP (digital light projector) technology from TI (see Figure MEMS3a). This MEMS technology plays an important role in the MEMS market and is used for video presentations, home theaters, and movie theaters.

In the last 10 years, MEMS have been becoming increasingly important in our daily lives. They are present in automobiles, consumer electronic devices (smartphones, video game devices, etc.) and emerging consumer medical applications. They attribute more than 60% of semiconductor sensor revenue – ICs built together with MEMS sensors (IC insight’s “MEMS 2010” report).

## 1.2 ROADMAPPING MEMS TECHNOLOGY

In 1965 Gordon Moore wrote [9] that: "The complexity for minimum component costs has increased at a rate of roughly a factor of two per year. Certainly over the short term this rate can be expected to continue, if not to increase." This trend, which is referred to as "Moore's Law," has been the predominate path for technology roadmapping used by the semiconductor industry's International Technology Roadmap for Semiconductors (ITRS). However, a growing trend in manufacturing summarized in an article by Tummala entitled "Moore's Law Meets Its Match" [10], concerns the integration of functional diversity into chips. This path of integration is now commonly referred to as More-than-Moore.

The ITRS engaged in discussions concerning how a formal roadmap should be constructed according to the More-than-Moore trend, and published a More-than-Moore White Paper [11]. In it a set of minimum requirements was developed that should be met in order for technology roadmapping to be viable. These requirements were defined in the More-than-Moore White Paper as:

- A restricted set of figures of merit,
- An existence of a community of players,
- A willingness to share information,
- A potential market of significant size inducing a wide applicability of the roadmap,
- A convergence of opinion among a majority of the key players on the progress trends that these figures of merit are expected to follow.

Many of these requirements were already ripening in the MEMS industry. Founded in 2001, the MEMS Industry Group (www.memsindustrygroup.org) is the trade association advancing MEMS across global markets. Through conferences, workshops, and collaborative projects (both online and in person), MIG brings together the MEMS supply chain, in a neutral forum to address critical challenges to MEMS commercialization. MIG works to accomplish this mission by enabling the exchange of non-proprietary information among members; providing access to reliable industry data that furthers the development of MEMS technology and promoting the greater commercial development and use of MEMS and MEMS-enabled devices.

During its May 2010 technical members' meeting, MIG's members recognized a growing industry concern over the rising

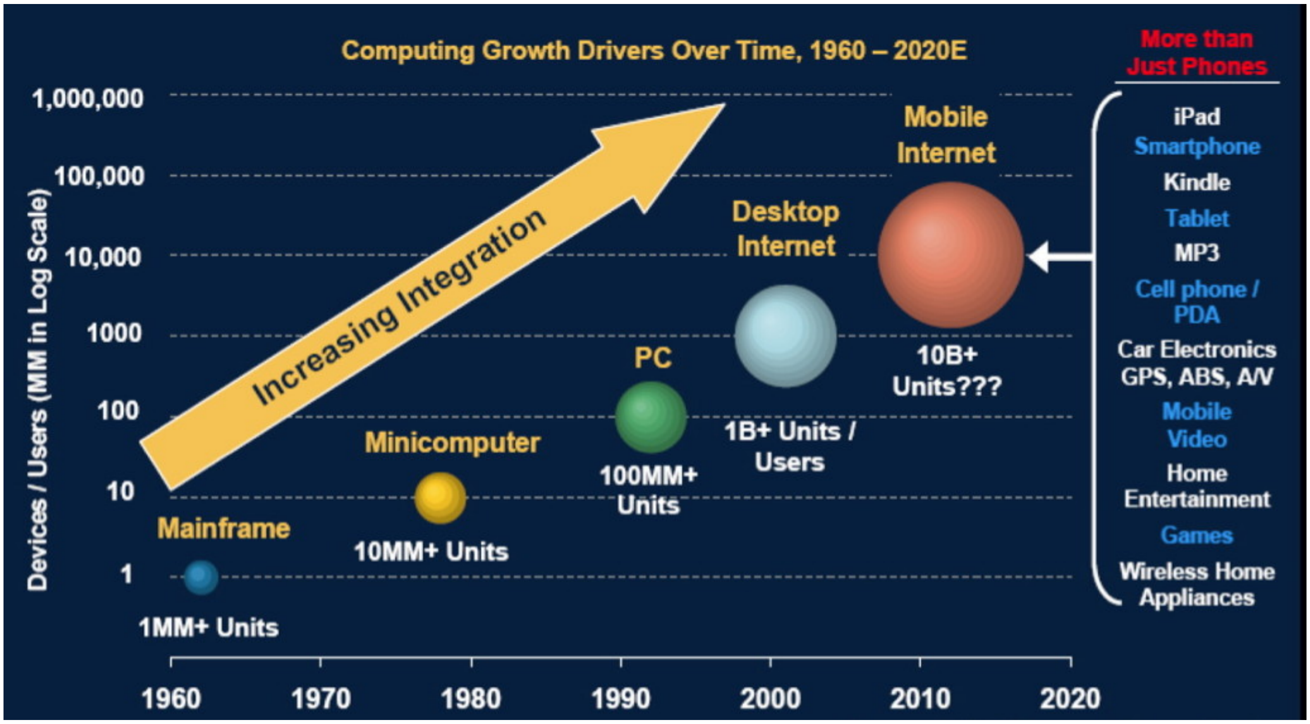


*Figure MEMS5 Illustration of the time evolution of the computer from mainframe, mini, PC, laptop, to the present era of mobile Internet. Each step has an accompanying exponential growth in the number of units manufactured and sold (Source: 2009 Morgan Stanley Estimates).*

cost of device testing and concluded that the lack of testing standardization was increasing the time and cost of MEMS innovation. The percentage of testing a device was calculated to be between 20 and 50% of the total device cost, with most complex and promising devices having the highest test costs. This realization led MIG to partner with NIST to organize a workshop in March of 2011 on MEMS Device Testing Standards. The outcome was a report entitled MEMS Testing Standards, A Path to Continued Innovation [12].

The rising cost of device testing was becoming an industry-wide issue that brought together the companies to understand and to find ways to solve a common problem.

MEMS technology was also being recognized as a market of significant size. MEMS device manufacturing was forecasted to grow rapidly in consumer electronics-related applications. iSuppli had forecasted growth of almost 30% compounded annually [13] in smart phones and tablet computers.

In the time between the MIG spring 2010 and 2011 member workshops an iNEMI MEMS Technology Working Group (TWG) was established (summer of 2010) and tasked to develop a new MEMS Chapter for the 2011 iNEMI Roadmap. The MEMS TWG completed its work and submitted the MEMS/Sensors Chapter in November of 2010. Following this, the MEMS TWG proposed to the ITRS's International Roadmapping Committee (IRC) to develop a joint iNEMI/ITRS MEMS Roadmap following a model for the iNEMI/ITRS Packaging TWG. This proposal was accepted by the ITRS as a pilot program and then ratified the following spring.

A major challenge to roadmapping MEMS technology has been the diversity of applications for MEMS, which include pressure sensors, ink jet printer cartridges, accelerometers, digital light projectors, bolometers, gas sensors, surgical tools, microphones, portable medical diagnostic systems, and more. Furthermore, manufacturers had risen from a long history of this one-device one-application paradigm where each device had a unique design and a unique manufacturing process. In contrast, the ITRS brand has a specific focus: roadmapping the technological growth of the microprocessor and memory. Though there had been much thought within the ITRS on the evolution of Moore's Law to include More-than-Moore functional diversity, there were still many questions concerning how this would be accomplished for a technology as diverse as MEMS.

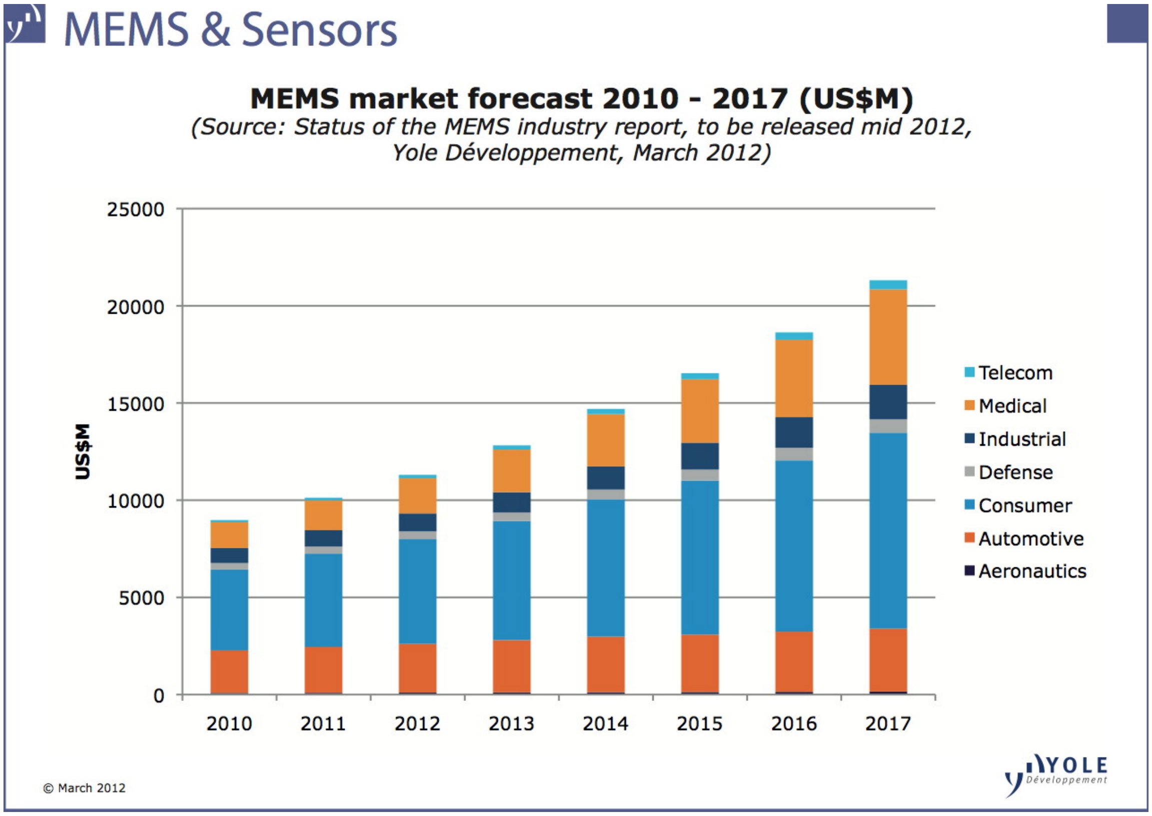


*Figure MEMS6 Bar chart depicting the growth of the MEMS market and separated by market segment. Source: Yole Development Status of the MEMS Industry presented at MEMS Industry Group's M2M Forum May 8-10, 2012, Pittsburg PA.*

The MEMS TWG chose to align its effort towards MEMS technologies associated with “mobile internet devices.” The thinking behind this strategic focus is well exemplified in Figure MEMS5, which graphically depicts the evolution of the computer from mainframe to mini, PC, desktop, and the new mobile Internet devices. This choice in strategic focus is further supported by studies by Yole Development [14] (see Figure MEMS6) reporting that the largest segment of growth in MEMS manufacturing is aligned with mobile internet devices. The ITRS is well known for roadmapping the semiconductor technologies associated with the evolution of the computer, so the adoption of this strategic focus for the MEMS TWG’s roadmapping effort was a key to reaching the buy-in, both within the ITRS and with the MEMS industry, for moving forward.

## 1.3 MEMS MARKETS

MEMS devices are integrated into larger systems, such as automobiles, video projectors, smart phones, and game controllers. In most cases the MEMS devices add useful functionality to the system, and in some cases the MEMS devices enable the core functionality of the system. MEMS accelerometers used in smart phones sense the vertical orientation of the phone to rotate the image on the display. The added functionality simplifies the user interface, but the phone can still operate without it. In contrast, a video projector using Digital Light Projector (DLP) technology and an inkjet printer could not function without their MEMS devices.

The growth of the MEMS market in the 1990’s was dominated by automotive applications. However, the introduction of MEMS technology into game controllers and smart phones in the last decade shifted the market toward consumer electronics applications. The MEMS devices in consumer applications were primarily accelerometers and microphones, but soon gyroscopes (angular rate sensors) and magnetometers (electronic compass) followed. A market forecast by Yole Development entitled “Status of the MEMS Industry” was published in 2012 [14]. Figure 6 summarizes the results of this study, revealing the top three MEMS applications, in order of the market segment, are consumer, automotive, and

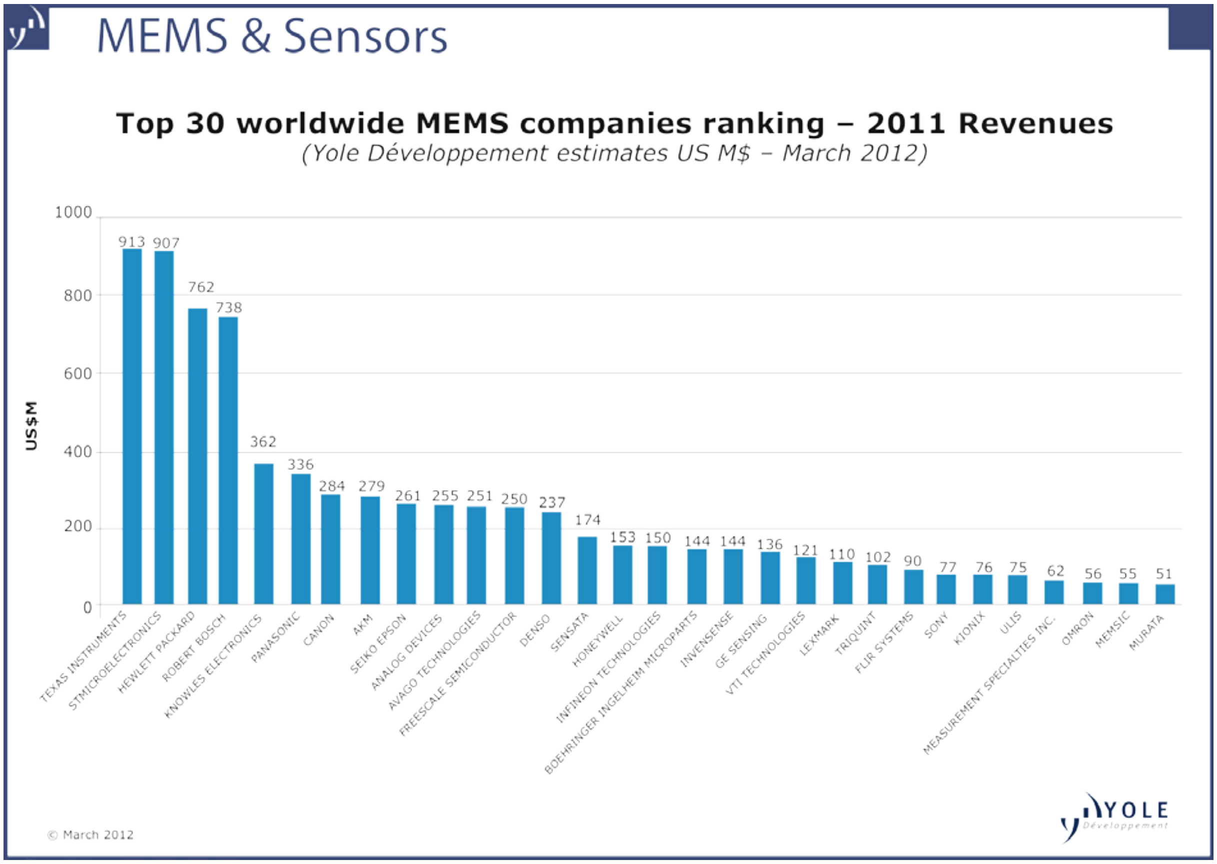


*Figure MEMS7 Bar chart of the 30 top worldwide MEMS companies in order of 2011 revenues. Source: Yole Development Status of the MEMS Industry presented at MEMS Industry Group’s M2M Forum May 8-10, 2012, Pittsburg PA.*

medical.

