HETEROGENEOUS INTEGRATION ROADMAP

2021 Edition

Chapter 11: MEMS and Sensor Integration

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Chapter 11: MEMS and Sensor Integration

1.1 Introduction and Scope

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This chapter focuses on sensors – MEMS in particular – and summarizes the current state-of-the-art in design and packaging of MEMS-based inertial sensors. This chapter acts as the technical working group's position paper and is intended to provide a framework for continuing the development of the roadmap for heterogeneously integrating sensor packaging technology in the future. It does not provide a historical view or overview of current and future challenges in packaging of discrete MEMS devices and sensors. In the context of the overarching goal of 'heterogeneous integration', the discussion in this chapter takes an upstream view in the signal processing chain by focusing on integrating sensors with other parts of the signal processing chain.

In this edition, the working group has chosen to focus the discussion and to define the issues for heterogeneously integrating MEMS-based sensors to other parts of the signal processing value chain as applied to automotive, handheld/consumer, and medical healthcare applications. It establishes background to continue expanding the scope of roadmap efforts by adding other sensor types, and to continue the visioning process for potential solutions. The chapter begins by discussing the challenges of formulating a heterogeneous integration roadmap. Then follows a discussion of MEMS packaging and assembly and the commonality of the MEMS signal processing value chain. Next, the applications of inertial sensors in automotive, consumer and medical/healthcare are reviewed beginning with a market overview.

After that, the heterogeneous integration technologies utilized in MEMS, the materials used in these technologies and the foundational technologies of co-design, simulation and modeling are presented. The chapter concludes by talking about how this chapter links to the other TWGs and discusses some challenges and opportunities on the roadmap ahead.

1.2 Creating a Roadmap for Heterogeneous Integration of MEMS Technologies

The goal of a roadmap is to provide a viewpoint on the challenges and a way forward for the future. Creating a one-size-fits-all common roadmap applicable to all sensor types is daunting. This problem is due to the vast variety of physics working principles, device types, materials and applications which create different requirements on heterogeneous integration. Hence, the working group's position is that **there is no single roadmap applicable to the heterogeneous integration of MEMS sensors**.

Traditionally, the challenges in the semiconductor packaging industry have been driven by the quest for continued miniaturization to enable faster, smaller, and more cost-effective devices. This trend has been fueled by continued shrinking of the physical geometry of silicon processes primarily in the digital domain. Unlike digital signal processing, sensors are unique in their manufacturing processes. Their functionality is not related to, or driven by traditional silicon-based approaches. Sensors are manufactured in a variety of different ways depending upon what aspect of real 'analog' they sense. In the context of this chapter, sensors are defined as devices that sense physical phenomena and convert them to electronic signals (i.e. electronic bits).

There is no single methodology that can be applied to all sensing modalities. In addition, shrinking a sensor does not always make it work better; there often must be a minimum size for a sensor to work because of the physics of the sensing. Also, we do not always have the same principle as there is in digital circuits of having large numbers of devices on a chip. Some devices can be integrated in array form or coupled together, but in other sensor types the integration of multiple devices is limited. Hence, there is no "Moore's Law" that guides sensor packaging. There is no photolithography-based density scaling or pin-count roadmap that can be used to develop a sensor packaging roadmap.

Sensors is a general term, typically used to identify every device that senses the real 'analog' world around us. The analog world around us consists of varied types of phenomena and elements such as motion, sound, magnetic fields, light, liquid, gas, materials, and more. Accordingly, there are multiple different types of sensing devices that industry continues to develop depending upon what phenomena is being sensed (see Figure 1).

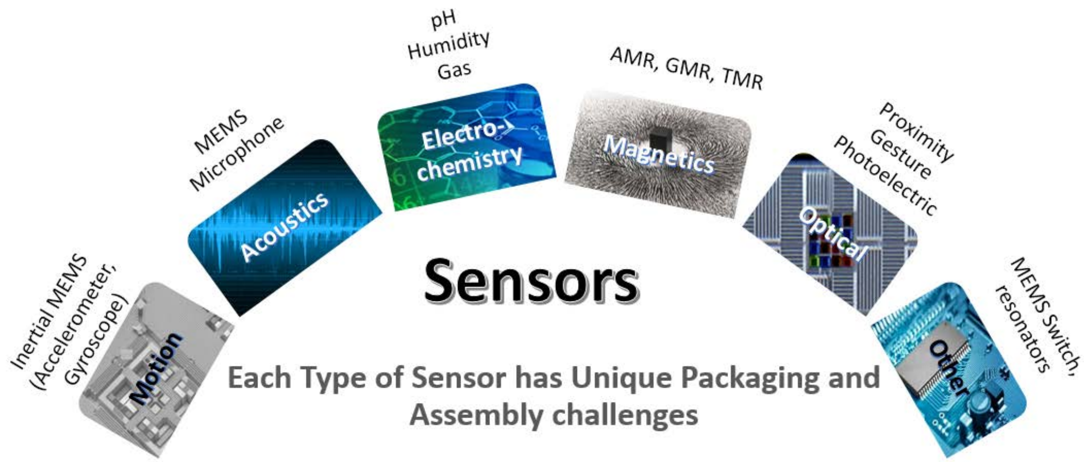

Figure 1: Different Types of Sensors based on sensing modality

To sense different physical phenomena in the analog world, the sensing elements and sensing methodologies differ significantly. Some examples are as follows:

- Motion is sensed by using the principles of capacitance, piezoelectric, or thermal conductance effects
- Change in light is sensed by the principle of photon reflectance and transmittance
- Acoustics or sound is sensed in a variety of different ways, viz. change in capacitance, or vibration in piezo-electric material
- Gases and chemical composition are sensed by electrochemistry
- Others…..

Packaging of sensor devices brings unique challenges, in that sensing elements are required to interact with the outside real world. Sensing sound requires an open porthole wherein sound can get into contact with the sensing element; a motion-sensing element is required to be placed in a moving part (or directly mounted on a moving part); gas or chemical sensors are required to be in a different gaseous or chemical environment; sensing optical elements must be directly exposed to the light; and similar other examples. While traditional semiconductor packaging challenges remain, sensors packaging creates additional different issues that must be addressed.

The major challenge in developing a Sensor Integration roadmap is that it can encompass any future electronics device that can sense and convert to an electronic signal. The potential for developing discrete sensors is infinitely varied and diverse. It becomes difficult, if not impossible, to predict what packaging approaches can be designed, or how these devices operate as discrete devices while being integrated with other electronics functions in a signal chain. This task is further compounded by the fact that each application may have different operational environments and performance requirements. For example, when it comes to operational environment, inertial MEMS sensors must be mounted on the moving element of the system, which is quite different than a gas sensor wherein packaging must have a physical opening for gas to interact with the sensing element. Furthermore, if we consider only inertial MEMS-based sensors, using them for automotive applications requires high reliability, repeatability, and long life; using them for consumer handheld applications requires lower cost, a short life cycle, higher mechanical reliability challenges, and relatively lower thermal challenges.

We see that in certain application spaces and certain types of MEMS, a set of common challenges allows application specific/device roadmap comments to be made. We will attempt to point out, for classes of devices/applications, etc, some requirements looking forward for 5-15 years and the challenges that lie ahead.

1.3 Commonality of Signal Processing Value Chain

The signal processing value chain remains more or less common across all applications. For implementing the use of electronic devices or electrical systems in any application – e.g. automotive, healthcare, mobile, etc – the basic functionality that is required includes sensing and actuating, conditioning, communications, storing, intelligent processing, and power management. Figure 2 shows the overall signal processing chain:

- Sensors which interact with the analog world consisting of different physical phenomena. These sensors are the bridge between the analog and digital world.
- Signal-conditioning functions that modify noisy, small, weak analog signals by various techniques of amplifying, modifying, and converting the digital signals.

- Digital signals are further processed intelligently by firmware methodologies, or miniaturized hardware platforms.
- Conditioned signals are transmitted downstream by various methods of connectivity in RF, microwave, or millimeter-wave domains.
- Cloud and/or data centers are the central locations where the digital signals undergo high-performance computing that enables interpretation, understand of phenomenon, and transformation for decision analysis, reactions, and predictions.

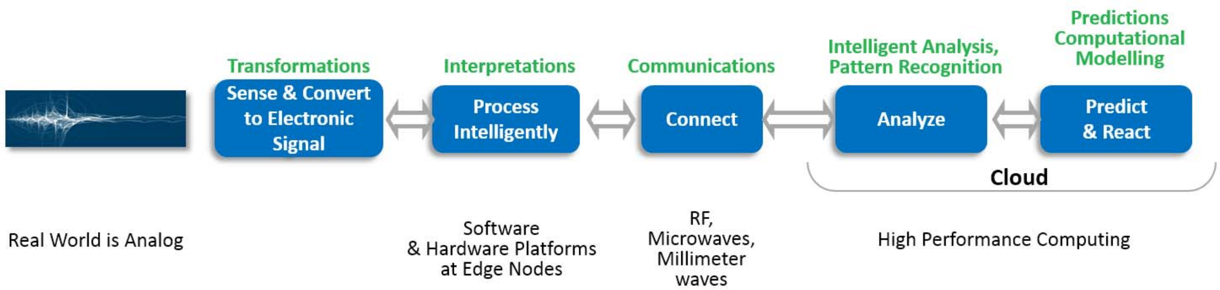

Figure 2: Sensor Signal Processing Chain

Sensors remain at the forefront of the "internet of everything". Continued advances in discrete sensors are enabling systems designers to increasingly digitize every phenomena in the real world. In the digital domain, systems designers are challenged by how to manage the deluge of digital data; in the hardware domain, system designers are challenged by how to integrate the hardware devices (i.e. device functionalities).