## 1.4 MAJOR MANUFACTURERS

The top 30 worldwide MEMS device manufactures are shown in Figure MEMS7, and ranked in terms of 2011 revenues. The top four manufacturers are listed as Texas Instruments (digital light projectors), ST Microelectronics (smart phone inertial sensors), Hewlett Packard (ink jet printer cartridges), and Bosch (automotive sensors), produce approximately 43% of the revenues out of the list of the 30 companies listed.

## 1.5 APPLICATIONS

The MEMS Technology Working Group's focus has been on consumer portable, MEMS devices used in gaming, smart phones and tablet computers. We expand our discussions in this 2013 update to include automotive and the emerging market of consumer medical. Each of these applications has different requirements for the MEMS devices. In automotive applications, for example, the airbag sensors are life critical, requiring a high reliability of the MEMS devices. The main driver in consumer applications is low cost. These applications are more tolerant to lower performance and reliability.

### 1.5.1 AUTOMOTIVE

As automobiles become more complex, signal processing technologies are increasingly being used to create the automobile of the future. We are asking a lot from our cars; adapt to changes in driving conditions, provide driving directions, keep in touch with the office and family members, and provide quality audio and video entertainment—all while providing more safety and running more efficiently than ever before. No easy task.

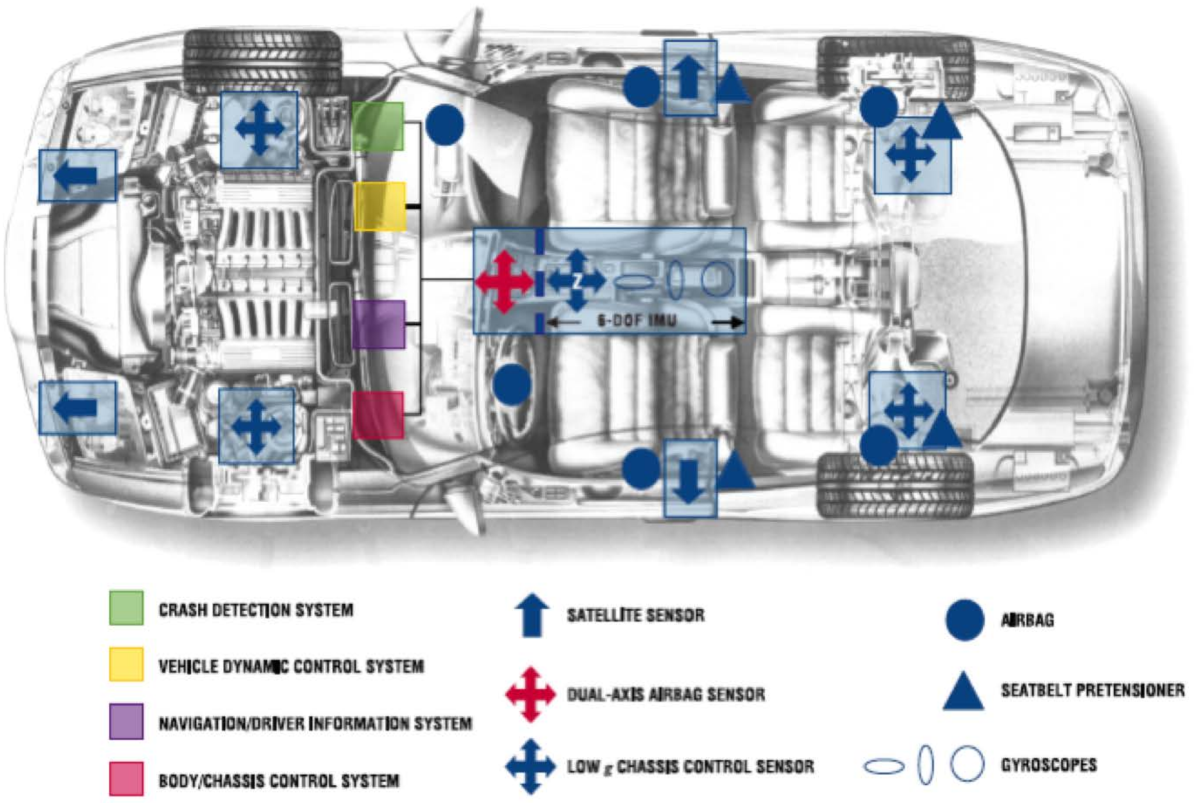


*Figure MEMS8 illustrates the many inertial sensors used in a fully featured car today. In some cases, there are up to 15 axes of inertial sensors (accelerometer and gyro) used. As there are only six possible degrees of mechanical freedom, it is obvious that many of these sensors are redundant. We have arrived at this situation because historically each system has been purchased from different suppliers. But today the concept of a cluster of inertial sensors sending their information to whatever system needs it is becoming the goal of many automotive OEMs. Can you say "Plug and Play"?*

No part of the car exemplifies this more than its safety systems. While most of us know that cars today use MEMS accelerometers to sense rapid deceleration for airbag deployment, what we may not appreciate is MEMS inertial sensor technology is continually evolving and has found many other safety and convenience applications in automobiles beyond airbag systems.

The most common application beyond airbag systems is the almost ubiquitous Automatic Braking System (ABS). Until very recently, most ABS systems did not use an inertial sensor. They simply read wheel speed and apply pulsed braking if the wheels are thought to be skidding. However, most all-wheel-drive systems and some newer high performance ABS systems, look at longitudinal acceleration to determine if the chassis is still moving. This is particularly important for all-wheel-drive equipped vehicles where all four wheels may have lost traction due to the application of drive torque.

The most important performance parameter MEMS accelerometers were able to address for ABS is zero g bias and sensitivity stability. In general it is assumed that the minimum available deceleration force available (even on slippery surfaces) will be about 100mg (0.98m/s2). So the combination of zero g bias drift and sensitivity variation must not vary more than 100mg over the automotive temperature range. MEMS accelerometers with a typical zero g bias stability of 16mg and sensitivity drift of 0.3% over the automotive temperature range are ideal for this application.

Electronic Stability Control is another application for MEMS sensors that assists the driver in regaining control of the automobile just as it is starting to skid. An ESC system uses a yaw rate sensor (or MEMS gyroscope), a low g MEMS accelerometer, wheel speed sensors (which may also be used by the ABS system) and steering wheel angle input. Wheel speed from each wheel is measured, and the predicted yaw (or turn) rate of the car is compared to that measured by the gyroscope and the intentions of the driver (as predicted by the steering wheel angle). A low g accelerometer is also used to determine if the car is sliding laterally. If the measured yaw rate differs from the computed yaw rate, or lateral sliding is detected, single wheel braking or torque reduction can be used to make the car “get back in line”.

ESC systems require a yaw rate sensor with fairly low noise (typically less than 0.5 degrees/sec) and low sensitivity to mechanical vibration. Just as in ABS, the accelerometer must be very stable over temperature, as small amounts of lateral acceleration must be measured. MEMS gyros and accelerometers have surpassed other technologies on these performance requirements.

Roll over detection systems employ a roll rate sensor to read the roll rate. The roll rate is integrated to determine the roll angle of the vehicle. An accelerometer reading vertical acceleration (Z axis) is also required as large roll angles may be encountered in banked curves with no possibility of roll over. Better roll over detection systems also use another accelerometer to measure lateral acceleration as a vehicle striking a curb or other object while sliding sideways is much more likely to roll over.

MEMS Gyros used for roll over sensing do not require the same resolution as those used in ESC systems, but they must have excellent rejection of external shock and vibration and have a larger dynamic range. MEMS gyroscopes are now commonly used in this application because of their insensitivity to external shock and vibration.

### 1.5.2 CONSUMER PORTABLE

This report considers consumer portable devices to be computer systems or peripherals that incorporate MEMS technology; to enable and enhance their mobile use. These applications signify the next step in the evolution of computers, which started with the mainframe, and evolved to mini computers, desktop computers, laptop computers, and finally the smart phones and tablet computers. The trend into mobility frees us from the desk and allows us to move into the world while staying connected with each other and with information systems.

The release of the Nintendo Wii in November 2006 can be considered to mark the beginning of consumer portable MEMS device applications. The Wii wireless controller incorporated a 3-axis MEMS accelerometer that determined motion and position of the controller (Figure MEMS10, top right [15]), bringing a new dimension to game playing applications. The remote allows the user to interact with the console using gestures and by pointing at the screen. The accelerometer and optical sensor that are built into the remote enable this functionality.

Apple introduced the iPhone in June 2007. Analogous to how the Wii remote revolutionized gaming, the iPhone can be considered to have revolutionized mobile phones. The iPhone advanced the functionality of mobile telephones by providing a more advanced graphical user interface with Internet browsing and email, among other things. The MEMS accelerometer technology detected the direction of gravity, which enabled the display to rotate so that it was always kept upright, and also provided an interface to game applications that could be purchased from the "app store."

The MEMS technologies introduced into these applications gained rapid consumer acceptance, evidenced by their rapid growth in sales. Figure MEMS10, top left, shows relatively flat sales of Nintendo gaming consoles until the introduction of the Wii [16]. Figure MEMS10, lower left, shows Apple sales for iPhones exceeded revenues for their other product offerings within two years of its introduction [17]. The MEMS technologies that supported these consumer portable applications did not require the same levels of accuracy and reliability as the automotive applications from which the technologies evolved. The primary drivers for these applications were cost, size, and low power dissipation.

Another significant component of the consumer MEMS evolution was in the area of packaging. Previous MEMS products, mostly automotive sensors, had a cost structure that allowed the use of mechanically robust, open cavity packages, such as ceramic DIP packages. The benefit of such packages was that the MEMS device could be mounted in an elastically isolated way, decoupling it from package induced stresses. However, such package technologies were much too expensive for the consumer market. Methods for using low cost, plastic packages were required to meet cost targets.

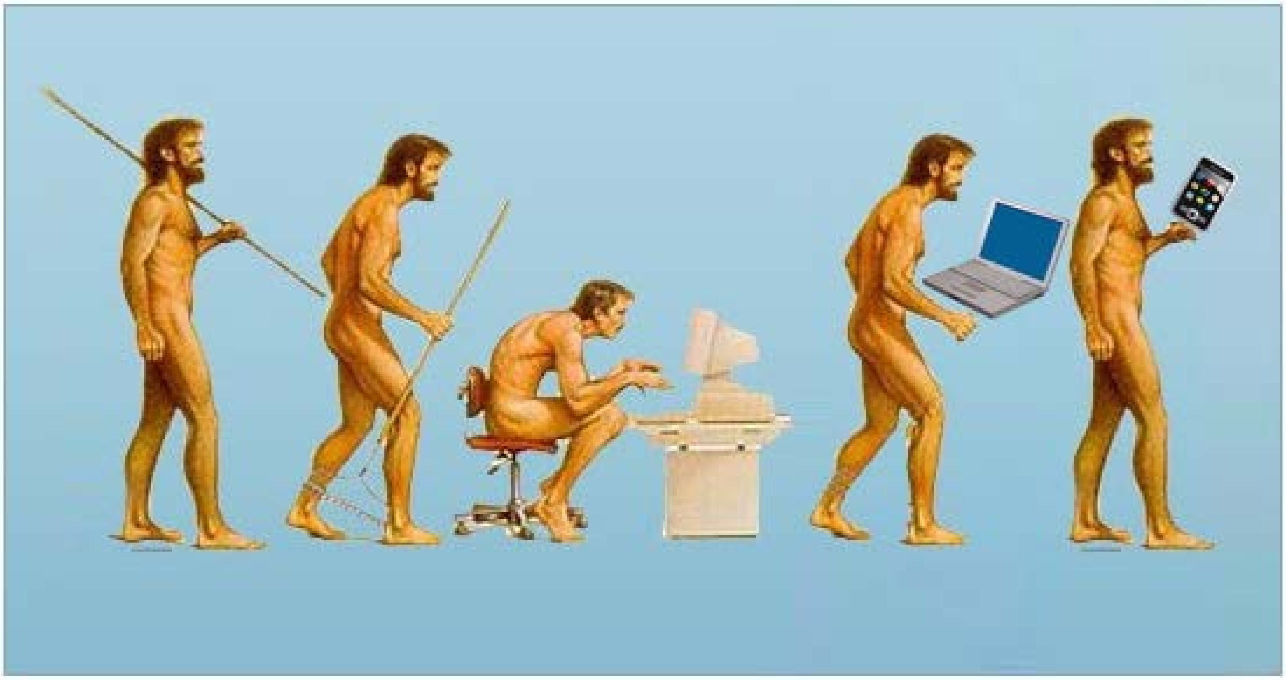


*Figure MEMS9 Illustration depicting how consumer portable devices free us from the desk, allowing us to interact with the world while still remaining connected with each other and the Internet.*