1.4 MEMS and sensor market overview

MEMS and sensors are at the heart of new features coming out in the latest generation of cellphones and wearables devices. The first iPhone introduced in 2007 had 5 sensors. The new iPhone12 and Galaxy phones contain up to 20 sensors. We expect this trend to continue as more and more sensors reach the power consumption specifications and small form factor needed for consumer applications. Besides phones, many verticals markets are becoming attractive to sensor makers.

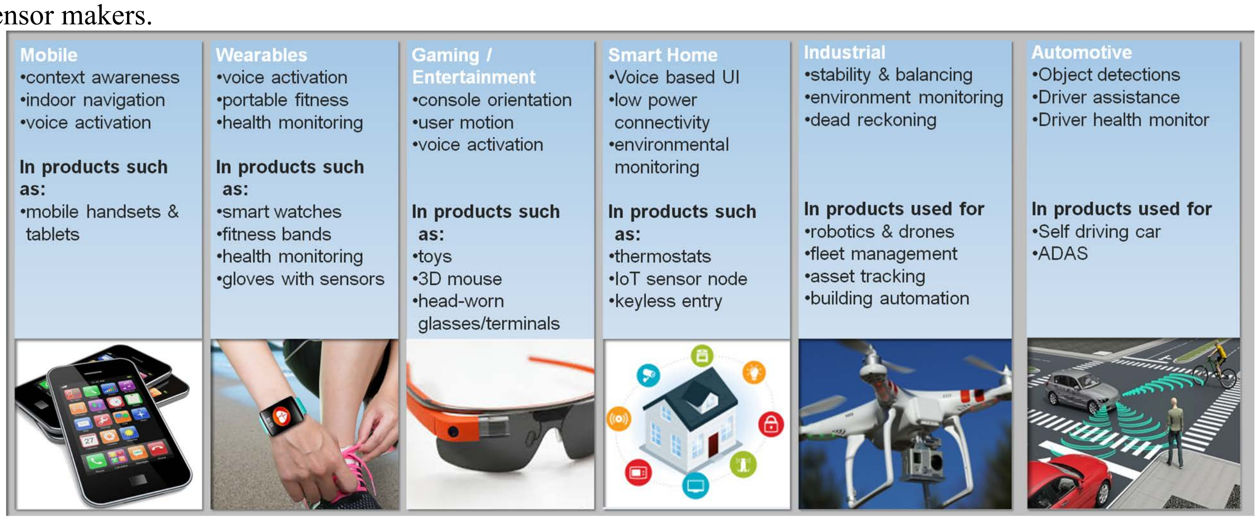

Figure 3. Product's function enabled by sensors

In Figure 3 we have listed 6 vertical markets with associated functions enabled by sensors. Starting with the first one, mobile phones can become context-aware through usage of sensors. A simple use-case is a person placing a phone close to the face. The phone changes the display light and UI based on this information. More complex situational awareness scenarios can be envisioned – for example, the phone understands you are taking the subway and provides information on the train-time table. In the automotive field, sensors are used to enable ADAS for different types of autonomous driving levels. This field is expected to drive a large adoption of different types of sensors. For example, inertial sensors need to improve to provide more accurate locations for GPS-denied conditions. The list of sensors needed in the most advanced cars keep growing: LIDAR, stereo camera, thermal camera, proximity sensors, etc. Even inside the vehicle the list of sensors keeps growing as car makers race for the ultimate user experience. Here we find air quality sensors, driver health monitoring sensors, as well as odor sensors. According to Yole Développement, MEMS-based sensors are projected to generate $18 billion in revenue by 2025 (non-MEMS sensor revenue will be even higher). This projected revenue spans broad market applications that include automotive, consumer, Internet of Things (IoT), medical, healthcare, military, aerospace, and industrial markets.

1.5 Automotive Application drives for integration of MEMS sensors

Automobiles are incredibly complex platforms wherein every aspect of driving such as safety, controls, comfort, infotainment, communications, and efficiency are now requiring the use of electronic signal processing technologies. Historically, the most common use of inertial MEMS is in various automotive passive safety systems such as air bag systems, automatic braking systems, electronic stability control, and roll-over detection. These are maturing applications wherein sensors have been integrated with ASICS. These discrete MEMS sensors are used within the automobile and work based on event-based detection; these sensors typically do not communicate back-and-forth with the vehicle.

This TWG sees three key drivers in automotive electronics, viz., (1) Autonomous driving; (2) Advanced driver assist systems and infotainment; (3) electrification of vehicles. The adoption of electric vehicles and the phased transition towards self-driving vehicles is changing packaging constraints due to integration that goes beyond the traditional IC packaging challenges. There are several companies that have made groundbreaking progress towards fully autonomous vehicles. Google/Waymo has been developing its self-driving technology using test cars riding on roads in several states generating driving-related knowledge-based experience. Uber has a dedicated test facility to develop experience to create an autonomous taxi fleet. Motional (erstwhile Nutonomy/Aptiv) has teamed up with Hyundai to commercialize Level 4 autonomous vehicles. Some of Tesla's electric vehicles have been equipped with hardware needed for self-driving.

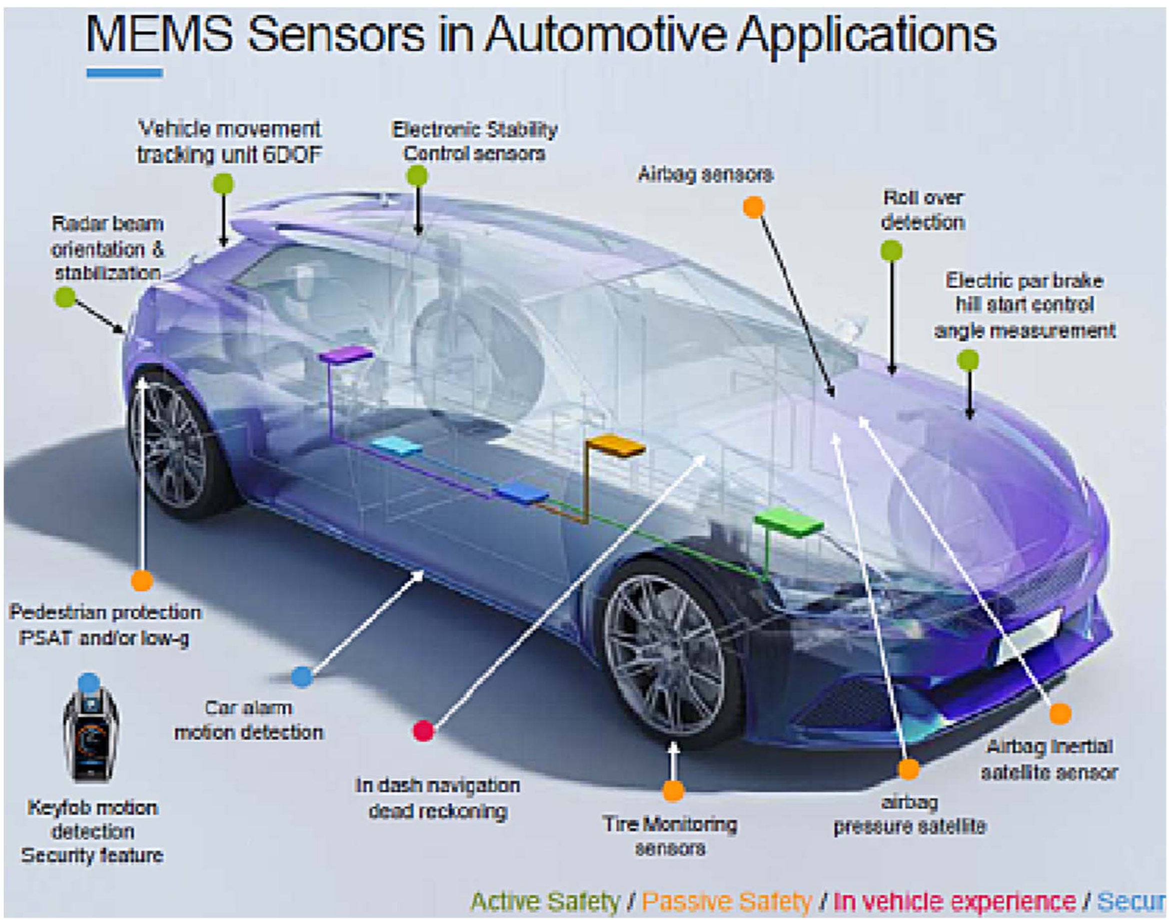

Figure 4: MEMS and Sensors in Automobiles

Emerging uses of inertial MEMS sensors for Automotive Vehicles

ADAS applications:

1. Key fob and Car alarm – motion detection as security feature
2. Hill start control and electric braking – Tilt measurement

Navigation applications:

1. Radar beams – orientation and stabilization
2. Vehicle tracking – dead reckoning, 6-DOF motion tracking

ADAS is a category that encompasses a variety of applications. There is a broad range of ADAS applications wherein inertial MEMS is making inroads for cabin comfort. Inertial MEMS-based vibration and tilt measurements are being used to design driver- and passenger-seat suspensions to automatically adjust for curves and bumps as a function of vehicle speed. Similar inertial MEMS-based sensors are mounted in suspension wells to detect road vibrations, which in turn is calibrated as road noise signature. These noise signatures are used to cancel the noise in the vehicle cabin, thereby increase cabin comfort.