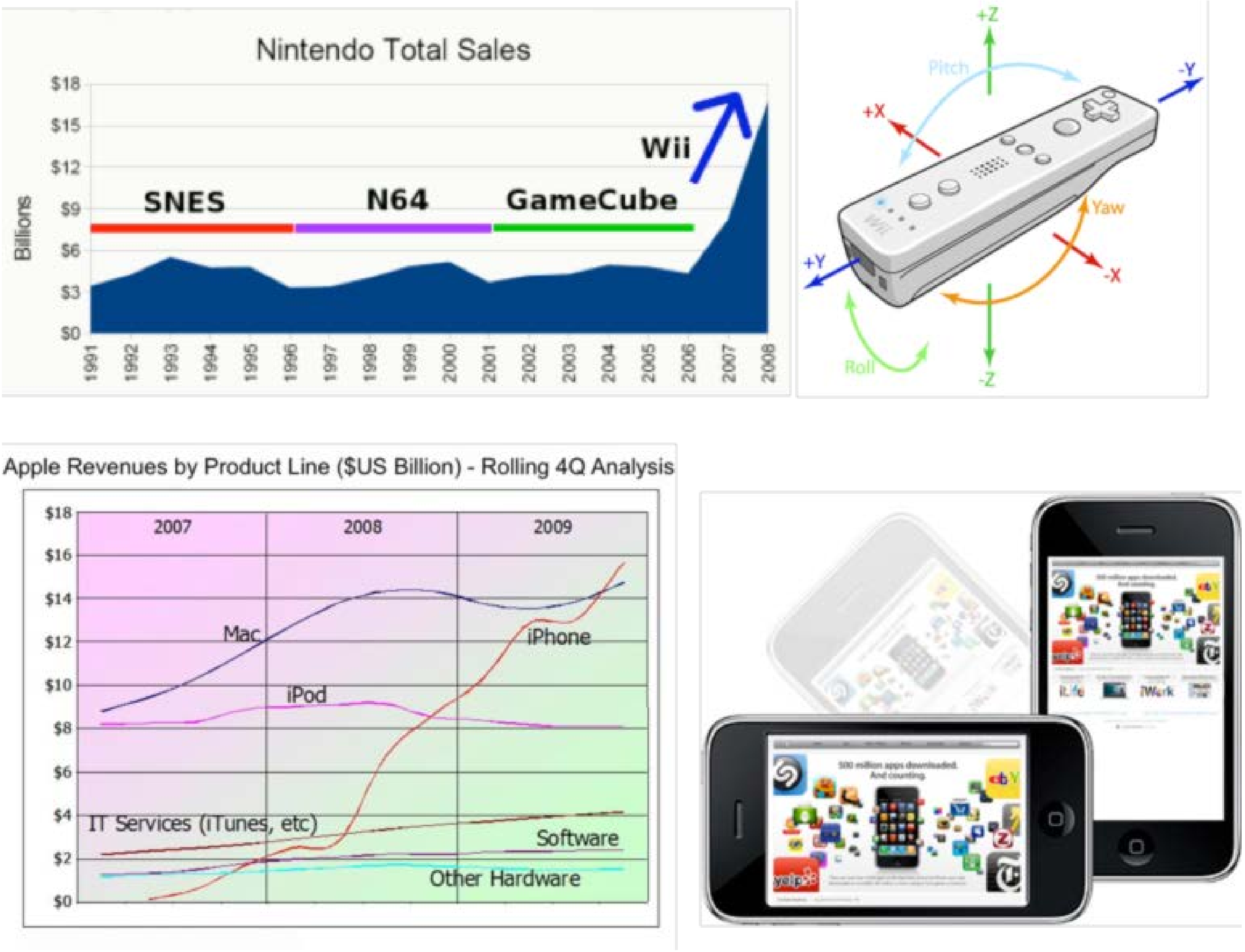


*Figure MEMS10 Nintendo's annual revenue from 1991 to 2008 (top left) revealing the explosive impact of Wii sales. The Wii wireless remote (top right), which incorporated a 3-axis accelerometer to sense displacement and rotation. Apple's revenues by product line are shown (bottom left). The functionality enabled by MEMS accelerometers to maintain an upright display is illustrated (bottom right). Source: http://www.straferight.com, http://www.osculator.net/, http://itcandor.net/2010/02/01/apple-results-q409/, http://askiphone.net/locking-your-iphone-screen-in-portrait-vertical-orientation/*

This lead to technologies for capping the MEMS device, to allow plastic over-molding and the development of sophisticated die attach and stress relief methods.

Figure MEMS11, presented by Len Sheynblat, Vice President of Technology, Qualcomm CDMS Technologies, at MIG's M2M 2012 Forum [18], lists current and future sensor technologies in handsets. The listing includes devices currently used, such as accelerometers, gyroscopes, magnetometers (compass), pressure, and microphones, as well as a vision of future devices for applications that include environmental and health monitoring.

Another important aspect of the evolution of MEMS sensors is the addition of on-board computation. For many years, MEMS sensors were pure analog sensors with a simple voltage (or current loop) output. But as technologies evolved that allowed the connection of a MEMS sense element to a CMOS ASIC, digital functionality became available. At first this functionality was used in a simple way to set sensor parameters or perform self-test operations. But soon the availability of digital logic was used to generate digital output, data buffering, and in time, data computation and sensor fusion. This evolution allows functionality to be moved from a system's central processor to the "smart" sensor, offloading that

## Sensors Trends for Handsets

- Accelerometer
- Magnetometer
- Gyro
- Ambient Light
- Proximity
- Pressure
- Touch
- Haptics
- Fingerprint
- Health
- Environmental
- UV & RGB
- Humidity
- Microphone

- Motion characterization
- Contextual awareness
- Personal health & fitness
- Smart TV remote controller
- Gestures
- Sensor-aided navigation
- Biometrics & fingerprint wakeup/unlock
- Heart rate & blood sugar monitors
- CO / pollutant detector
- Multi-media video/camera/audio
- Touch detection
- Haptic feedback
- Building floor detection

*Figure MEMS11 Sensors trends for handsets, presented by Len Sheynblat, Vice President of Technology, Qualcomm CDMS Technologies, at MIG's M2M 2012 Workshop, Pittsburg PA.*

processor for higher level functions (or lower cost). Of course, this increased level of functionality requires an increased level of testing. Although the methods for testing a digital ASIC are well understood, testing a mixed signal ASIC which is intended to be connected to an electromechanical MEMS element is much more complex.

The consumer portable MEMS device technologies that this working group has focused on are accelerometers, gyroscopes, and microphones. The working group has also included an assessment of RF MEMS resonators, switches, and varactors in this report. Section 3 of this report lists the key attributes of these device technologies over a 5-year span (2012 – 2017), which are considered short-term needs by iNEMI and ITRS who typically define long term needs to be 10+ years.

A major conclusion drawn from the 2012 ITRS MEMS Roadmap was that the back-end of MEMS manufacturing (packaging and testing) can consume >50% of the total manufacturing cost [Figure MEMS12] yet virtually all R&D investment has been in the front-end of manufacturing (devices and process development). The research investment portfolio can be partially attributed to a lack of articulation of the problems faced by the back end of manufacturing, and their importance. The development of a consensus opinion that documents the issues facing the industry, which is the primary output from technology roadmapping, can be used as a tool to optimize R&D investment that meets critical manufacturing needs in a timely manner.

This roadmap considers both the evolution of discrete MEMS devices and integrated MEMS technologies. This term "discrete" MEMS is used to refer to devices that perform one function. For example, a 3-axis accelerometer with an integrated ASIC is referred to as a discrete MEMS device for the purposes of this discussion. Integrated MEMS, also

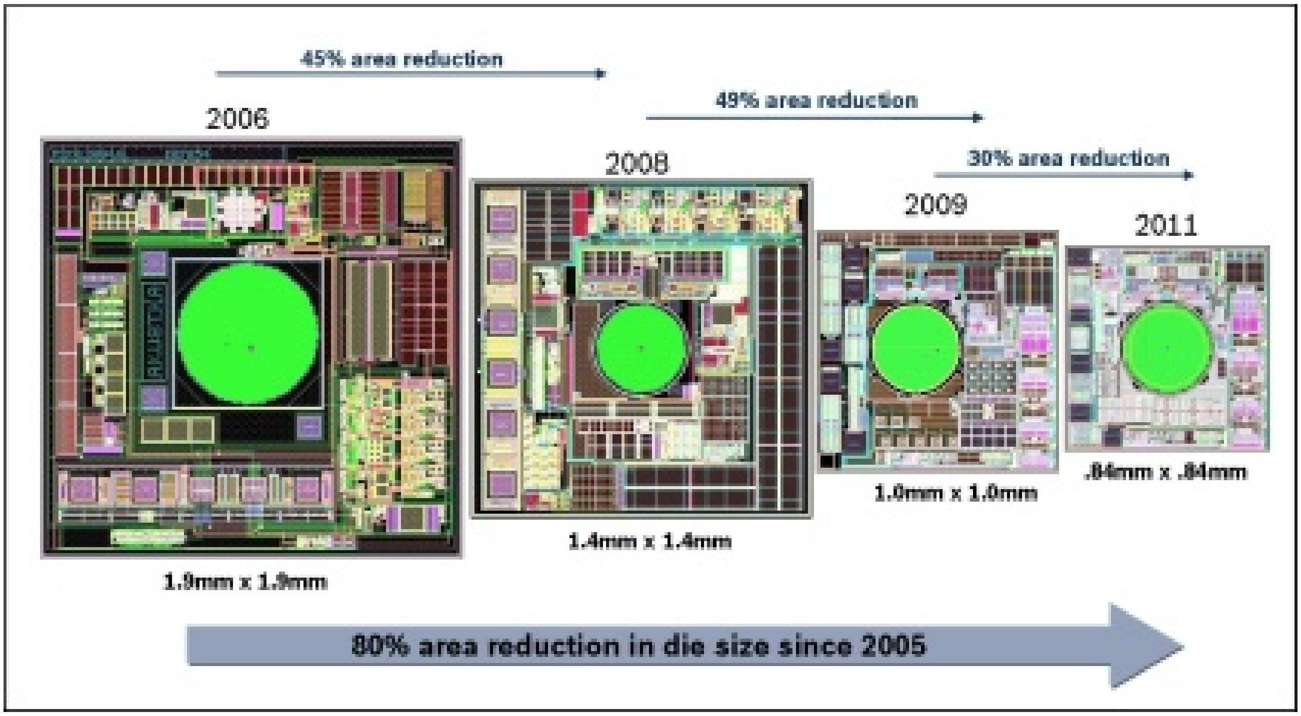


*Figure MEMS12 Example of the continuous incremental improvement of MEMS devices. The MEMS microphone chip size from Akustica saw an 80% reduction between 2006 and 2011.*

referred to as multimode sensors, refer to the integration of sensing functions, such as accelerometer and gyroscope, in the same package.

Discrete MEMS devices are expected to see a continuous incremental increase in performance, and reduction in cost and package size. The greatest challenges for them are related to packaging: decreasing package size while at the same time drastically lowering cost. There are no known solutions to meet the packaging and cost projections out to 2017.

The MEMS TWG sees the greatest challenges for MEMS technologies in relation to their integration path. The integration path towards the Inertial Measurement Unit (IMU) is to integrate a 3-axis accelerometer, 3-axis gyroscope, 3-axis magnetometer (compass), and a pressure sensor (altimeter). This is referred to as a 10 degree of freedom (DOF) multimode sensor. The TWG focused its attention on the accelerometers and gyroscopes, however, future iterations of the roadmap should include magnetometers and pressure sensors. Pressure sensors are MEMS devices that will be integrated in the future IMUs used in mobile devices. Though magnetometers are not, by definition, MEMS devices, they are inclusive to the More-than-Moore paradigm.

Multimode sensor technologies face challenges in assembly and packaging, especially for integration of the IMU at the package level, yet these are challenges where interim solutions are known. The greatest concern for multimode sensor technologies, with no known solutions, relates to testing. Possible solutions relate to moving as much of the testing as possible to earlier steps in the manufacturing process, such as wafer-level tests. This will require the ability to accurately predict performance at the package-level from the wafer-level tests. Other solutions include advancing know-how for MEMS design for testability and even to develop ways to eliminate testing, referred to as to “design for no test.”

There is a continuing need to extend knowledge of the physics of failure in MEMS. This is especially relevant for RF MEMS devices, where their adoption in many applications has been hindered. Extending knowledge of the physics of failure will enable suppliers to improve their reliability and to develop reliability focused, accelerated test methods. It is recognized that there is knowledge for specific devices that resides with companies; however this knowledge has traditionally been kept secret for commercial advantage. Some sharing of such information may become beneficial at an appropriate later time.

The MEMS TWG examined the near-term technology requirements for the MEMS technologies in this roadmap. While there is a desire to expand discussions to include the long-term, the committee must first reach a consensus on how this will be done. It may be that long-term requirements for MEMS will concern integration path, e.g., integration with multiple sensor technologies; advancing ASIC requirements to microcontroller, package level integration versus 3D staking technologies versus monolithic integration paths. Thus near-term requirements may concern the incremental advances in device performance metrics within the long-term integration cycles.

Roadmapping the integration path will require accurate cost analysis, ensuring that future predictions are consistent with the resources and technology needed to deliver to the market place within cost constraints. This methodology can be usefully employed to cost/price discrete MEMS devices and predict the production developments needed for the immediate future. However, accurately costing future integrated MEMS devices represents a significant challenge. Particularly challenging is: estimating the structure of costs to solve the technical problems in integrating fundamentally different components, the costs of developing cost-effective test equipment and the formidable task of packaging in large scale manufacturing.

### 1.5.3 CONSUMER MEDICAL

The rapid increase of digital data and connected technologies is revolutionizing healthcare. The healthcare system used to be highly centralized, disease oriented and focused on acute care. It is changing today towards keeping people healthy, raising each individual's awareness of their health and inducing efficient behavioral changes. As they become empowered to maintain a healthy lifestyle, a large portion of them is eager to collect data about their health, track trends over time and share their health performance on their social network. Others could have a mild condition that can benefit from continuous monitoring. This growing part of the population with the desire to monitor lifestyle and health is often called the Worried-well. Worried-wells are information seekers. In the last decade, worried-wells were searching the web for symptoms they would experience, looking to correlate them with possible health conditions. In the last few years, websites have been introduced to connect people with similar conditions or symptoms (e.g. patients-like-me). In the future, the worried-wells will have a new army of technologies at their disposal to monitor and improve their health. Silicon and MEMS technologies are making that revolution possible.

Today the mobile phone can already provide a great deal of health information. Accelerometers can track activity and sleep. Built-in optical sensors are available that can sense heart rate when the user is touching the phone. The camera in the phone can be used for purposes as diverse as checking the calorie content of a food item, or identifying your emotions based on facial expression recognition. A broad spectrum of mobile phone apps has been developed to analyze this data, and deliver it to the consumer in an intelligible and actionable manner. A recent survey by Mobihealthnews reported 13,000 consumer health apps available on the Apple store as of August 2012 [19].

Not every health parameter can be measured with a mobile phone. They often suffer from the lack of continuous recording and inaccuracy in data interpretation due to the inherent lack of capability in knowing the exact location of the phone at a certain point in time. Wearable sensors, often called wearables, are addressing these limitations. Being worn on

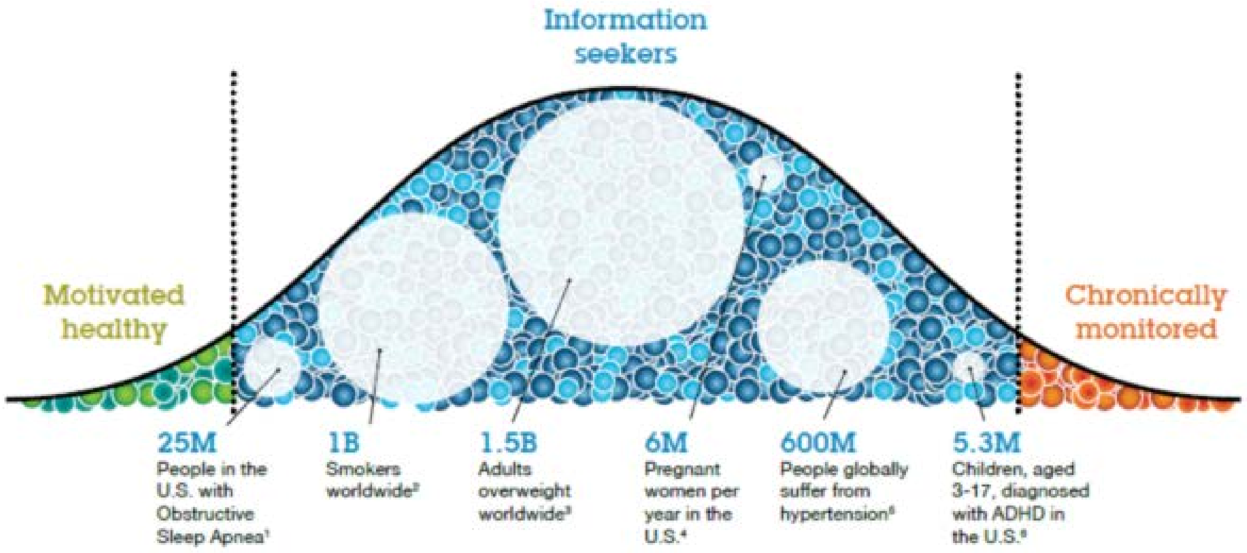


*Figure MEMS13 Distribution of worried-wells with market size estimation. (From IBM Institute for Business Value)* the body, they allow the user to continuously track health parameters, and to identify possible deviations to one's normal profile. Their location is typically known, which allows for more accurate and reliable data interpretation. Finally they enable measurements that would not be possible with the phone alone. Examples of wearables available today include heart-rate sensors such as Polar, Adidas, Sunto and activity monitors such as Fitbit, Nike FuelBand, Jawband or Philips Directlife. Big challenges remain in terms of reducing the size of these devices, reducing power consumption and ensuring reliable performance in all situations of daily life.

## *Worried Well Market Forecast*

The worried-well is a growing part of the population, and the keenest information seekers are the ones who are at risk of major health issues. A study by the IBM Institute for Business Value estimates that 1.5B of the word population is overweight, representing a large population at risk of obesity and its indirect consequences, 1B smokers are subject to cancer and 600M people suffering from hyper-tension are at risk of cardiovascular diseases and heart failure. 25M people with sleep apneas are also subject to car and work accidents. Figure MEMS13 shows the distribution of the worried-well population across different health conditions. It clearly does represent a much larger market than the chronically ill or the motivated healthy that are the target of most of the medical or fitness devices today on the market.

It is expected that the market for wearable devices will reach more than 100 million units annually by 2016, driven by consumer and healthcare adoption [20]. These devices, ranging from heart rate monitors for measuring an individual's performance during sports to wearable blood glucose meters, will all enable greater detail in tracking, monitoring, and care – often through connections provided by mobile phones. Building new sensing functionalities in wearable devices will enrich the information that they can track, providing a more accurate and holistic picture of health. Wearable sensors are a fast growing market that will put new requirements on MEMS technologies.

The MEMS market is expected to increase 13% annually going from 11.5 billion USD in 2012 to 21 billion USD in 2017. A quarter of this market is attributed to cell phones and tablets, reflecting the integration of an increasing number of MEMS sensors in these devices. The incorporation of MEMS technologies into smart phones enables new functionalities that are product differentiators in demand by the consumer. Smarter consumer health devices are a big potential market but it needs smaller and lower power sensors than what are used in the current generation of consumer (fitness) products.

## *MEMS Technologies for Consumer Medical*

**Inertial sensors (Accelerometers, gyroscopes and magnetometers)** - Inertial sensors are a key component in drawing one individual's health status. Activity level can be used to monitor caloric burn rate for athletic trainers and dieticians. Activity level and patterns of activity also relate to illnesses that make people weaker and affect their movement. Accelerometers are widely used to compute step counts, activity counts, calorie expenditure (with pretty low accuracy) or some specific scores (e.g. Fuel points from Nike). But these are often not sufficient to characterize an individual's gait, for which gyroscopes need to be added. Alteration in the gait pattern can reflect the apparition of diseases, or the on-set of pain. Finally magnetometers are needed if the absolute positions of the body limbs are needed. The development of accelerometers has largely been driven by the automotive industry, and low-power accelerometers are now available. Gyroscopes however are still suffering from their high power consumption, which prevents their wide adoption in wearable devices. Low-power gyroscope designs specifically targeting personal around the body use would significantly alter the adoption of gyroscopes in continuous portable monitoring applications.

**Microphones** - The body emits sounds from many different sources, which can be used for monitoring of body functions and assessment of health – including physiological and psychological health – on a continuous basis. The plurality and richness in body sounds certainly represents an opportunity for health monitoring, which by nature shall be multi-modal. However, this also represents a major challenge to health monitoring as multiple sound sources overlap and combine to form sounds that we are able to measure externally. MEMS technologies have the potential to achieve reliable body sound monitoring.

**Electronic Nose (eNose)** - E-noses are gaining interest from markets such as food monitoring, healthcare, public safety and security, and first success stories have started to emerge. "Smell" is considered to be one of the ideal methods of non-invasive monitoring as it requires no contact to the substance under investigation. One of the main sensing approaches to identifying "smells", which are complex mixtures of vapors, is to use multiple sensing elements in a system that is often referred to as an electronic nose or e-nose. In an e-nose system, each sensing element responds slightly differently to a given odor, and when analyzed together, a characteristic response pattern, an odor fingerprint, can be formed. There is a growing demand in scalable, array-able, integrated and low power sensing elements that can be customized for detection of chemicals in specific application conditions. Several array-able sensor technologies have been developed over recent years for electronic nose systems, albeit with individual challenges and limitations. Yet these solutions are not fulfilling the requirements of integrating a miniaturized electronic nose into portable consumer electronics. Increasingly, MEMS-based detection solutions are emerging as potential solutions to the limitations in chemical sensors.

**Ultrasound** - Among the many applications of micromachined ultrasound transducers, several emerge targeting worried well, thus departing from the original industrial and mainly medical applications. For example, linear arrays of micromachined ultrasound transducers (MUTs) could be used in Doppler mode to measure blood flow and thus direct heart beat frequency. MUTs can also be used to heat portions of the body at relatively large depth to ease pain or to enhance the healing processes.

# 2 DIFFICULT CHALLENGES

The MEMS Technology Working Group has adopted the following MEMS technologies for roadmapping:

1) Accelerometers
2) Gyroscopes
3) Inertial Measurement Units (IMUs)
4) Microphones
5) RF MEMS

These device technologies were chosen because they map directly with the MEMS technologies that are adopted in the rapidly growing consumer mobile market.

A survey of R&D investment in MEMS technologies yields the initial observation that virtually all the investment has been in the front-end of manufacturing: device and process development. MEMS manufactures, as a result, have a diverse set of methods and tools for MEMS device development; the “know-how” to make devices is available.

In contrast, a small percentage of the public R&D investment has gone into the back-end of device manufacturing; assembly, packaging, and testing. The greatest challenges for the MEMS technologies are related to their integration aspects, and are primarily linked to the back-end of manufacturing, packaging and test. As mobile internet device manufacturers work to decrease size and weight, extend battery life, and integrate new functionalities, their pull on MEMS device manufacturers is for smaller package size and integration. The MEMS manufacturers refer to the integration of devices as multimode sensor technologies. The challenge is to produce 10 degree-of-freedom (DOF) MEMS inertial measurement units (IMUs), which incorporate 3-axis accelerometers, 3-axis gyroscopes, 3-axis magnetometers (compass), and a pressure sensor (altimeter). The requirements 10 DOF multimode sensor technologies are creating challenges primarily at the back-end of manufacturing.

## 2.1 ACCELEROMETERS

MEMS accelerometer chips are becoming increasingly commonplace with mobile Internet devices. They provide the sensing capability for automatic screen rotation, and their use is expanding, including their growing use for game applications.

MEMS 3-axis accelerometers manufactured for consumer electronic applications are expected to see continuous incremental improvement in performance over time. The improvements are expected in resolution, bias, and drift, with resolutions improving by a factor of 2 from 1000 □g to 500
accelerometers comes from the projected cost reductions, moving from $0.50 per die down to $0.20 per die by 2017.

The Global Positioning System (GPS) unit in many mobile devices is used to find a location and track movement, but an inertial measurement unit (IMU) is required when GPS signals are unavailable, such as in tunnels, inside buildings, or when electronic interference is present. The IMU would consist of a 3-axis accelerometer, a 3-axis gyroscope, a 3-axis magnetometer (electronic compass), and a pressure sensor (altimeter). Current MEMS technology can produce an IMU at the board level.

## 2.2 GYROSCOPES

The inclusion of a gyroscope in mobile devices allows for the detection of more detailed movements by a user compared to the traditional accelerometer included in earlier models, such as the first generation iPhone™, manufactured by Apple. Compared to accelerometers, MEMS gyroscopes have faced significant technical challenges to become adopted into mobile applications due to their extreme sensitivity to package stress effects and their requirements for high precision large actuation and high quality vacuum packaging. As a result, commercialization lagged behind that for accelerometers and the price for gyroscopes was also substantially higher.

Gyroscopes are expected to see a continuous incremental increase in performance, especially in the resolution and zero g bias level. The major challenges for 3-axis gyroscopes are related to cost reduction and package size reduction. However, as with the accelerometers, the most difficult challenges faced concern their integration in the IMU.

## 2.3 INERTIAL MEASUREMENT UNITS

MEMS Inertial Measurement Units are currently defined as a device that contains tri-axis accelerometers, tri-axis gyroscopes, tri- axis magnetometers, and a pressure sensor. IMUs are referred as 10 degrees of freedom (DOF) devices because they contain 10 sensors that are integrated into one package. The integration can occur at the package level (co-integration), by stacking technologies (3D stacking), or integration of some or all of the devices at the chip level (monolithic integration). Device manufacturers are racing to produce these devices, increase their performance, and lower their cost.

The greatest challenges for IMUs are associated with assembly, packaging, and testing. New packaging material and technologies are required. Advances in chip stacking technologies (3D) that meet requirements, including mechanical stress control, of inertial MEMS sensors are also needed. Finally, as the number of sensing functions increase towards 10 DOF, the challenges of testing these devices become more complex since the single device must be subjected to 3D movements, rotation, magnetic field, and pressure. The complexity drives up the cost of testing, which is in opposition to the demand of continuously decreasing device cost – the new “Moore’s Law” of heterogeneous integration: adding new functionalities while maintaining or decreasing cost.

## 2.4 MICROPHONES

Since their introduction, MEMS microphones have continued to shrink in size and improve in performance, while at the same time have been following a rapid price reduction curve as overall volumes have increased. The future trend is for more of the same. Die shrinking, die stacking and chip scale packaging approaches will continue to lead to smaller and smaller microphones over the next decade. At the same time, consumer electronic device manufacturers continue to request higher performance microphones. Higher signal-to-noise (SNR) microphones are required, as microphones need to satisfy more use-cases in a single mobile phone than ever before; mainly near-ear talking, speakerphone, and video recording. Wider bandwidth microphones are also becoming more important to support wider bandwidth mobile phone networks and laptop Voice-over-Internet-Protocol (VoIP) as well as video recording of both voice and music. Smaller microphones are needed to support new applications in small form factor devices like mobile phones, which use more than one microphone for stereo recording or noise suppression. Additionally, smaller microphones will be necessary to support the aggressive cost down targets required by the high volume, price sensitive consumer electronics market, especially as they adopt multiple microphones in a single device. Based on these future demands, microphone manufactures will have to support a significant amount of technology innovation in the coming decade.

Microphones require distribution around the system for functionality (e.g., noise cancellation). For this reason, there is not a pull to integrate multiple microphones in a single package. Instead, the push is for developing digital I/O interface to reduce noise over long signal lines.

MEMS microphones are expected to see a continuous incremental increase in performance, while decreasing in size cost. Integration for microphones is moving in the direction of advancing ASIC functionality and I/O.

## 2.5 RF MEMS

The incorporation of RF MEMS into mobile devices is intended to lower power dissipation by the radio and to lower the chip count in the device. RF MEMS are still in the process of increasing their reliability and lowering cost before they will be adopted in mobile devices. RF MEMS are expected to increase in performance and reliability. The biggest challenge in RF MEMS is enhancing reliability and lifetime (e.g., number of operations). Some of the future performance metrics have no known solutions, e.g., signal isolation requirements.

### RF MEMS RESONATORS

The MEMS resonator inherently has higher temperature expansion coefficient than the Quartz, therefore it would have higher frequency drift over temperature if without a proper compensation. A proper temperature compensation scheme for the MEMS resonator together with the timing circuit and low noise PLL are necessary in order to make a stable timing reference. The MEMS oscillator products can be differentiated from the frequency ranges of applications and the level of phase noise and jitters from the integrated solution. The major source of the phase noise and phase jitter comes from the compensation loop and PLL circuit. These are the areas that draw the major development to up grade the performance of the MEMS oscillator. For cell phone application, the power consumption is always a concern. This creates more challenges to the design of the compensation and PLL circuit. There are few Si based MEMS oscillators that have the phase noise and jitter within the 2 ppm range and with reasonable low power for cell phone application.

### RF MEMS SWITCHES

There are several key challenges to the commercialization of RF-MEMS switches. The foremost barrier is achieving a cost low enough to be competitive with more conventional switching solutions. The prime cost driver is the hermetic or possibly near-hermetic packaging required to protect the MEMS and contact surfaces from moisture and organic contamination. This packaging must have minimal impact on the high RF performance and must be compatible with standard semiconductor back-end flows. Another key cost element is the requirement for circuits to generate and control the high voltages needed to minimize die size and maximize reliability. These circuits should consume negligible power, provide a standard control interface and avoid introducing any RF interference. The final piece in the cost puzzle is achieving high yield, ideally across 200 mm wafers.