Figure 5 shows optical images distorted by vibration. These vibrations can be a function of many different subsystems such as vibrations from the road, from the suspension, from the mounting of the optical sensor itself, etc. MEMS-based sensors that measure vibration can be mounted in the optical systems to correct this distorted noise and provide clear optical images.

Figure 5: Optical image distorted by vibration

Table 1 Relative Performance Specification for using Inertial MEMS in Applications

Metric	Typical Consumer	Typical Industrial	Typical Navigation /Avionics
Gyroscopes			
Noise Density (°/sec/√Hz)	0.02	0.004	< 0.004
Ang. Random Walk (°/√Hz)	TBD	0.2	TBD
In-run stability (°/hr)	>15	< 6	< 1
Bias repeatability (°/sec)	> 6	0.2	< 0.2
Accelerometers			
Dynamic Range (g)	< 4	> 40	> 12
Noise Density (µg/√Hz)	250	25	TBD
Vel. random walk (m/s/√Hz)	> 3	0.03	TBD
In-run stability (µg)	100	10	< 10
Bias repeatability (mg)	> 1000 X	25	
Power	Battery Operated, Ultra-Low power is must	Low power	Nice to have low power

There is increasing need for designing electronic parking systems wherein brakes get deployed automatically when parked on an incline. The system measures the inclination of the vehicle, determines how much braking force is required, and applies it. The key benefit of electronic brake systems is they can get rid of mechanically designed parking brake levers and associated hardware. This reduces the weight and cost of the vehicle – a necessity for efficient use of fuel or battery.

Autonomous vehicle navigation

The design of an autonomous vehicle requires that vehicles are tracking or are self-aware continuously at any given point in time. In today's vehicles, drivers (whether human or remote) rely on GPS-based navigation which relies on continuous availability of a satellite signal. However, satellite signals can be disrupted or distorted by tall buildings, tunnels, location on the earth's surface, etc. For autonomous driving, wherein there is no human or remote intervention, the continuous tracking of vehicles becomes a major problem in the absence of GPS signals, or distorted optical, LIDAR, or radar signals. An inertial MEMS-based sensor referenced to the gravitation force of the earth provides a foolproof way of knowing a vehicle's positioning at all times. Gravity remains constant at the surface of the earth. A MEMS-based inertial measurement unit (IMU) is part of a navigation device that uses continuous computations, linear motion and rotation sensors to continuously calculate dead-reckoning position, orientation, direction, and speed of movement of a moving object without the need for localized external references. Table 1 shows the typical specification required for IMU-based sensors for navigation to be able to provide centimeter-level position accuracy. In general, it shows the specifications required for autonomous navigation will be 10-100x in terms of precision relative to consumer applications.

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2. Davies, "Google's Self-Driving Car Company is Finally Here, https://www.wired.com/2016/12/google-self-driving-car-waymo/#:~:text=Starting%20today%2C%20the%20drive%20for,says%20Waymo%20CEO%20John%20Krafcik.
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1.6 Medical/Healthcare/Wearables

Medical Wearables devices which utilize accelerometers, gyroscopes, or IMUs as inertial sensors have a high potential in medical applications. They allow monitoring patient activity, helping patients in their rehabilitation progress, and even preventing seizures in cases of mental disorders. Today inertial sensors such as accelerometers and gyroscopes are mainly required for:

- Metabolic and cardiovascular monitoring
- Respiratory and movement disorder
- Assistance living/Fall detection
- Rehabilitation systems and therapeutics

Moreover, wearable devices offer a great opportunity for use of accelerometers and gyroscopes. Indeed, they can help people stay in shape thanks to activity trackers. Accelerometers may help save the lives of those who are elderly or who have difficulty standing. These sensitive accelerometers are used in fall-detection devices. They sense when someone has suddenly fallen by determining the change in their velocity and in the direction they are moving. If the device determines that the values for these two variables fall into the danger category, it will automatically send a fall alert to the medical guardian. Sensors and products for healthcare application are summarized in Table 2:

Table 2: Sensors and Products in Healthcare

	ECG	PPG	Microphones	Inertial	Ultrasound	Electro-chemical	Temperature	Pressure	EEG
Smartwatches	✓	✓		✓				✓	
Wristband	✓	✓		✓					
Patches	✓			✓	✓		✓		
Rings									
Earpods / Hearing aids	✓	✓	✓	✓			✓		
Smart glasses		✓							
Smart lenses						✓		✓	
Headset									✓
Smart clothing	✓			✓			✓		

Only for the purpose of healthcare applications

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Here are some examples of healthcare devices that include accelerometers:

Figure 6: Philip's smart watch

Figure 7: Apple Smart Watch

Figure 8: BioStampRC

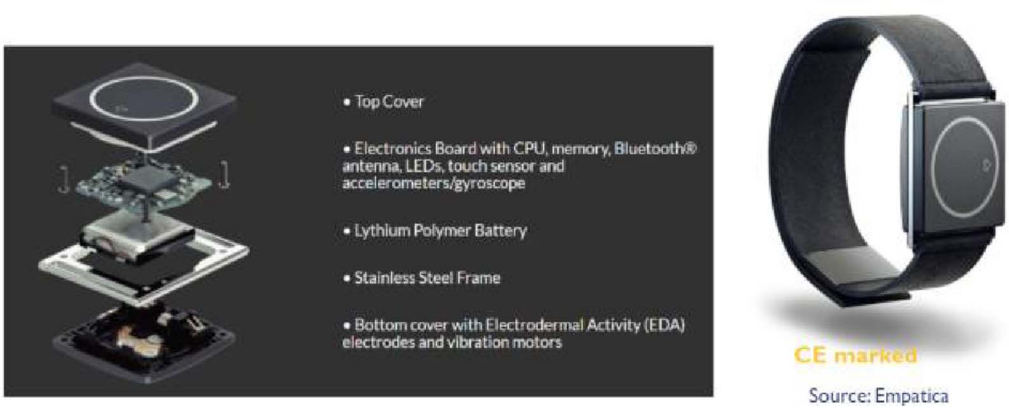

Figure 9: Embrace watch

- Philips's smart watch is a connected health-monitoring unit that includes a blood pressure monitor, scale, watch, and thermometer. It is equipped with an accelerometer and optical heart rate sensor.
- Using Apple Watch's accelerometer to detect micromovements, the software captures when the wearer is sleeping and how much sleep he or she gets each night.

- The BioStampRC is a flexible, wearable non-invasive sensor specifically for medical research to capture movement and biometric data. It contains an accelerometer, 6-axis gyroscope, and electrodes to capture electrophysiological data, such as from an EMG or ECG.
- The Embrace watch is a wrist-worn wearable for epileptics. It detects possible convulsive seizures and instantly alerts caregivers:

Example motion sensing requirements are specified by Analog Devices in Table 3:

Table 3: Motion Sensing Requirements

	Pedometer	Fall	Optical Heart Rate	Tap (SW)	Sleep	Motion Switch	ECG	ADXL362/ ADXL363
g Setting	2 *g*	8 *g*	4 *g* or 8 *g*	8 *g*	2 *g*	2 *g*	4 *g* to 8 *g*	2 *g* to 8 *g*
ODR (Hz)	100	400	<50	400	12.5	6	<100	400
Power Consumption	1.8 µA	3 µA		3 µA	1.5 µA	0.3 µA		10 nA to 3 µA
FIFO (Sample Sets or Time)	150	Deeper is better	1 sec	Deeper is better	20	No	1 sec	512 sec or 13 sec
ADC	No	No	Yes	No	No	No	Yes	No/yes
Noise (m*g*/√Hz)	<1	<1	<1	<1	<1	<1	<1	175 µ*g* to 500 µ*g*
Data Collection	24/7	24/7	Sporadic	24/7	On motion		Continuous during exercise	All
Required Feature	RSS, 8-bit	Trigger mode FIFO		Trigger mode FIFO	Low noise	MCU off		All except RSS

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Medical implant

Miniaturization in the field of sensors and electronic microsystems is a tremendous opportunity for implantable medical devices. Indeed, the size of components allows considering placing them in places of the body hitherto impossible (the heart, the eye, the ear, an artery, a muscle, bone, etc.). It is possible to measure pressure, temperature, blood flow or to stimulate electrically or mechanically as close as possible to desired areas. So far, in the case of implantable devices, electronic components are placed in a titanium box, which is introduced beneath the skin under the pectoral muscle or in the clavicular region. An electric probe then connects the housing to the location of measurement or treatment. An example of such a titanium case is shown in Figure 11. In order to enforce ethical behavior among manufacturers of medical devices, various national and supranational regulatory organizations exist. Most export markets accept the norm ISO 10993 for the biological evaluation of medical implants. Biological effects have to be studied according to the nature of body contact and duration, such as cytotoxicity, sensitization, irritation or intracutaneous reactivity, systemic toxicity, subchronic toxicity, genotoxicity and heaemocompatibility. So, there is a long process for introducing a product into the market.