Another key challenge is clearly demonstrating the required reliability for the application use cases in the range of environments where they will be applied. Sufficient lifetimes have been demonstrated for many applications on limited sample quantities through direct long-term testing. These tests imply that RF-MEMS switch contact are capable of the required reliability but such testing is not sufficient to establish a statistical basis for high volume defect projections, especially over early life. While several accelerated reliability tests have been proposed, unfortunately none has yet proven validity. The cycling reliability is particularly impacted by hot switching events. For mobile applications, new solutions will be needed to enable contact switching at full power. Additional reliability limitations arise in some technologies due to metal mechanical yield or creep under stress leading to irreversible behavior shifts as well as from charging of dielectrics used to prevent actuator shorts.

A final challenge for some applications is achieving high reproducibility in the resistance between contact closures. Residual films on the contact surfaces, especially organic, lead to increased variability.

### RF MEMS VARACTORS

As with switches, the primary challenge is achieving the required cost point, although the application value and performance requirements enable a somewhat higher cost basis. The packaging poses different challenges from contact switches as RF parasitic minimization and moisture prevention become the prime focus. On-wafer thin-film sealing techniques provide a good solution but further development is required to extend bandwidths with lower parasitics and to increase the robustness of the seal layers to survive intense packaging steps such as injection molding.

Dielectric charging is a key reliability limitation of many RF-MEMS varactors, especially those that apply the control voltage directly to the capacitor. This is greatly influenced by residual moisture so sealing to prevent moisture ingress is mandatory.

While hot tuning is not a reliability limitation for capacitive switches, the switching operation will be impacted above some threshold RF voltage where the device will not open until the voltage is reduced. At even higher voltages, the device may close unintentionally.

# 3 TECHNOLOGY REQUIREMENTS

The device technologies adopted for MEMS roadmapping are accelerometers, gyroscopes, microphones, and RF MEMS. The trends of inertial sensors, accelerometers and gyroscopes, are examined in terms of their implementation as discrete devices and in terms of their path of integration towards the inertial measurement unit. The trends of the discrete device technologies show a continuous incremental improvement in performance, lowering cost, and reducing package size. A second trend is the integration path: integrating multiple MEMS sensor technologies in a single package, advancing the functionality of the ASIC and I/O, or both.

The MEMS TWG engaged in the development its Technology Requirements Tables by beginning with mapping out device performance metrics and integration path. It was recognized that the greatest challenges faced by MEMS were at the back-end of manufacturing (packaging and test), the committee applied the device performance metrics to determine the requirements from the end of the process, beginning with testing, and worked forward in the manufacturing process to packaging and integration, and finally in design and simulation.

The roadmap includes information on discrete MEMS devices and the integration path towards the inertial measurement unit. The term “discrete” MEMS is used to refer to devices that perform one function. For example, a 3-axis accelerometer with an integrated ASIC is referred to as a discrete MEMS device for the purposes of this discussion. By the same reasoning, a MEMS microphone chip co-integrated (packaged together) with an ASIC would be considered a discrete MEMS device by this definition.

We define integrated MEMS as the integration of multiple functions, such as accelerometers together with gyroscopes, in the same package. The integration can take place in at the package-level integration, 3-D stacking, monolithic chip-level integration, and or a combination of these approaches. The specific approach will likely be different depending on the manufacturer and must ultimately be cost driven.

## 3.1 ACCELEROMETERS

The English physicist George Atwood (1746–1807) invented the accelerometer in 1783. Accelerometers have now been in use for almost a century, with the use of resistance-bridge-type accelerometers finding application in bridges, dynamometers, and aircraft [20]. MEMS accelerometers were proposed in 1979 in a paper on a batch-fabricated silicon accelerometer [21]. The early commercial MEMS accelerometers were of the piezoresistive type realized by silicon bulk micromachining. However, the advent of surface micromachining and capacitive sensing technologies in the late 1980s and early 1990s took MEMS accelerometers to their first major commercial success in automotive applications. By the late 1990s, expedited by the more stringent automotive safety regulations, the adoption of MEMS accelerometers for airbag crash sensing in automobiles was wide spread. During the 2000s, automotive accelerometer applications further widened to rollover detection and electronic stability controls, among other functions. Adoption was slow, however, for the consumer motion and tilt sensing applications until the price, size, and power consumption of MEMS accelerometers were finally in line with market requirements toward the late 2000s. The shipment of the Nintendo Wii and the Apple iPhone, each equipped with a 3-axis MEMS accelerometer, were landmark events, pioneering the ubiquitous usage of MEMS accelerometers in consumer handheld products. Today, a 3-axis MEMS accelerometer is increasingly employed in conjunction with a 3-axis magnetometer for personal navigation or with a 3-axis MEMS gyroscope to constitute an IMU (Inertial Measurement Unit) to fulfill the needs for complete motion sensing.

### TECHNOLOGY REQUIREMENTS

*Table MEMS1 Technology Requirements for Discrete (3 axis) MEMS Accelerometers*

Discrete (3-axis) MEMS accelerometers are expected to see a continuous incremental improvement in performance and reduction in package size. Methods for advancing the performance of the discrete accelerometers, e.g., resolution, bias, drift, and power consumption, exist and are being optimized. The challenge, however, is to meet the cost reduction and package size requirements.

There is a trend in the inertial sensor industry for smaller, lower power and lower cost products. This puts a higher burden on final test costs to be reduced further.

## 3.2 GYROSCOPES

The first MEMS gyroscopes were made of quartz and based on the piezoelectric principle. They were adopted in luxury cars during the late 1990s. Early commercial silicon MEMS gyroscopes were actuated with a permanent magnet. These were gradually replaced by electrostatically actuated silicon gyroscopes, which were introduced in the early 2000s. Today, silicon and quartz MEMS gyroscopes are widely employed in automobiles for electronic stability control, rollover prevention, and GPS navigation. Their adoption has been hindered by the pricing requirements for the consumer applications. However, recent technological breakthroughs and cost reduction have finally enabled market penetration in cell phones, video game controllers, and cameras/camcorders.

### TECHNOLOGY REQUIREMENTS

*Table MEMS2 Technology Requirements for Discrete (3axis) MEMS Gyroscopes*

Similar to accelerometers, discrete (3-axis) MEMS gyroscopes are expected to see a continuous incremental improvement in performance, a continuous reduction in package size. Methods for advancing the performance of the discrete gyroscopes, primarily for resolution, exist and are being optimized. The challenge, however, is to meet the cost reduction and package size requirements.

## 3.3 INERTIAL MEASUREMENT UNITS

The trend for MEMS inertial measurement devices is their integration of towards the Inertial Measurement Unit. Today, a 3-axis MEMS accelerometer is increasingly employed in conjunction with a 3-axis magnetometer for personal navigation or with a 3-axis MEMS gyroscope to constitute an IMU (Inertial Measurement Unit) to fulfill the needs for complete motion sensing.

### TECHNOLOGY REQUIREMENTS

*Table MEMS3 Integration Path for MEMS Inertial Measurement Units*

MEMS Inertial Measurement Units (IMUs), with tri-axis accelerometers, tri-axis gyroscopes, tri- axis magnetometers, and a pressure sensor, are expected to reach 10 DOF in the package by 2014, moving on to integration at the wafer-level and/or chip-level by 2015. Interim solutions are known for the production of the devices.

The biggest challenges for these devices will be testing. There are some interim methods for testing multimode 10 DOF MEMS integrated at the package level, which are based on measurements of known good die, however, there is still great concern about the device yield issues of this approach. This problem worsens by 2017, where there are no available methods to test wafer-level and/or chip level integrated 10 DOF multimode sensors within the targeted cost requirements.

There is a trend in the Aerospace and Defense IMU market to replace higher end inertial sensors (Fiber Optic Gyros, etc.) with MEMS-based IMU’s because they can be smaller, lower power and less expensive, while providing similar performance of the traditional higher accuracy inertial sensor technologies. Third party system integrators are also taking lower performance MEMS inertial sensors and re-applying higher accuracy calibration algorithms to turn them into higher performing IMU’s.

MEMS test handler companies, such as Multitest, are addressing the need to reduce the cost of test by trying to combine several different axes of testing into the same stimulus, to reduce the test and handling time. This is needed for 9DOF and 10DOF products.

## 3.4 MEMS MICROPHONES

For fifty years, acoustic components such as microphones, speakers and transducers had remained fundamentally unchanged. One such component, the Electret Condenser Microphone (ECM), has been used in billions of portable electronic devices such as mobiles phones and portable computers (laptops, netbooks, tablets, etc.). An explosion of new technologies enabled a compelling array of new features in smaller form factors in the 90s, and at the same time mobile phones and notebook computers evolved into more complex and powerful multimedia devices that needed to support real-time audio and video communications in a wide range of environments ranging from hotel rooms to rock concerts. These new use-cases needed small, thin, well-matched microphones that could be assembled with the rest of the device in the standard automated manufacturing line. Though MEMS microphones had been demonstrated, it was not until it became clear that the changing acoustic requirements in consumer electronic devices were pushing beyond the limits of ECM technology, and device designers and manufacturers began to look towards MEMS microphones to meet their needs.

MEMS microphones offered many benefits over ECMs that allowed device manufacturers to meet the more stringent needs of their customers. The first silicon microphones were adopted for two main reasons—1) silicon microphones are smaller in size than ECMs while having the same or better acoustic performance and 2) silicon microphones also have the advantage over ECMs that they are compatible with automated IC assembly equipment, improving manufacturing throughput and yield. These features were the main drivers of the first major wave of analog-output silicon microphone adoption in mobile phones that occurred in 2003–2005.

The first digital-output MEMS microphones were introduced in 2006. Portable computer manufacturers were the first to adopt the digital-output MEMS microphones—not only because they were thin and surface-mountable, but also because for the first time, designers were able to position the microphone in the bezel of the laptop (the best acoustic location) and run the audio traces around the screen and down into the base of the laptop without using thick shielded cabling for protection from radio frequency (RF) and electromagnetic (EM) interference.

Analog and digital-output microphones have continued to both shrink in size and advance acoustic performance, and as a result have increasingly become adopted in the mobile phone and laptop market. Many laptops now contain a digital microphone array in the bezel with the camera for VoIP communications, and recently, some mobile phones have been introduced that use two or more microphones for noise suppression. These applications along with new market areas such as wired and wireless headsets have helped push the forecast for MEMS microphones to above 1B units in 2013 (iSuppli, February 2010).

The first silicon microphones were multi-chip-modules with one transducer chip and a second IC containing a pre-amplifier and/or an analog-to-digital converter. These two devices are then wire-bonded to each other within the MEMS microphone package. Fabrication of the MEMS die can be internal in captive fabrication facilities but are more often outsourced to MEMS foundries. More recently, products using a single-chip microphone technology called CMOS MEMS were introduced. In this case, the MEMS transducer element is fabricated in the CMOS alongside the circuitry using the metal-dielectric layers that are deposited during the standard CMOS process flow in standard semiconductor foundries. This type of technology has the advantage of requiring less overall silicon area than its two-chip counterparts, leading to smaller, lower cost microphones.

Most MEMS microphone products today utilize two-chip technology. In fact, the two-chip approach has become so standardized that some of today's MEMS microphones suppliers do not actually design or manufacture their own MEMS or ASIC die but rather, they purchase these die from other semiconductor suppliers, meaning that a number of different MEMS microphone suppliers actually use the same MEMS die and/or ASIC for their products. These largely undifferentiated products play an important role in the MEMS microphone market as they provide a steady stream of second source products. However, consumers of MEMS microphones still rely on those MEMS microphone suppliers that design their own MEMS microphones for product innovation.

MEMS microphone performance is not based solely on the design of the actual MEMS microphone die, but relies heavily on the package design as well to provide the proper front and back air volumes as well as an appropriately sized acoustic port to optimize the microphone performance. Incorrect design of the microphone package can lead to a reduced sensitivity or SNR (Signal-to-Noise Ratio) to a poor frequency response, including unwanted resonances. The MEMS microphone package is typically a substrate-based package with either a laminate or metal lid. The acoustic port of the microphone can be in the lid or in the substrate depending on how the manufacturer wants to mount the microphone in the end application, and the MEMS die can be located directly over/under the acoustic port, or off to the side depending on the front/back air volume requirements of the particular MEMS die. Packaging can be done in a microphone supplier's a dedicated packaging and test facility but most often, MEMS microphone suppliers leverage the expertise and capacity of standard semiconductor packaging houses for the packaging their MEMS microphones.

### TECHNOLOGY REQUIREMENTS

*Table MEMS4 Technology Requirements for MEMS Microphones*

MEMS microphones are expected to see performance increases, especially for signal to noise ratio, frequency response, and current consumption. Manufacturers agree that solutions are known to reach these performance metrics. Microphones require distribution around the system for functionality (e.g., noise cancellation). However, some manufacturers have begun integrating multiple transducers on the same die, allowing an improvement of Signal to Noise Ratio (SNR) [22]. Integration aspects for microphones are also moving in the direction of advancing ASIC and I/O functionality, the details of which may have commercial advantage implications and thus not openly discussed. Issues related to testing include:

- Testing microphones at the device level does not guarantee similar performance once the microphones are integrated into the system. This is one of the issues that differentiate testing of MEMS microphones from inertial sensors.
- Methods are needed to test microphones out to 20 kHz in the production environment.
- Methods are needed to test high S/N ratios (≥68 db) that can be carried out in the high noise levels of the manufacturing environment.
- Industry has to test 100% of the microphones in order to get the required ppm quality level. Are there advancements that can be made so that 100% of the devices do not need to be tested or building in self-test?
- As MEMS microphones become integrated with more functionality, including adaptive processing such as automatic gain control, directivity, and noise cancellation, testing becomes more challenging. Testing these functionalities requires additional parameters including multiple input levels, spatial position, and time.

## 3.5 RF MEMS

RF MEMS devices include thin-film bulk-acoustic wave resonators (FBAR), surface acoustic wave resonators (SAW), resonators (timing devices), capacitive switches/varactors, and metal contact switches. In general, these device types have found or will find use in wireless communication products as discrete devices, e.g., a FBAR filter mounted to a board or mother chip, or a Si MEMS oscillator replacing a quartz part in an existing socket. The performance of the MEMS discrete parts is typically on par or better than the previous generation product (MEMS or non-MEMS). Its low cost allowed rapid adoption. The rate of adoption for parts that have greater performance benefits, but no clear cost benefits, tend to be slower due to various economic factors and to technology maturity and demonstrated reliability of the existing part that the MEMS part would replace. One example of the latter is the reliability of the packaged parts containing MEMS switches (capacitive and metal contact). Market place introductions, when performance enabled new products have no significant cost barriers compared to the desired function of the product, have been relatively rapid and assisted by the use of existing, more mature MEMS process technology such as Si micromachining used in airbag sensors or inkjet printers. The time at which the RF MEMS devices are produced in high-volumes often occurs when the MEMS function is integrated with the CMOS, BiCMOS, or bipolar semiconductor die. The timing for this integration will be primarily driven by cost. Until that time, initial introductions will occur in the following order: 1) favor discrete die (e.g., FBAR devices), 2) 3D stacking of the RF MEMS chip above or below the IC (e.g., variable capacitors), and 3) monolithic integration with the IC, which will potentially reduce the bill of materials by removing customized MEMS packaging from some devices and enable new applications due to integration and cost reduction.