Figure 11: Cardiac stimulator (with permission of Medtronic)

Figure 12: Accelerometer for medical application

Cardiac activity

Moderate leisure-time physical activity is safe and clinically recommended for most patients with cardiovascular implantable electronic devices (CIEDs) (ie, implantable cardioverter-defibrillators [ICDs], cardiac resynchronization therapy [CRT], and pacemakers). Most implanted devices automatically collect and store daily physical activity data obtained from an internal sensor, incorporated for the primary purpose of rate-responsive pacing. As the patient moves or accelerates, piezoelectric crystal sensors detect changes in the frequency and amplitude of body motion, generating an electrical signal that is proportional to patient movement. Modern pacemakers employ MEMS accelerometers. Medtronic is a leading manufacturer of MEMS-based defibrillators and pacemakers. The main advantages of using accelerometers are their simplicity, reliability, low energy consumption, use of standard leads, high sensitivity at the onset of exercise, and high correlation between physical performance and rate acceleration, observed under various conditions, including walking and daily life activity. Furthermore, the response is more physiologic than with a piezoelectric sensor, because it is less sensitive to vibrations and is more closely correlated with the level of exercise. As an example, ST commercialized an ultra-low-power high-performance three-axis linear accelerometer with digital I2C/SPI serial interface standard output. The MIS2DH is a device that has been conceived for medical and healthcare applications, including body-implantable products, whenever the sensor itself is not used as a life-sustaining component. It has user-selectable full scales of ±2g/±4g/±8g/±16g and is capable of measuring accelerations with output data rates from 1 Hz to 5.3 kHz.

Today, the challenge is to achieve an encapsulation of silicon die as small as possible. Depending on the device being encapsulated, different approaches are suggested. As an example, Medtronic proposed recently the miniaturized Micra™ Transcatheter Pacing System (TPS) which is delivered percutaneously, via a minimally invasive approach, directly into the right ventricle and does not require the use of leads (Figure 13). The capsule weighs 1.75 g and its volume is 0.8cc.

Figure 13: Micra™ transcatheter pacing system (with permission of Medtronic)

Vestibular implants

MEMS such as accelerometers and gyroscopes may have strong interest from the medical field for vestibular sensory loss. This serious disturbance causes an individual to suffer visual blurring during head movement and disequilibrium. Nausea and vomiting are common side effects. Bilateral vestibular sensory loss is disabling. Existing publications indicate several hundred thousand patients in Europe and the USA and several million patients worldwide. After intensive research starting in the mid 90's, suitable technological concepts are ready to increase the quality of life of patients affected by vestibular disorders. Such a neural prosthesis will be able to restore vestibular information by stimulating the semicircular canals thanks to the information provided by motion sensors. Figure 14 shows a representative device concept.

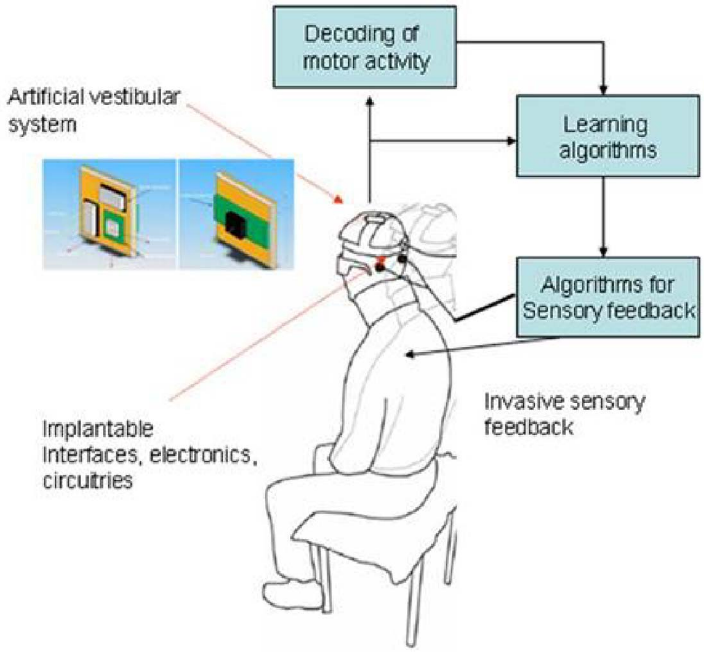

Figure 14: Device concept of a functional vestibular prosthesis

A vestibular implant needs to detect head and body movements with respect to external space. The availability of miniaturized linear acceleration and angular velocity sensors is indeed crucial for its development. The signal processing, electric stimulation and electrode development, even if peculiar to the specific motion information that they have to deliver to the nervous system, are roughly equivalent to the established cochlear implant.

References:

Activity sensor (https://www.cardiocases.com/en/pacingdefibrillation/specificities/programming-exercise/medtronic/medtronic-sensor)

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https://books.google.fr/books?id=1kSTIvrqN4sC&pg=PA146&lpg=PA146&dq=accelerometer+cardiac+stimulator+market&source=bl&ots=VrUXVS46xV&sig=ACfU3U2dcehvYWPTw8ltVyU0kXrQ_CWUPQ&hl=fr&sa=X&ved=2ahUKEwikn9md0JzqAhVRzIUKHQFBBUkQ6AEwAnoECAkQAQ#v=onepage&q=accelerometer%20cardiac%20stimulator%20market&f=false

1.7 Mobile/Consumer accelerometers, gyroscopes, magnetometer

MEMS and other types of sensors are essential to the success of the mobile space; the ability to sense the world is key to the experience of the users. The modern smartphone houses a variety of sensors that gather input from the environment. The phone can track your movements for health tracking (accelerometers), GPS, compass heading, and microphones for sounds (“Hey Siri” and “OK Google”). Most of these sensors are implemented using MEMS. For example, the MEMS microphone that can pick up your voice over the ambient noise around you is more sensitive and much smaller than what was available just 3-4 years ago.

The iPhone 11 has 7 different MEMS devices, as follows:

1) compass
2) accelerometer/gyro
3) pressure/barometer
   and
4) four MEMS microphones

A MEMS device is also responsible for the rotation when you change the phone position from portrait to landscape. A MEMS accelerometer from STMicroelectronics supplies information for all three axes, covering a range of +/-2g’s. These are useful for most phone-related uses but also enable gaming on a handset where you can tilt or turn your phone to provide input to a game.

The added challenge for adoption in the mobile space is to make the devices smaller, to consume less power and to cost less. The smartphone is the main driver of the mobile space, but these requirements also apply to IoT, laptops, tablets and other mobile devices. With more functions going into smartphones to better sense the world, there will be less space available. Everyone wants a phone that does not require constant charging; this will mean that battery and display will take up as much space as possible, so the balance of space is left for the other major components. Figure 15 shows the common devices in our phones today, and Figure 16 shows the space occupied by the battery in an Apple iPhone X.