The MEMS TWG has adopted 3 types of RF MEMS devices, which fit items classes 2 and 3 in the preceding paragraph: resonator, varactor, and switch. These three are expected to find use in mobile internet devices, such as smart phones and tablets, in the near term.

### RF MEMS RESONATORS

There are number of companies trying to displace the traditional quartz oscillator with a Si-based MEMS oscillator for the frequency reference used in clock and timing applications. The Si-based MEMS oscillator has the advantages in shock resistance, smaller form factor and are more suitable for mass production. The MEMS oscillator can be also integrated with the timing circuit into a much smaller package than the Quartz oscillator.

### RF MEMS SWITCHES

RF-MEMS contact switches hold great promise for improving performance and increasing the integration of the RF front-end of wireless systems. RF-MEMS switches can provide far lower losses, higher isolation and higher linearity than their solid-state counterparts. This is of increasing value as the number of bands and modes that must be supported in a mobile platform continues to grow. Possible monolithic integration with standard CMOS brings the promise of low-cost and small size. Many high-performance devices have been built using RF-MEMS including a wide range of switches. However, none has yet reached commercial success, both due to remaining technical challenges and due to rapid advances in more conventional switching technologies.

### RF MEMS VARACTORS

RF-MEMS varactors and capacitive switches hold even greater promise for improving performance and increasing the integration of the RF front-end of wireless systems. Instead of switching between sets of fixed elements, RF-MEMS varactors can provide direct adjustability to the RF circuits and have loss performance similar to fixed passive elements. This enables a simplification of the systems by a reduction in the multiplicity of signal paths. Achieving these benefits requires more complex control than simple switching. Note that analog MEMS varactors are not practical in most applications due to variability over temperature and influences of voltages induced by RF power. Practical RF-MEMS varactors are typically formed from arrays of capacitive switches to provide the necessary reproducibility and robustness. The technology is similar to RF-MEMS contact switches but with crucial differences. Monolithic integration with standard CMOS is fundamentally easier and has already been accomplished. Capacitive switches are more robust to switching under RF power and have significantly higher cycling lifetimes than contact switches.

### TECHNOLOGY REQUIREMENTS

*Table MEMS5 Technology Requirements for RF MEMS Devices*

RF MEMS devices are all expected to see a continuous incremental improvement in performance. The major cross-cutting challenge that RF MEMS must face in order for their introduction into mobile internet devices is reliability: increasing their reliability, development of reliability simulation tools, and development of methods for accelerated lifetime testing. RF MEMS also specifically call out a requirements for inductors with Q>50 integrated and methods for minimizing interconnect length and loading at the package level.

The RF MEMS resonators described in the table are intended for timing, to replace discrete quartz crystal-based timing devices with a silicon-based technology that can be integrated in the IC package, or on-chip. RF MEMS resonators are expected to continuously increase in performance in all of their performance metrics. The greatest challenges are achieving requirements in temperature stability, phase noise, and current consumption, with no known solutions as early as 2016.

RF MEMS switches are expected to continuously increase in performance in all of their performance metrics. The greatest challenges are achieving requirements in temperature stability, phase noise, and current consumption, with no known solutions as early as 2016.

RF MEMS varactors are expected to continuously increase in performance in all of their performance metrics. These devices face challenges with no known solutions by 2014 in all of their performance metrics.

# 4 POTENTIAL SOLUTIONS

## 4.1 DESIGN

The evolution of design and simulation tools for MEMS is as varied and as broad as their manufacturing approaches and transduction mechanisms. Cross-cutting many physical domains (including biological, optical, and chemical), design tools and methodologies have focused on the core areas of mechanical and electrical engineering as these fields gave birth to transducers, sensors and more high volume products such as accelerometers, gyroscopes, and pressure sensors that operate electromechanically. Design solutions have matured, but often in diverging directions. In mechanical engineering, where customization to end needs is critical, and where material science, manufacturing technology, multi-physics, and varying geometric scales come into play, finite-element modeling (FEM) solutions such as CoventorWare and ANSYS are utilized. In electrical engineering, where standardization is critical to modularization, system- level (ECAD) tools utilizing languages such as SPICE, Verilog, and VHDL have become important for circuit analysis and VLSI design. The long-perceived challenge in MEMS has been to bring these tools together, to close a gap where standardization stands at odds with customization.

There is no one design flow for systems incorporating MEMS as there is in the semiconductor world, where a top-down design approach dominates. In the MEMS arena, the team designing these systems often includes material scientists, modeling teams, process engineers, MEMS experts, circuit designers, software engineers and packaging experts. Phenomena occurring on multiple physical scales must be designed or taken into account, from the nano-scale engineering of surfaces in an RF switch to the system software to analyze and control sensor and actuator signals. This issue is driving the need for co-design environments with standards for information exchange between design tools for the different domains.

- *Continuous Improvement of Simulation Tools* - MEMS devices are expected to see a continuous improvement in performance metrics. The simulation tools must also continuously improve in their capacity to predict those performance improvements. This will require improved links between device simulation and system simulation, more specifically, the integration of finite element modeling with ECAD tools. Fabrication process modeling should also advance so that material properties, and process-induced surface characteristics and stress fields can be more accurately predicted from a process flow.

- *Design for Testability* - A critical challenge for MEMS devices concerns testing, which already consumes about 1⁄3 of the manufacturing cost and is continuing to rise while at the same time the price of devices are expected to continue to lower. Furthermore, integrated 10 DOF multimode MEMS have no known solutions for testing. There has been a mantra in the MEMS community that designing a new device requires consideration of the package at the start of the process. Now, this mantra should be expanded to include the need for designing for test at the start. There are no formal algorithms to design MEMS for test, especially for integrated multimode MEMS sensors. The consensus opinion of the committee is that as much testing as possible should be moved upstream in the process and that design tools are needed to support this. There is also a call for “design for no test,” where research may further enable techniques to design systems that are self-testing and self-calibrating [12].

- *Simulation tools for predicting packaged device performance from wafer-level testing* - Manufacturers typically test their devices after they are fully assembled and packaged, and refer to this as device-level testing. An important piece of addressing testing challenges is moving as much of the testing as possible to the wafer-level, and to simplify and reduce the burden of testing at the end. This will require validated simulation tools and methodologies to predict the effects of assembly and packaging from wafer-level test data.

- *Reliability simulation* - Accurate predictive models using information from the design and fabrication process are needed in order to predict and optimize the reliability of MEMS. These models may also prove useful in developing accelerated reliability test methods. Addressing this need requires research and the advancement of knowledge of the physics of failure, so that the models can be developed.

- *Cost modeling for packaging and integration* - Cost analysis is an important tool for ensuring that future predictions of the price of a MEMS component are consistent with the resources and technology needed to deliver it to the market place[21]. Currently, the methodology can be usefully employed to cost/price discrete MEMS devices and predict the production developments needed for the immediate future. Advancing predictive models of integration paths for MEMS could be useful for technology roadmapping over the long term.

- *Need for Co-Design Environments* - Systems incorporating MEMS devices are growing in their level of integration and complexity, often including multiple MEMS sensors/actuators/structures, analog and digital circuitry, micro-controllers, custom packaging and software algorithms. Many of the delays in bringing MEMS-based systems to market stem from errors made in integrating the MEMS with the rest of the system, causing costly re- designs. Co-design of the product enables designers to catch composition errors early and also enables designers to optimize the entire system, trading off requirements between the MEMS and electronics, and packaging. The result is higher product performance, lower manufacturing costs and faster time to market.
- *Standards for Information Exchange* - In order to facilitate co-design, standards of information exchange are needed especially in the area of modeling so that designers working with different design tools can work together. Designers working at different levels of abstraction must be able to ensure that models give consistent results and that models at a given level of abstraction are compatible. Furthermore, there must be traceability between different levels of abstraction, so that changes to a schematic design map to changes in physical design (layout) and vice versa. In the EDA world, much work has been done to standardize information exchange and assure compatibility and traceability, but in the MEMs world solutions to these design-flow challenges are largely ad hoc. Also, in the EDA world, exchange of information between foundries and designers is standardized through design kits. Even though standardization of MEMS fabrication processes has been very limited to date, standardization of information exchange is recommended.

## 4.2 FABRICATION

MEMS manufacturers were primarily vertically integrated, with in-house design teams, and clean room manufacturing, packaging and testing facilities. This paradigm shifted after the turn of the century towards virtual manufacturing, sharing the high cost of clean room facilities by working with foundries. The capabilities of the foundries (fabs) vary from fab-to-fab depending on the tier. Tier One fabs support consumer market-driven devices, like accelerometers, inkjet, and microphones. They typically support 8” wafer fabrication platforms, driven by the aggressive price targets and more seamless integration with ASICs. These fabs typically internally fund the latest tools in multiple paths to support the huge volumes required of those markets. The Tier One fabs have little interest in supporting small, startup driven R&D activity. Conversely, Tier Two fabs tend to be very good at supporting startup activity. They typically support 6” wafer fabrication platforms and tend to have single path tool sets with typically bottlenecked areas like photolithography and deep reactive ion etching (DRIE). They can be very flexible to work with, and support multiple markets and low volume applications. Tier Two fabs have some protection from market demand decreases since they are not as reliant on one customer or market. However, since they are unable to support high-volume needs, the Tier Two fabs tend to be niche-market driven, concentrating on middle-to-low volume applications where a higher MEMS value and corresponding cost can be absorbed by the system. To Nano or Not- to-Nano is also a differentiator among fabs in general. While the presence of sub-micron capability is not exclusive to Tier One or Tier Two fabs, the fabs that can support it are better poised to leverage the opportunities resulting from the convergence and integration of micro- nano technologies.

Standardization of MEMS fabrication processes is a controversial issue often debated at MEMS technical meetings, including those organized by the MEMS Industry Group. MEMS technology has its origins in development of custom fabrication processes to achieve the high performance through unique designs, materials, and process induced material properties. Customization can often offer a distinguishing feature to the MEMS device performance. Semiconductor manufacturing also has its origins in customization, but as the market grew the industry eventually adopted manufacturing standards. It still remains to be seen if MEMS manufacturing will follow this same path. Today, most of the MEMS standard processes, like MUMPs®, are stuck in a dichotomy, victims of their own success, because what they do best is also their hindrance to large scale production acceptance. While they are very good at supporting a wide variety of applications in one single process run, they conversely are not tight enough from a process and specification window perspective to be adequate for a killer application or device.

As a result, foundry customers often request customized fabrication despite the fact that standard processes are often offered at a much lower cost. Consequently, much of the infrastructure and development for a particular process does not get passed on from Customer A to Customer B, resulting in higher initial development costs for Customer B. The foundry model is often to co- invest with the customer to develop the custom processes. However, the customer is often not willing to pay for this up front and so the foundry has to develop creative means to support the endeavor: cost sharing, flexible payment terms, and a commitment to lower production pricing down the road are often in the mix. The higher bottom line costs to the fab lead to quarter-to- quarter hand wringing and cash flow issues. One approach is to convince the traditional development-centric customers to pay to maintain processes during lot downtimes, in order to keep the “pump primed” and reduce the effort to spin back up the processes when they bring a new development run. Yet most are unwilling to commit to such an approach even though it leads to more stable processes in the long run.

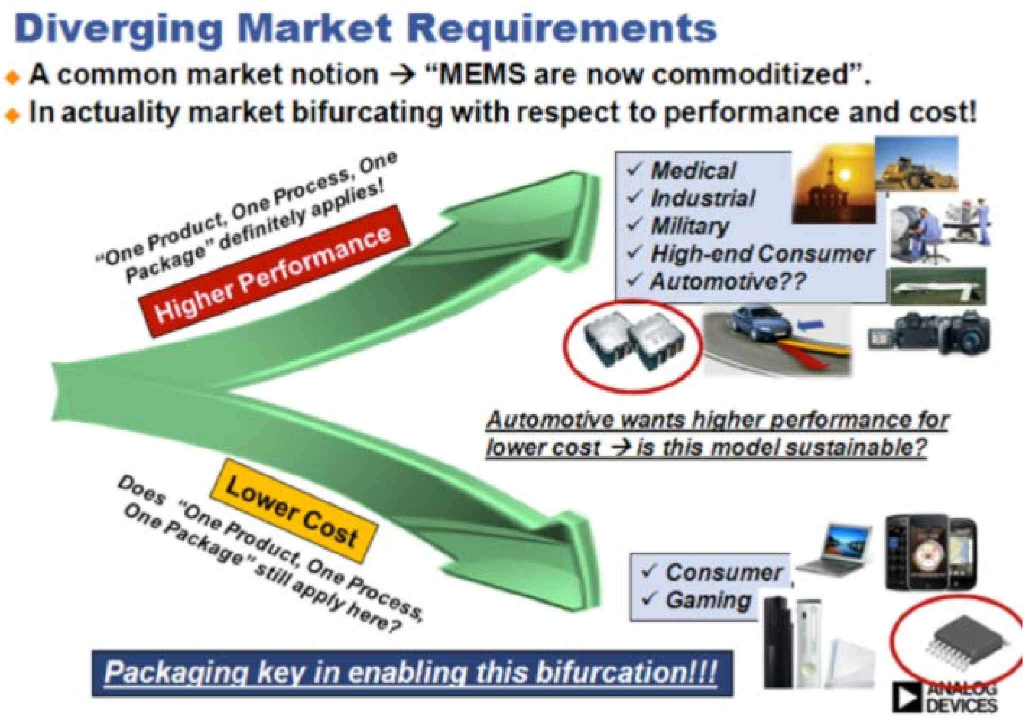
Many of the startup customers come from a university lab environment where they either had established the process themselves or licensed it from the university. Their initial expectation is that the process transition will be seamless, but it rarely turns out this way because the unfortunate nature of MEMS processing results in the same process using similar tools producing varied results from one fab to another. Thus there is a cost to transitioning – it's not as simple as "throwing it over the wall" – and customers are not very excited to swallow this cost. The licensed processes are typically at a very early stage and often have skewed data overselling the legitimacy and stability of the process. The foundry will usually go through a list of qualifiers (is the market potential real? is the customer's approach solid? is the company sustainable?) in order to decide whether or not a cost-share investment will pay off. This can be a difficult decision because the MEMS foundry cannot be an expert in the myriad of markets it supports. The foundry typically has limited funding to support indirect work so there is intense pressure to allocate its budgets so a good probability for the return on its investment is paramount. All customers want their development to be cheap, fast, and good. In reality, only two of those three can be realistically achieved. You can have it cheap and fast, but it won't be good; or have it cheap and good, but it won't be fast; or have it fast and good, but it won't be cheap.