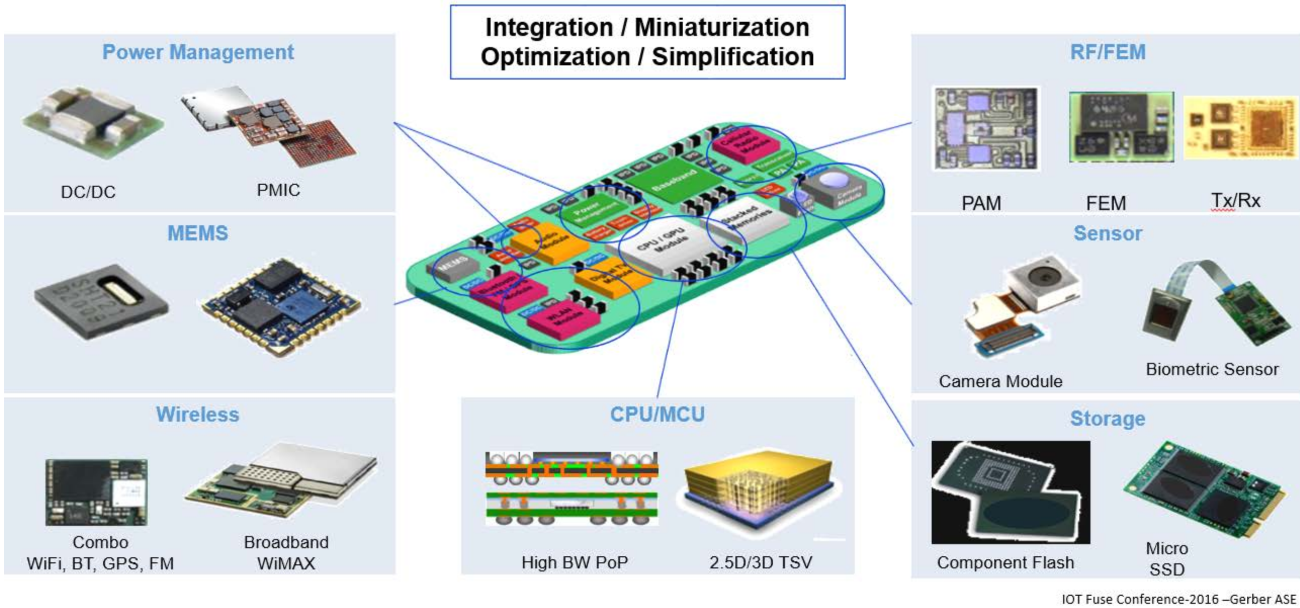


Figure 15: Common Devices in Phones

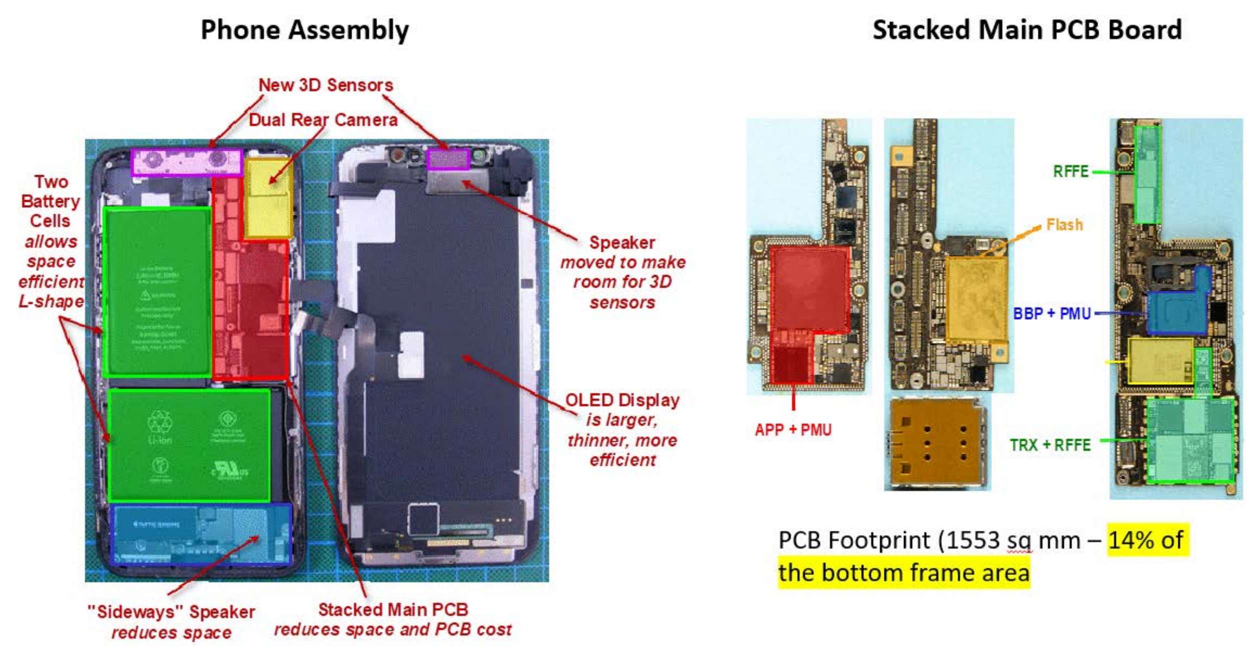
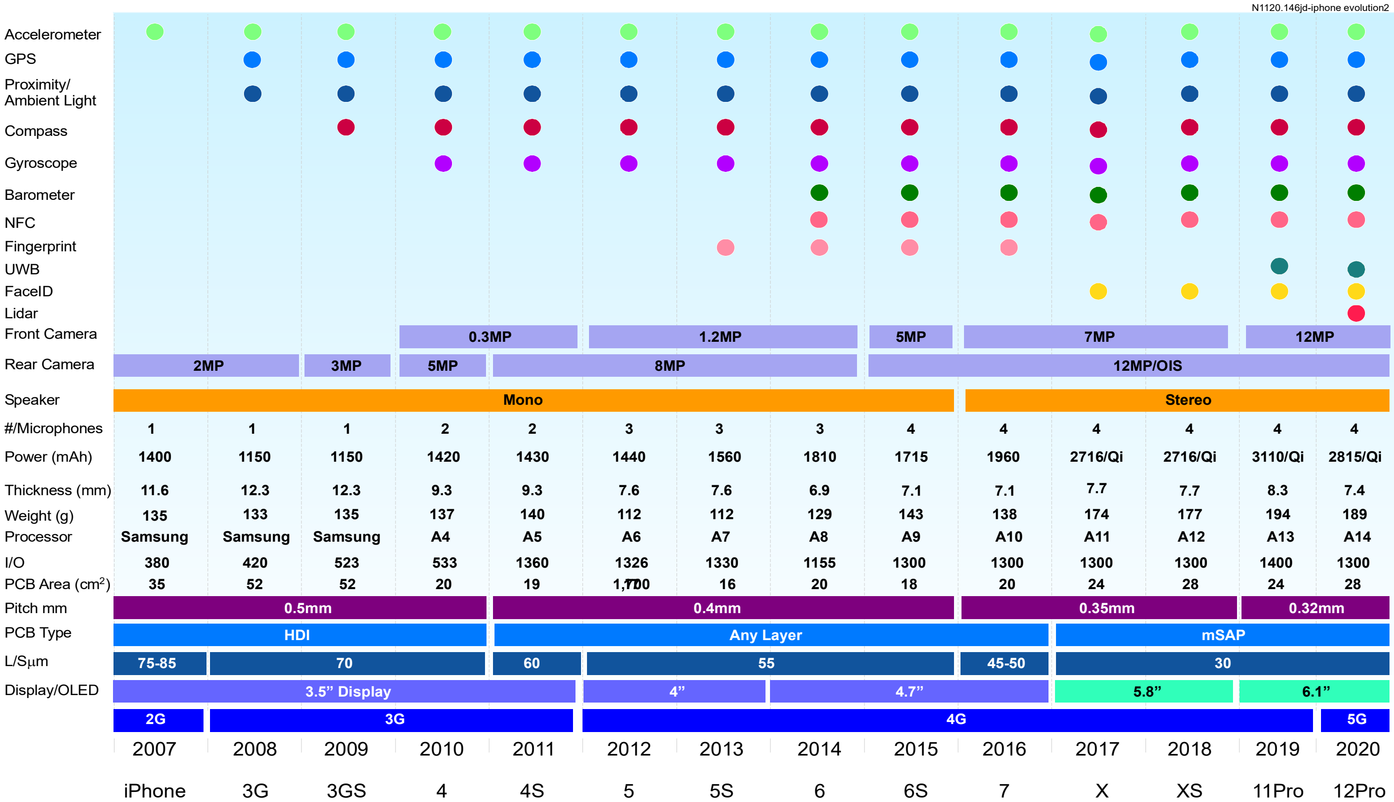


Figure 16: Space allocation in an iPhone X

Figure 17 shows the evolution of the Apple iPhone from the very first in 2007 to the iPhone 12 today; the upper section shows the integration of new sensors into the phone along with the technologies needed to support these devices in terms of substrate technologies, battery power, interconnect pitches, etc.



Note: Specs for main model - not larger display or lower priced versions

Figure 17: iPhone evolution

1.8 Summary of MEMS Integration Package Structures

We will now discuss the specific technologies by which MEMS are integrated with other parts of the system. We will begin with the first part of the signal chain, which is MEMS coupled to its driving/sensing electronics. We will then cover multiple-sensor integration and some application-specific integration issues. This section will be followed by a review of some key technologies used in the heterogenous integration of MEMS.

Monolithic Integration

There are multiple ways in which MEMS are combined with their driving and sensing electronics. Monolithic integration involves creating a fabrication process capable of supporting both the MEMS and circuit functions on a single substrate.