From a process tool and material perspective, the biggest current issue is wafer turnaround times for anything non-standard, such as custom SOI, thick/thin Silicon, or substrates with custom doping or resistance properties. 12-16 week lead times are not uncommon today. This delay impacts the foundry's ability to manage its billings and resultant cash flow, and puts tremendous pressure on the foundry to make up time in processing. Reliance on aggressive scheduling puts the foundry on thin ice with respect to tool down time or inevitable process issues, impacting the entire line in a trickle-down effect. If the foundry can't invoice to plan and get paid regularly, funding has to be shifted to keep the fab running so the ability to bring in new tools and develop/maintain in- house processes is stifled. Aggressiveness in schedule leads to shortcuts in processing which can be catastrophic down the line at the end of the process run.

The legitimization of MEMS processing through consistent, repeatable performance and standard approaches should be the strategic focus for foundries. While new processing techniques are always exciting, it would be more beneficial to the industry to see foundries continuing to press and improve upon current capabilities to drive costs and schedules down. This approach would result in a wide and deep market of standard processes, which could be targeted by designers rather than a design that needs an entirely new process. By continuing to exercise and exploit current capabilities, the foundries will have created an economic driver as well to convince the MEMS design industry to commit to a suite of standard processes. It will be up to the foundries to develop processes capable of supporting diverse applications so there is some meat to the offering other than a low price. Tools are going to continue to get better and cheaper, and more will become specific to MEMS fabrication. This will drive down processing times and costs, and allow more foundries to enter into the nano feature size arena with well- known processes capable of supporting medium volumes rather than experimental prototype processes. Continued investment in the foundry's internal process development will be vital; however, the foundry will need a sustainable, external business in order to support such budgets.

Government could play a role in this by offering contracts specific to creating and establishing these standards, though this would be a dramatic shift in strategic focus the past decade where most of the funding goes toward the more-sexy, next greatest widget rather than the more- vanilla, basic infrastructure needs of the industry. Setting such standards would lead to better integration with CMOS and other outside synergistic technologies for MEMS and allow for more economical, wafer-scale packaging approaches. Communicating these processes to the academic world through focused training would get this message to those early-stage designers to convince them to take the easier path of standard process, yet still allow them to experiment with new cutting-edge processes in their own lab.

One possible route towards MEMS process standardization has an analogy to the standardization paradigm adopted in industrial machining [22]. A machine shop uses a suite of machines, such as mills, lathes, saws and benders, to perform specific functions. The same shop might make products as diverse as door hinges or engine blocks. Here, one finds standardization not in the process flow, but in the tools and methods that accompany each machine tool, such as drill bits, saw blades, cutting speeds, sheet metal gages and fastener sizes. Mechanical engineers have learned to work within these machine-specific standards when designing products. They specify 3.0 mm holes, for example, instead of 3.023 mm holes because the former can be drilled with a standard tool, which makes the part cheaper to produce; "standard drill bits". This paradigm could be applied to standardizing MEMS manufacturing. To improve our manufacturing efficiency and lower costs, the MEMS industry must start thinking about how to standardize at the tool and/or recipe level, similar to how a standardized set of drill bits accompanies the drill press. Standardization of MEMS silicon wafer specifications such as layer thicknesses of silicon-on-insulator devices, silicon-etch recipes to achieve specific depths or aspect ratios, and commonly used film deposition thicknesses are all within easy reach.



**Diverging Market Requirements**

- A common market notion → "MEMS are now commoditized".
- In actuality market bifurcating with respect to performance and cost!

"One Product, One Process, One Package" definitely applies!

Higher Performance

✓ Medical
✓ Industrial
✓ Military
✓ High-end Consumer
✓ Automotive??

Automotive wants higher performance for lower cost → is this model sustainable?

Lower Cost

Does "One Product, One Process, One Package" still apply here?

✓ Consumer
✓ Gaming

Packaging key in enabling this bifurcation!!!

Figure MEMS14 The diverging MEMS market driven by performance and cost.

## 4.3 ASSEMBLY AND PACKAGING

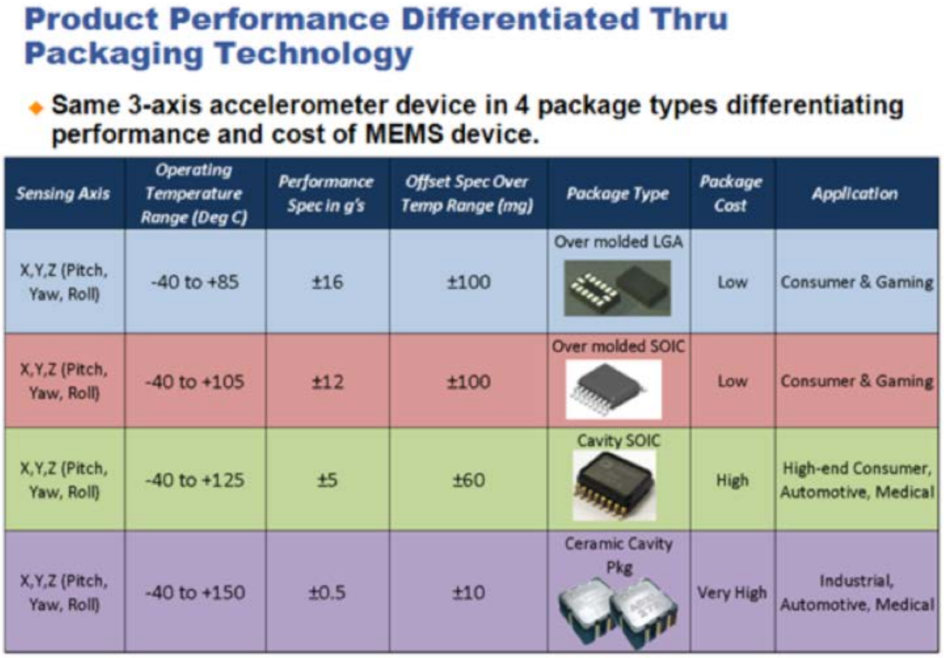
Packaging is a challenge for MEMS devices due to their sensitivity to mechanical stress. As the device performance is improving, packaging is becoming a key differentiator with respect to the overall product performance. The MEMS market is diverging into two segments. MEMS usage in the consumer market segment is rapidly and increasingly fueled by exploding application growth, particularly for the handset market. The consumer market segment is becoming commoditized and putting downward pressure on cost. The MEMS packaging for this segment of the market has adopted low-cost standard packaging solutions. The other end of market segment spectrum is driven by high performance MEMS products. These high-end applications are required by the industrial, military, medical, automotive and high-end consumer market segments. These applications are also on the rise and packaging for this segment is a particular challenge. MEMS packaging has become one of the top enablers of this market bifurcation thru product cost and product performance. This market bifurcation is illustrated in Figure MEMS14.

With regard to linear sensors, consumer MEMS applications are now using a standard over- molded plastic packaging solution. These MEMS devices tend of have wider specifications with respect to product performance (example: offset shift). With relatively wider specs, it is now possible to use today's existing lower stress material set to use standard over molded packages for these products. This has enabled the lower cost MEMS products which in turn have proliferated MEMS devices in all sorts of everyday consumer applications.

In the high-end applications market, the product specs are much tighter. A standard plastic molded package cannot be used for these ultra stress-sensitive devices or devices with tighter specs or for specialty MEMS products. Novel packaging approaches, primarily cavity type packages are typically used for these applications. Depending on the sensitivity of the device and the product spec, plastic or ceramic cavity package is used.

### *Packaging as differentiator for MEMS product performance*

Figure MEMS15 shows an example of how MEMS packaging solutions can differentiate product performance. It essentially shows how one can take the same MEMS device and, depending on what kind of package one puts it in, to truly differentiate product performance. This particular example shows how the same 3-axis accelerometer can be put in a standard over-molded plastic package (such as SOIC or LGA) and be targeted for the low cost, low performance consumer market. Putting the same accelerometer in a plastic cavity package can improve the performance but has higher cost compared to that of standard over-molded plastic package. Using a ceramic cavity package to assemble the same accelerometer will improve the product performance significantly. The cost of such a high performance package solution will increase significantly as well. The high-end cavity plastic or ceramic package can address the tighter specs for the industrial and automotive market for example. The key point is that as the MEMS devices are improving and the specs are becoming tighter, package is playing a much more significant role in either the success or failure of these products.

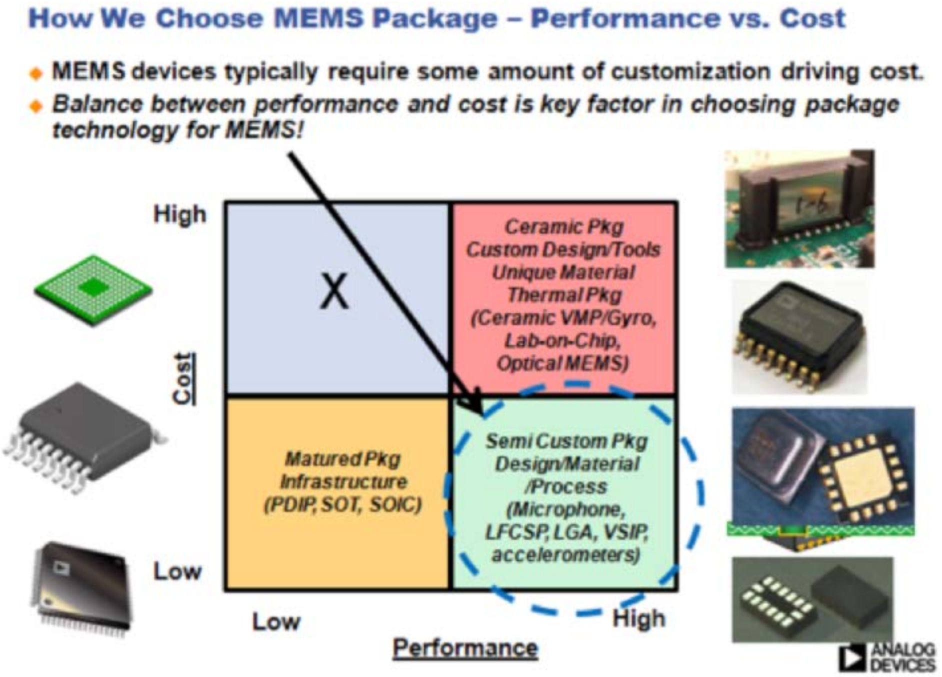


**Product Performance Differentiated Thru Packaging Technology**

- Same 3-axis accelerometer device in 4 package types differentiating performance and cost of MEMS device.

| Sensing Axis | Operating Temperature Range (Deg C) | Performance Spec in g's | Offset Spec Over Temp Range (mg) | Package Type | Package Cost | Application |
|---|---|---|---|---|---|---|
| X,Y,Z (Pitch, Yaw, Roll) | -40 to +85 | ±16 | ±100 | Over molded LGA | Low | Consumer & Gaming |
| X,Y,Z (Pitch, Yaw, Roll) | -40 to +105 | ±12 | ±100 | Over molded SOIC | Low | Consumer & Gaming |
| X,Y,Z (Pitch, Yaw, Roll) | -40 to +125 | ±5 | ±60 | Cavity SOIC | High | High-end Consumer, Automotive, Medical |
| X,Y,Z (Pitch, Yaw, Roll) | -40 to +150 | ±0.5 | ±10 | Ceramic Cavity Pkg | Very High | Industrial, Automotive, Medical |

*Figure MEMS15 How a package can differentiate MEMS product performance.*



**How We Choose MEMS Package – Performance vs. Cost**

- MEMS devices typically require some amount of customization driving cost.
- *Balance between performance and cost is key factor in choosing package technology for MEMS!*

*Figure MEMS16 MEMS package selection driven by cost versus performance.*

Figure 16 shows a performance versus cost chart as guidance for package selection for MEMS devices. Obviously the lowest cost is in the lower left quadrant with standard packaging but these types of packages do not support high performance MEMS products. On the other end of the spectrum, the top right quadrant shows specialized package solutions for MEMS. These packages do provide the high performance required by the devices but also are the highest cost package solutions. All the focus and development will need to be on the bottom right corner, which provides the best performance at the most efficient cost structure.

### *Pressing Needs and Possible Solutions for MEMS Packaging Technology*

The following is a list of the top needs in MEMS Packaging technology:

- *Integration of MEMS device and package design* – MEMS device design and package design should be done simultaneously. Failure to do so increases the risk of product launch failure. MEMS designers will need to understand the fundamentals of packaging while the MEMS packaging engineers will need to understand the mechanics of the key MEMS elements and the desired product specification upfront. Design FMEAs should be done holistically with the designers, manufacturing team, packaging team and the product test teams. At the end, the product and the package must be designed for one another. The term “package design” here is used broadly and also implies material selection and process controls.

- *MEMS specific material set development* – This is critical for the success and growth of MEMS, especially for the products to come down the cost curve. The largest infrastructure for packaging today exists in the area of transfer molded plastic packages. The increased MEMS device performance is making the use of these plastic packages for MEMS devices difficult if not impossible – clearly an over molded package induces higher stress on the device. Today’s lowest stress material set is not good for certain high performance. The MEMS manufacturers should collaborate closely with the material suppliers to develop the next generation material set specifically for stress sensitive MEMS devices. Having said that, there will always be certain MEMS devices which will drive custom package solutions such as DLP, pressure sensors, or perhaps even MEMS based RF switches.

- *Package standardization* - MEMS technologies require some sort of packaging standardization, so that costs can be lowered and the trend of a custom package for each MEMS device can be reversed. This can be achieved even for low stress cavity types of packages. One simple suggestion, among many to consider, is a line of cavity-type packages starting at 3×3 mm and with 1 mm increments to 7×7 mm. Packages should include a data sheet with all material characteristics and other key package parameters needed to accurately simulate the stress on the MEMS device and predict the packaged devices’ performance.

- *Advancement of 3D packaging technologies (TSV)* – Almost all MEMS devices are packages with a corresponding ASIC chip. Hence by definition MEMS packages are multi-chip packages. Stacked die technology is currently being used for package form factor reduction. The trend is to integrate multiple MEMS devices into a single package such as accelerometer and gyro or accelerometer, gyro and magnetometer sometimes even combined with a MEMS microphone. For such integration, System-in-a-Package (SIP) types of 3D package solutions will need to be used. The next frontier of the 3D package level integration is the development and wide adoption of TSV to stack the MEMS and ASIC. This will also lead to the Chip Scale Package (CSP) solution for MEMS devices.