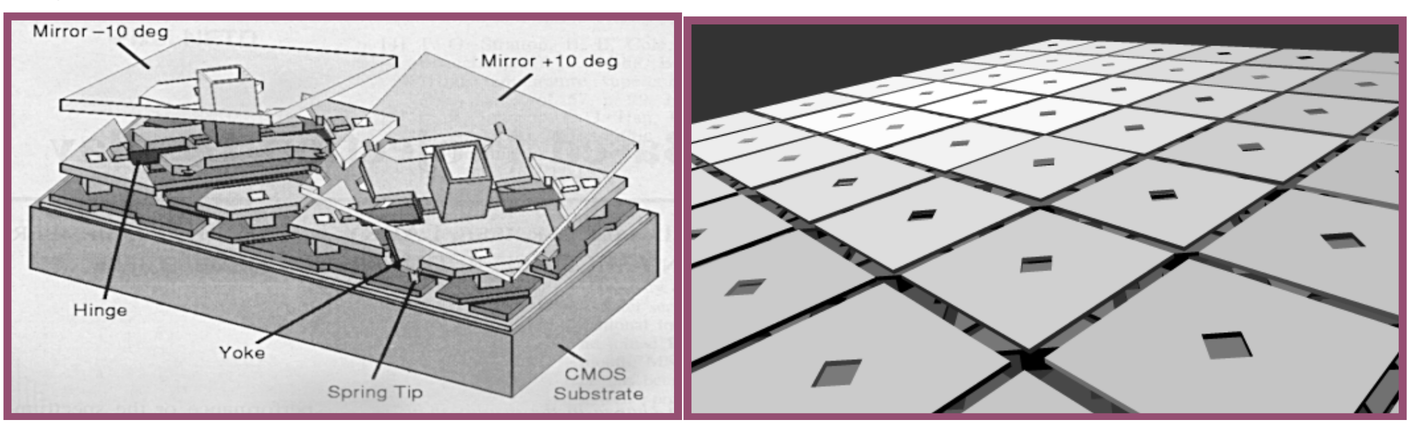


Figure 18: Texas Instrument’s DMD Technology

In the TI DMD shown in Figure 18, an array of tiltable MEMS micromirrors are built above CMOS logic address cells on a CMOS substrate. This type of integration enabled a compact form factor and good fill array factor.

Often a special area is reserved for the MEMS, as in the Analog Devices acceleration sensor shown in Figure 19. The MEMS sensor is created in the center of the die and the analog electronics surrounds it.

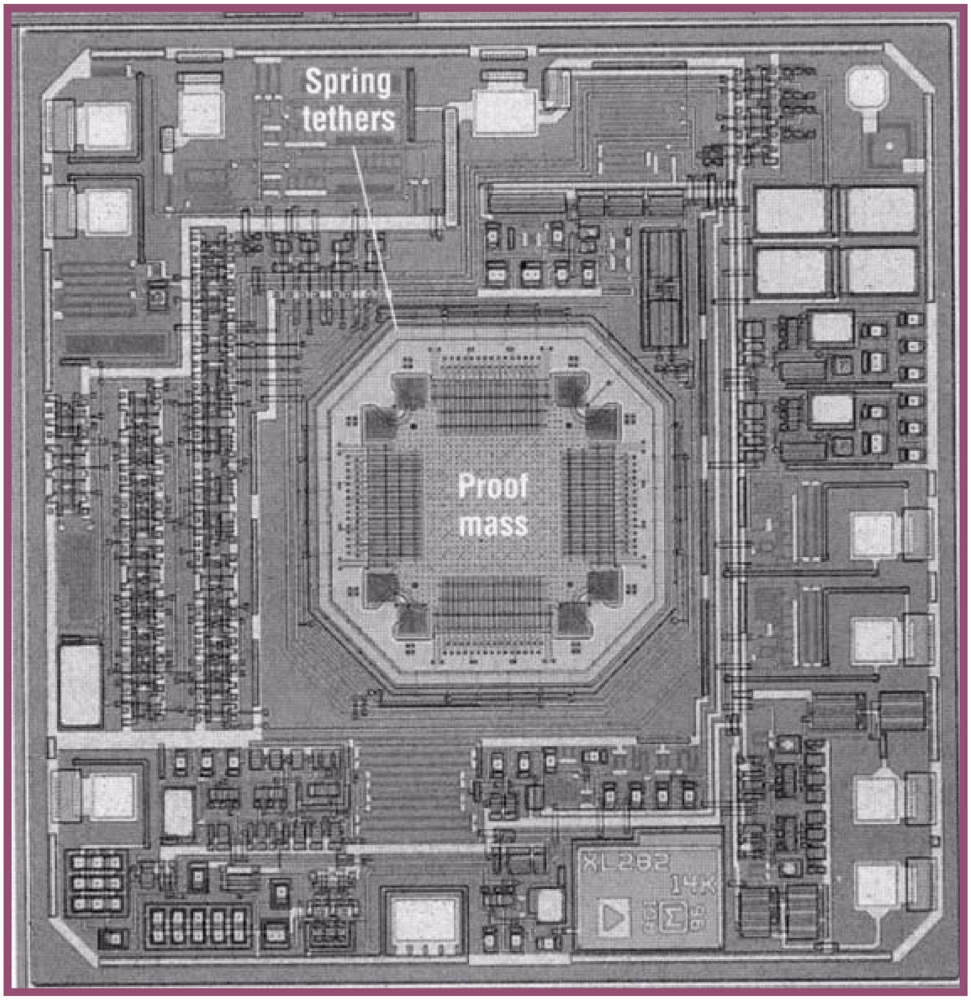


Figure 19: Early Analog Devices acceleration sensor.

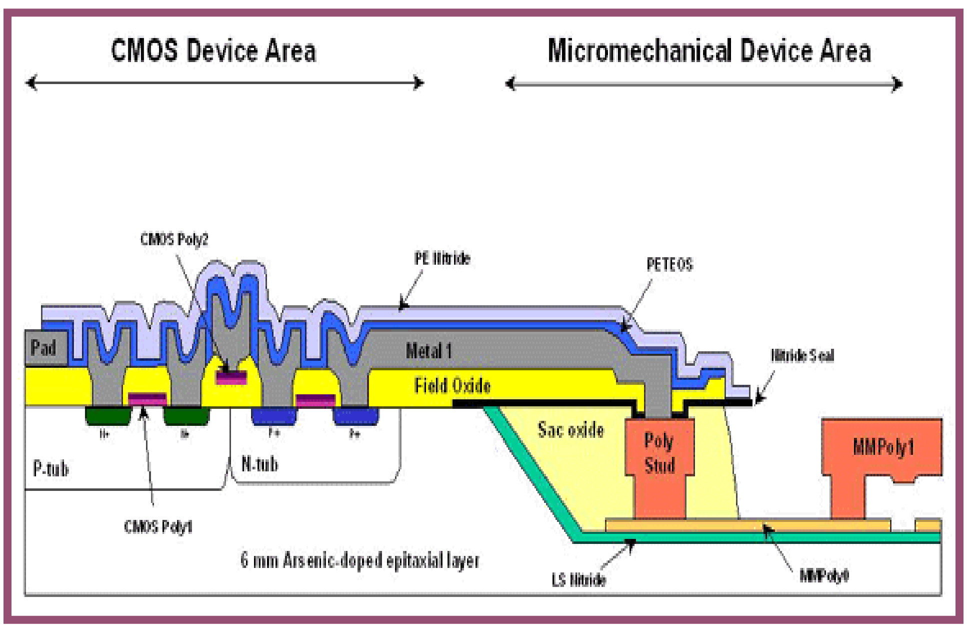


Figure 20: Integrated MEMS process from Sandia National Labs

In the Sandia integrated MEMS process shown in Figure 20, the MEMS are built first in a well and then the CMOS is added. In addition to the examples here, there are many more variations of integrated processes. The advantages of an integrated process are that signal processing and temperature compensation circuits are easily included on the same die. The sensing circuits are close to the sensors themselves. Some of the challenges are:

- MEMS and IC must have compatible processes
- Temperature budgets for the MEMS process limited due to the CMOS
- Materials compatibility; some preferred MEMS materials are not allowed in CMOS fabs
- Cannot use a Known Good Die approach with the MEMS

MEMS in CMOS (aka CMOS MEMS), CMOS Postprocess

CMOS MEMS uses the stack of IC gate and metal interconnect layers to form beams that act as the mechanical MEMS structures. The silicon substrate is etched away to free the structure. The top metal is used to mask the creation of mechanical structures.