- *Specialty package design and manufacturing* – Despite all efforts to customize and lower cost, some MEMS devices will always require custom package solutions. The best example of this is the MEMS microphone, which is one of the highest growth MEMS devices; propelled by its adoption in mobile phones. It essentially requires a package with a “hole” which serves as the sound port. DLP or light processing MEMS devices and fluidics MEMS are examples of MEMS products, which will also require some form of custom package solutions. The medical applications such as lab-on-a-chip and MEMS based implantable devices will be calling for very special material and process development such as organic based substrate.

## 4.4 TESTING

Testing MEMS devices is complex, requires sophisticated approaches and entails various challenges. The testing of these sensors involves a series of steps including calibration and validation, which in turn require applying external physical stimulus to perform both parametric and functional testing. Each class of device not only needs a test system capable of providing the required stimuli, but the physics of the stimulus, how it affects the device, and how data is processed and analyzed are key functions of these systems. With these features in mind, modular systems which can be expanded from very small volume engineering systems into high volume production automatic test equipment (ATE) systems is the direction the MEMS test industry is evolving today.

In order to meet the high volume and low cost requirements that are driving the MEMS market, the industry is undergoing a self-assessment in terms of how to reduce cost and become profitable. Being that capital equipment expenditure and test times are among the major drivers of the final device test costs in terms of cost/device, implementation of the design for testing philosophy has become a focal point for MEMS manufacturers. This philosophy is defined by design techniques, which add testability features to products, which in turn enable more efficient development and final product testing.

- *Standardization of Datasheets* – There is a lack of standard testing protocols for measuring device performance metrics reported in datasheets. This lack of standardization results in the inability of the customer to compare the cost and performance tradeoffs between the manufacturers. Instead, the customer must conduct their own performance tests or work with a third party to characterize and compare performance metrics. The MEMS Industry Group has recently published a *Standardized Sensor Performance Parameter Definitions* terminology document that defines performance parameters for accelerometers, gyroscopes, magnetometers, barometers, hygrometers, thermometers, and ambient light and proximity sensors. The group is now creating a new IEEE Standards Committee on MEMS Device Testing to publish this document as an IEEE Standard and to begin the process of standardizing testing protocols for each of the performance metrics.
- *Cost of test* - The cost of testing continues to rise yet system integrators expect prices to stay constant or even lower even with increases in performance and function - a non-sustainable situation. MEMS devices need to be stimulated mechanically—“shaken, rattled, and rolled”. These added requirements to the traditional electrical tests result in more expensive handler and longer testing times that result in lower throughput. The handlers also tend to be customized for each manufacturer. Standardizing the handlers may lower costs considerably. The cost of testing is also influenced by the requirements for tests by the customer, which may add expense but may not add any value. Standardizing tests on product performance, reliability, and device data sheets can also dramatically reduce the cost of testing.
- *Wafer-level testing* - A possible solution for lowering the cost of testing may be to move as much of the testing as possible to the wafer level. This will require knowledge and predictive models of and/or eliminate effects from assembly and packaging so that information from wafer level testing can predict the final packaged device performance. The goal would be to make the final tests of the finished device to become a simple verification of the expected performance. Wafer level testing should also be used to feed data forward in the process, including the designer, to improve designs and product yields.
- *Design for (no) test* - Also referred to as self-test/self-calibration. Another solution to lowering the cost of testing is to advance methods for self-test/self-calibration so that no testing is required. There is presently a lack of know-how for designing for testability and methods for self-test/self-calibration that can reduce the burden of test at the back end of manufacturing. Since design for test is very application dependent, methodologies will need to be developed for each device technology.
- *Accelerated reliability test methods* - There is a continuing need to extend knowledge of the physics of failure of MEMS devices. This is especially relevant for RF MEMS devices, where their adoption in many applications has been hindered due to reliability requirements. Extending knowledge of the physics of failure will enable methods to improve device reliability and to develop accelerated reliability test methods. Specific knowledge of reliability metrics and test methods resides in companies, but this information is not typically shared because it can be a commercial advantage to the company to keep it secret. Otherwise, the possible solution is to share the information that exists, evaluate gaps, and support R&D on developing knowledge on those areas that require it. Then, this knowledge can be applied to the development of standardized accelerated reliability test methods.

# 5 EMERGING MEMS AND MORE THAN MOORE

The MEMS Technology Working Group selects specific emerging MEMS technologies and applications in order to examine their suitability for adoption into our roadmapping process. This year, the TWG has selected “wearable” applications as a case study for exploring the concept of integration path as a case study for roadmapping More than Moore technologies.

## 5.1 WEARABLE TECHNOLOGIES

Examples of wearable technologies are shown in Figure MEMS17. Wearable devices are typically worn on the wrist, upper arm, chest, and head. They are used to measure the wearer’s movement, location (GPS), skin temperature, skin

Wearable Technologies

Devices

- Accelerometers
- Gyroscopes
- Magnetometers
- Pressure Sensor
- Microphone
- Temperature Sensor
- Conductivity Sensor
- Camera/Optical Sensor
- Micro Speakers
- eNose
- pH Sensor
- Humidity Sensor
- Galvanic Skin Response

Applications

- Caloric Consumption
- Exercise Intensity
- Exercise Safety
- Sleep Patterns
- Heart Rate
- Blood Pressure
- Walking Directions
- Gas Monitor
- Altitude
- Motion
- Shock
- Messaging
- Emergency Response

*Figure MEMS17 Sensors trends for "Wearable" technologies – The MEMS TWG has adopted this application as a case study for More than Moore roadmapping.*

conductance, etc. This data is then used to estimate caloric burn, distance and route travelled, sleep efficiency, etc. The wearer can use this information to become aware of how their living habits may impact their state of health and well being. For example, caloric burn can be used as a means to adjust diet in order to control weight gain (or loss). Understanding the quality of sleep may influence the wearer to become aware of and change poor sleeping habits and to arrange an optimal time for sleep.

The wearer typically uploads their data from their device to a website where it is saved, analyzed, and displayed. The data is uploaded by connecting the device to a computer or by using a wireless connection, often via Bluetooth, to upload by using an application installed on a smart phone. There are other types of devices gaining use that are not worn continuously throughout the day, such as weight scales and blood pressure cuffs, that also use this process to upload data.

Once the data is uploaded the wearer can view a summary and can also observe trends. For example, a daily summary might encourage the wearer to add a workout at the end of the day in order to reach a desired goal for caloric burn.. Trends can be extremely useful in helping the wearer become aware of the effects of their lifestyle and diet on the longer-term state of their health. Some websites allow the wearer to join groups to compete with others within their group and allow the wearer to choose to display their results and achievements on social networking sites such as Facebook. This sort of information can change deep-seated habits and help the wearer become healthier and/or achieve their fitness and health goals [23].

The number of users using these technologies is rapidly growing. For example, in late 2012 Nike announced that it had 10 million Nike+ users [24]. A Pew study published in January 2013 [25] estimated that 35 million US adults are currently using self-tracking technology. These wearable technologies have the potential to drive the growth of MEMS manufacturing in a similar way as the smart phones and tablets have.

## 5.2 MEMS SENSOR INTEGRATION PATH

The ITRS is well known for its success in roadmapping semiconductor technologies using the Moore's Law scaling paradigm. However, More-than-Moore (MtM) technologies, such as MEMS, do not necessarily follow such a scaling law. The MEMS Technology Working Group (TWG) is working as part of the overall ITRS effort on developing a paradigm for roadmapping MtM technologies. The group has engaged in discussions on the concept of "Integration Path" as a means for roadmapping MEMS. The concept of Integration Path is that integration of new sensing functions at the package or chip level happens incrementally. This idea comes from observing the evolution of the Inertial Measurement Unit (IMU).

The progression path of the IMU is illustrated in Figure MEMS18. It begins with discrete devices: accelerometers, gyroscopes, magnetometers, and pressure sensors. The next step (or generation) in the progression is where the accelerometers, gyroscopes, and magnetometers have been integrated as tri-axis devices. Then the tri-axis accelerometers and the tri-axis gyroscopes have been integrated together to create a device with 6 sensing functions. The progression path continues in the same way until the final 10 sensing function device, also referred to as 10 degrees of freedom (DOF) device, is developed. For the purpose of this discussion the example shown is simplified. Its does not distinguish between integration at the package level and integration at the chip level, or even specific types of package integration approached such as co-integration or 3D stacking. Also, the integration path might take other routes. For example, the 6-sensor device could just as well have been chosen to be a tri-axis accelerometer combined with a tri-axis magnetometer.

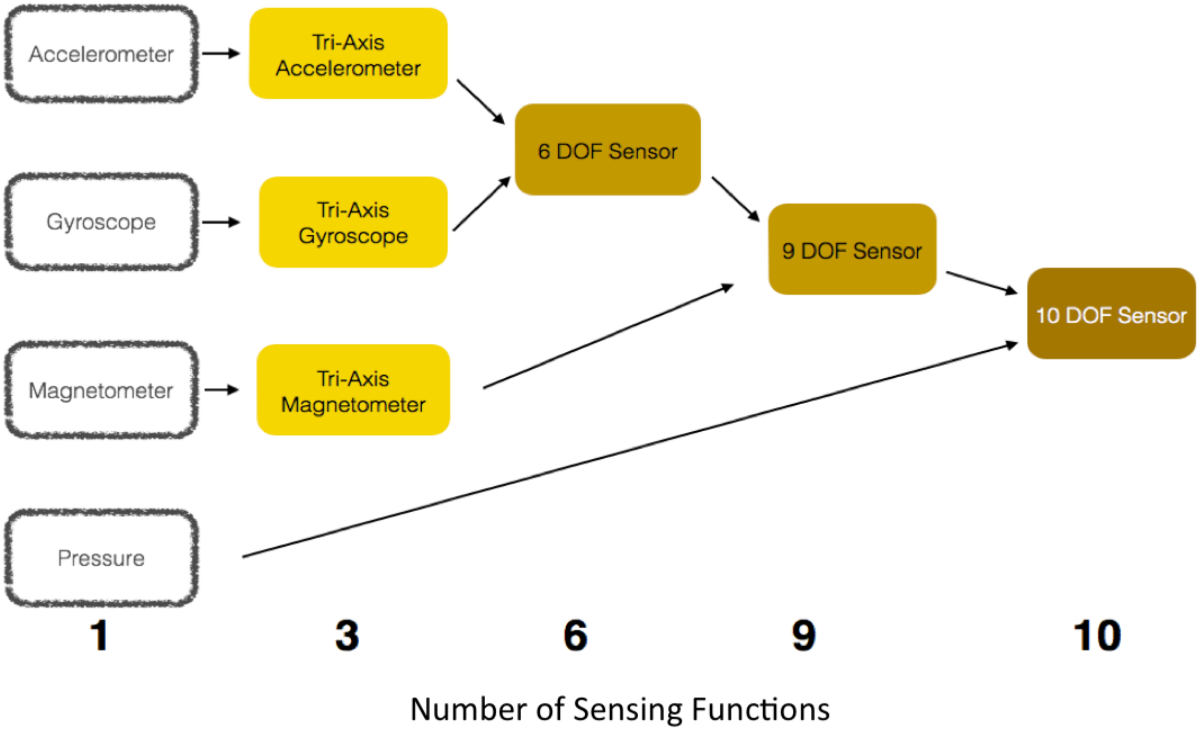


*Figure MEMS18 The concept of sensor Technology Path, illustrated by the evolution of the inertial measurement unit, is shown as the sequence of step starting from discrete sensors and then progressing to tri-axis devices, tri-axis combinations with 6 and 9 sensors, also referred to as degrees of freedom devices (DOF), and then finally the 10 DOF final product.*

The MEMS TWG is using Wearable technologies as a case study for MtM roadmapping using this concept of Integration Path. The left column of Figure MEMS17 lists the sensor technologies that are either currently used or envisioned to be included in wearable devices. The right column of the figure lists the types of sensing applications that is either already implemented or might later be implemented in these devices.

The paradigm demonstrated by the inertial measurement unit suggests that high volume applications are a key factor in driving device integration. Thus, one might expect that new devices would appear in wearables as discrete components. A high volume of manufacturing, as is the case for these consumer products, may be a requirement to drive the integration of the discrete components at the package level, especially since wearable technologies need to be compact, light, and consume low power while still continuing to provide ever increasing functionality.

The ultimate goal of our roadmapping effort is to discover those future gaps in manufacturing that must be solved in order for the industry to move forward. Thus, it is not so much for the purposes of technology roadmapping that a single Integration Path be developed or that even that the specific integration paths considered come true. In fact, considering alternate Integration Paths might further elucidate those gaps in manufacturing that require solutions and which industry is willing to collaborate in their solution.

# 6 CONCLUSION

The MEMS Technology Working Group has been roadmapping MEMS device technologies since 2010. The biggest challenge in starting our roadmapping effort was related to the large diversity of MEMS devices, processes, and applications. The working group's solution to this was to focus the scope of our discussions on a specific set of applications that fulfilled the minimum requirements for roadmapping [11], namely, MEMS technologies associated with smart phones and tablet computers. This selection was also aligned with the historical electronics domain of the ITRS; device technologies associated with microcomputers where smart phones and tablet computers can be considered to be the continuing step in their evolution.

The MEMS Chapter reviews the technology requirements for MEMS accelerometers, gyroscopes, inertial measurement units, microphones, and RF MEMS over the next 5 years. These technology requirements drive our discussion groups in design, fabrication, assembly and packaging, and testing, to discover crosscutting needs and technology gaps. A major outcome of our roadmapping effort is the observation that the back end of manufacturing, assembly, packaging, and testing, can consume ⅔ of the manufacturing cost. The back end is where the biggest challenges in manufacturing exist and is a topic of discussion where industry can share some information and collaborate in identifying possible solutions.

So far, our roadmapping effort is short term (5 years). The observations that we have made in our effort, exemplified by the evolution of the inertial measurement unit, suggest that MEMS technologies have a potential for long term roadmapping (>10 years) by considering integration paths for a specific application space. The working group is using "wearable" technologies as a case study for working with the concept of integration path.

Working with the MEMS Industry Group and iNEMI, we have begun to address the most pressing challenge that we have identified: standardization of testing protocols for MEMS device datasheets. In the past year, the MEMS Industry Group has developed and published a "Standardized Sensor Performance Parameter Definitions". A new IEEE Standards Committee on MEMS Device Testing is now being established so that this document can be published as an IEEE standard, and to begin standardizing testing protocols. iNEMI, in support of this, is beginning a MEMS Device Testing Project in order to survey current practices for device testing in order to develop industrial agreement on the adoption of standard protocols.

In the coming year we plan to complete our case study for integration path using the application of wearable technologies and contributing to the ITRS' discussion on cell phone on a chip. We also look forward to working with the iNEMI Project of MEMS Device Testing and supporting the adoption of MIG's Standardized Sensor Performance Parameter Definitions as an IEEE Standard.

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