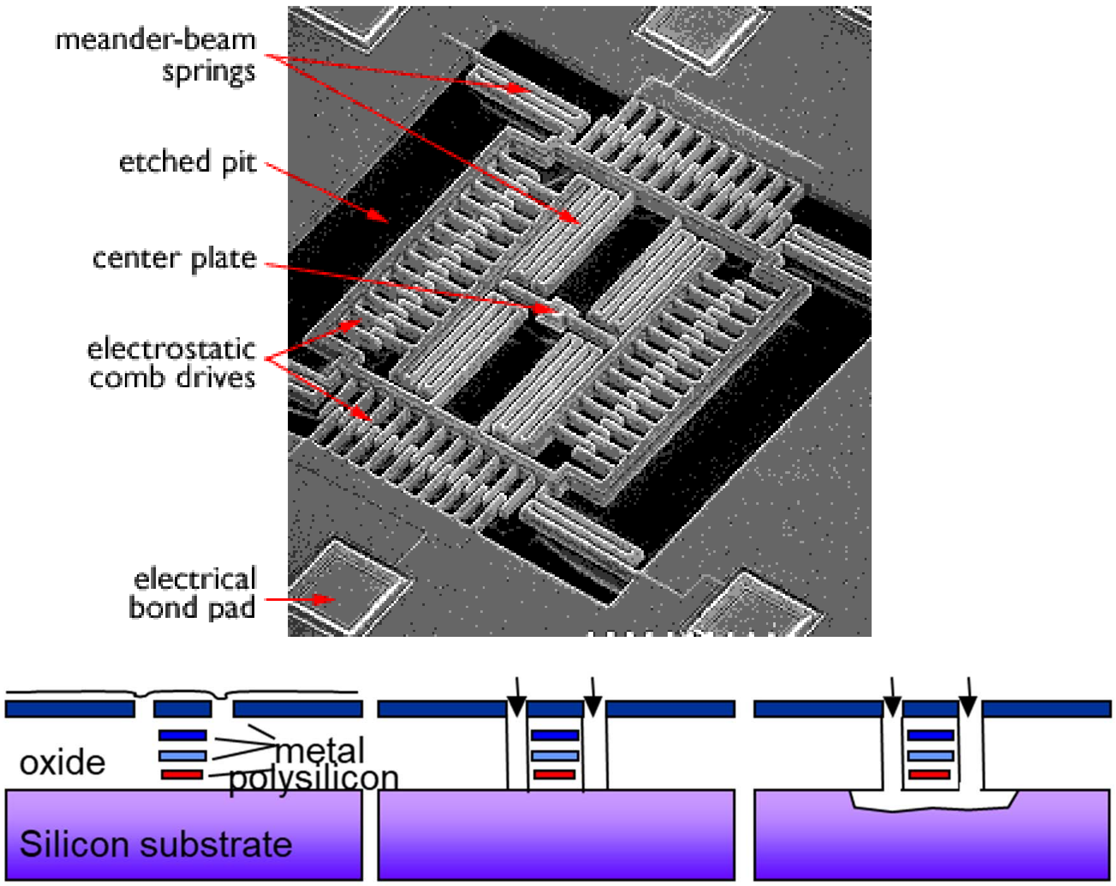


Figure 21: MEMS from CMOS – Courtesy of Carnegie Mellon University

"CMOS MEMS" Advantages: Very cost-effective due to wide availability of CMOS, easy integration with electronics. Some challenges are that mechanical properties are not optimized in CMOS in general. (This is changing, as CMOS foundries want flat layers too.) Additionally, issues with this type of integration are that the mechanical properties of the CMOS structures may not be well known or controllable, leading to unwanted stress in the MEMS beams when they are released.

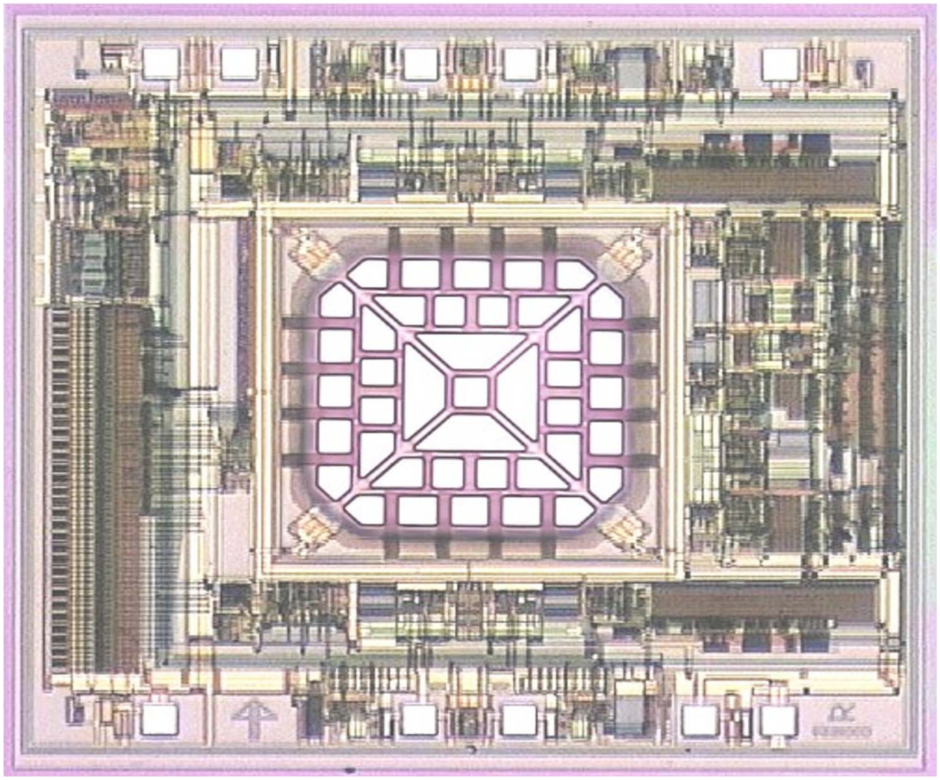


Figure 22. MEMSIC Thermal Acceleration Sensor

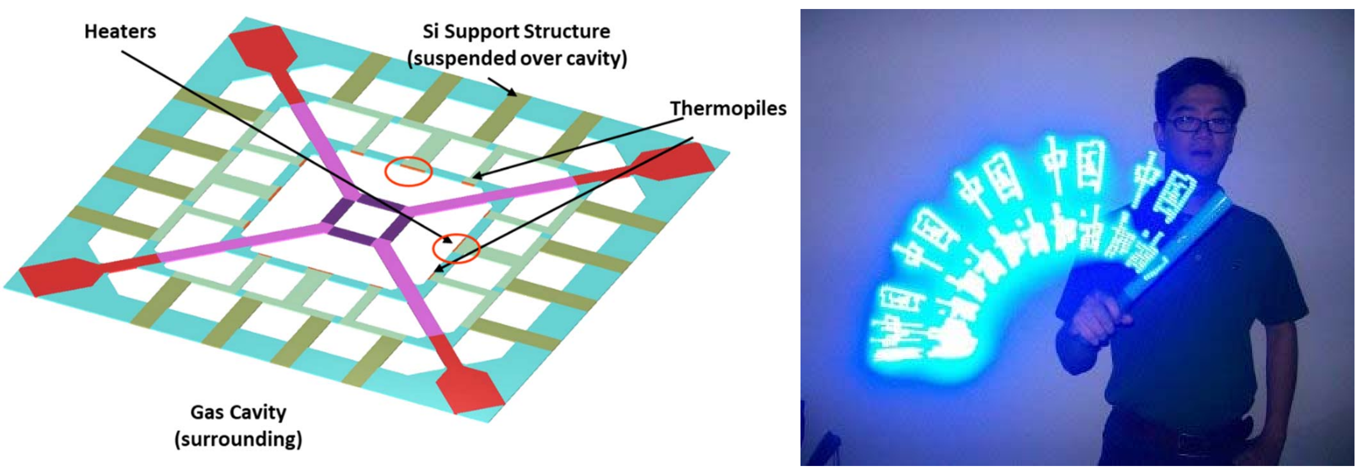


Figure 23: MEMSIC Thermal Acceleration Sensor Detail and Product

In the technology from MEMSIC shown in Figure 22 and Figure 23, an acceleration sensor is created using heaters and thermopiles fabricated in the CMOS process using the polysilicon layer. The acceleration sensor is integrated with circuitry such as an OTP memory, mixed-signal processing, digital filtering and temperature compensation.

MEMS-on-Top to Wafer-Level Integration

In the MEMS on top of CMOS, MEMS structures are built after the CMOS layer stack is constructed, or a separate MEMS wafer can be bonded or attached to the CMOS wafer. For example, in the technology from IMEC shown in Figure 24, micromirrors are built on top of foundry high-voltage 0.18µm CMOS 200mm wafers with 6 interconnect levels. The structural and mirror material is SiGe. This technology is part of their "CMORE" technology platform for heterogeneous integration.

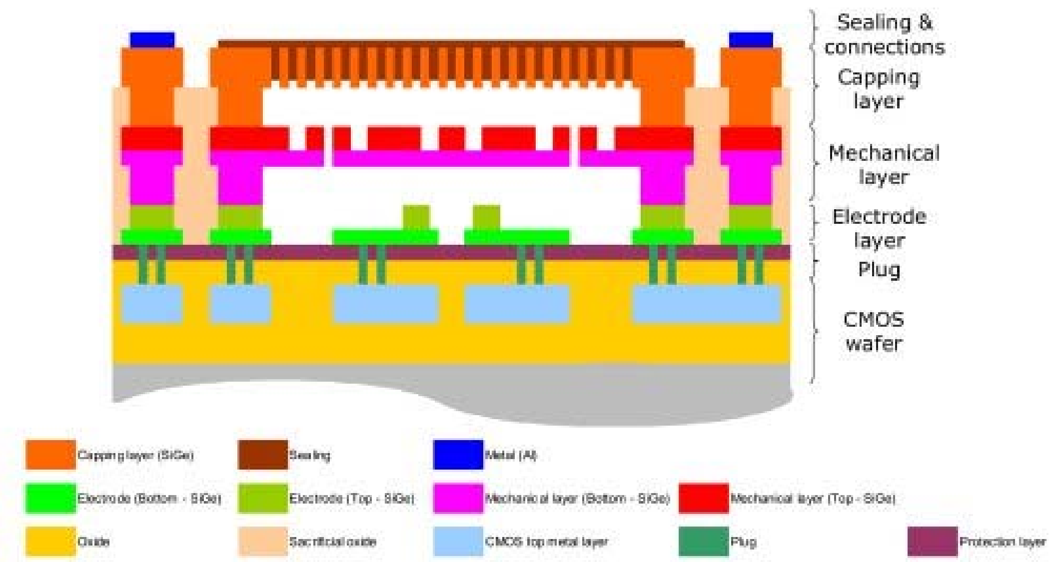


Figure 24: IMEC's "CMORE" technology

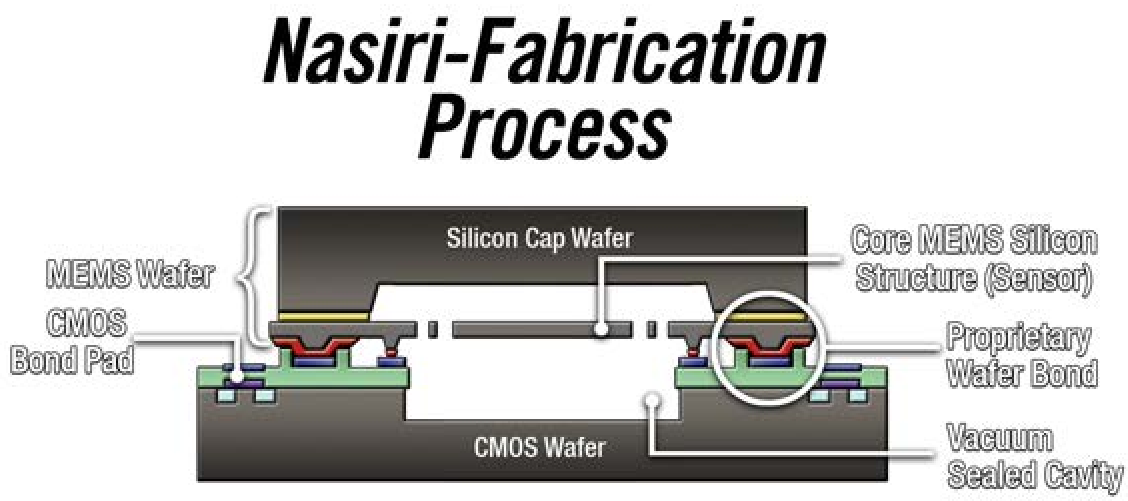


Figure 25: Invensense "Nasiri" process technology

Various methods of connecting separate IC and MEMS wafers can be utilized. One such example, shown in Figure 25 uses a proprietary wafer bond to connect a CMOS wafer with a MEMS wafer that has been capped with a cap wafer. An interposer wafer/layer may also be used for redistribution in the integration of 2 die for redistribution and addition of passives etc. Some characteristics of this integration approach are:

- Can optimize the MEMS and IC processes separately
- Parisitics and signal integrity not as easily managed as in monolithic integration
- MEMS usually capped

Separate Die Integration

One of the most common early integration methods is to have two chips placed side by side and wire-bonded as shown in Figure 26 from NXP (Freescale at the time of the photo). The MEMS device is shown on the right and is capped.

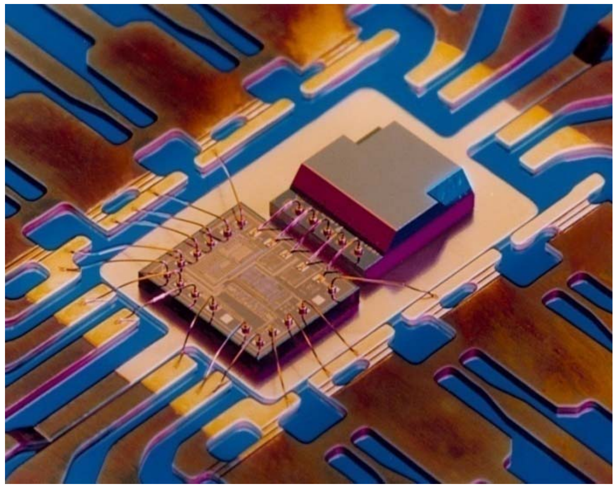


Figure 26: Side by side integration of ASIC and MEMS from NXP (formerly Freescale)

The side-by-side configuration is still used today. Another popular integration method is chip stacking with wirebonding between the chips. Again, the MEMS is usually capped and the edges are exposed for wirebonding.

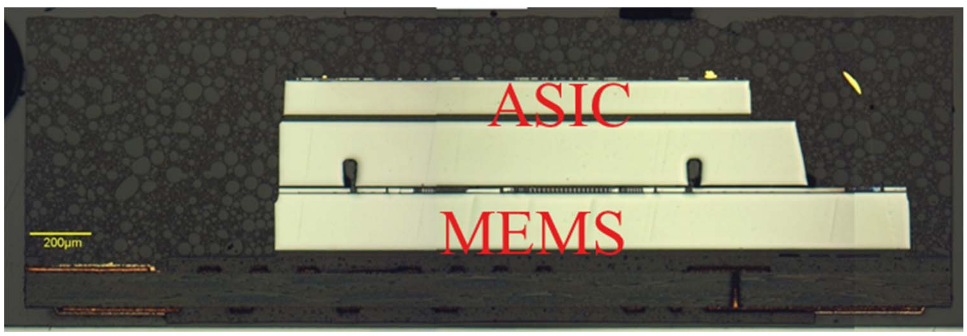


Figure 27: Chip stacking with wire bond

An interposer may also be used in the integration of 2 die for redistribution and addition of passives, etc. There are many variations of monolithic vs hybrid integration utilized in MEMS. However, some general comments can be made. Typically, monolithic integration offers the smallest overall form factor, and reduces the amount of external influence, but requires a more complex fabrication process that is more expensive and does not allow for pre-sorting chips into known good die. This is a big issue, as MEMS yields are not as high as IC yields currently. Using hybrid integration allows independent optimization of electronics and mechanics, and a reduction of process development time, but at the expense of more complex mounting and packaging

Multiple Sensor Integration

Many MEMS applications require the integration of 1 or more sensors. For example, navigation requires typically a gyroscope, an accelerometer and a magnetometer and/or pressure sensor. There have been attempts to create a single process to encompass the needs of multiple sensors. This goal is tricky, as the needs of the sensors are different. For example, gyroscopes require vacuum packaging but acceleration sensors are not packaged in vacuum and pressure sensors must be open to the medium to be sensed. Two processes that attempt to integrate multiple sensor types in a single process are the MandNEMS process from LETI and the MIDIS process from Teledyne/Dalsa. The challenge with a single process is to make an encapsulated cavity for gyropscopes as well as making good pressure sensors and acceleration sensors.

More typically, an approach is taken to chip-stack and wire bond as shown in Figure 28, where chips are stacked and/or placed next to each other and wirebonded, or to use a side-by-side approach on an interposer or other substrate as in Figures 29 and 30.

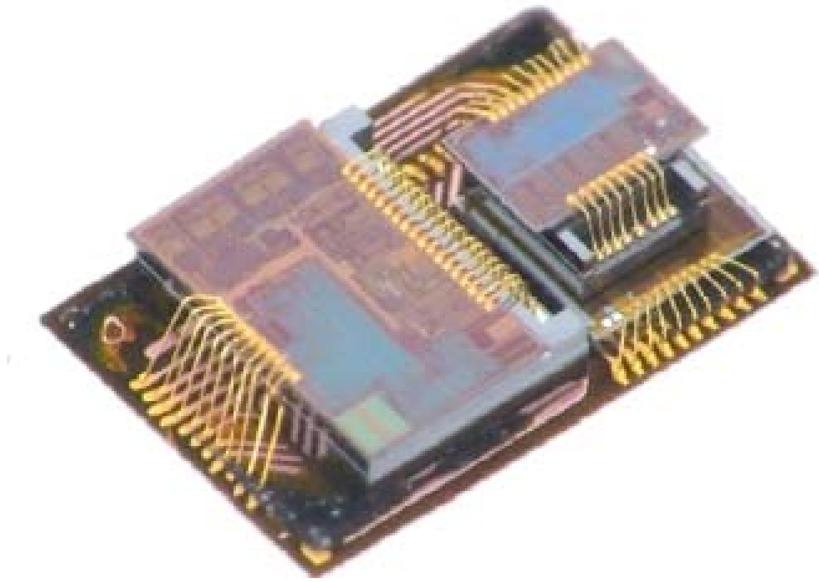


Figure 28: Chip Stack with wire bond example from Bosch

The multiple chip approach is also driving the use of interposers so that components sourced from different vendors may be combined and either wire bonded or bumped.

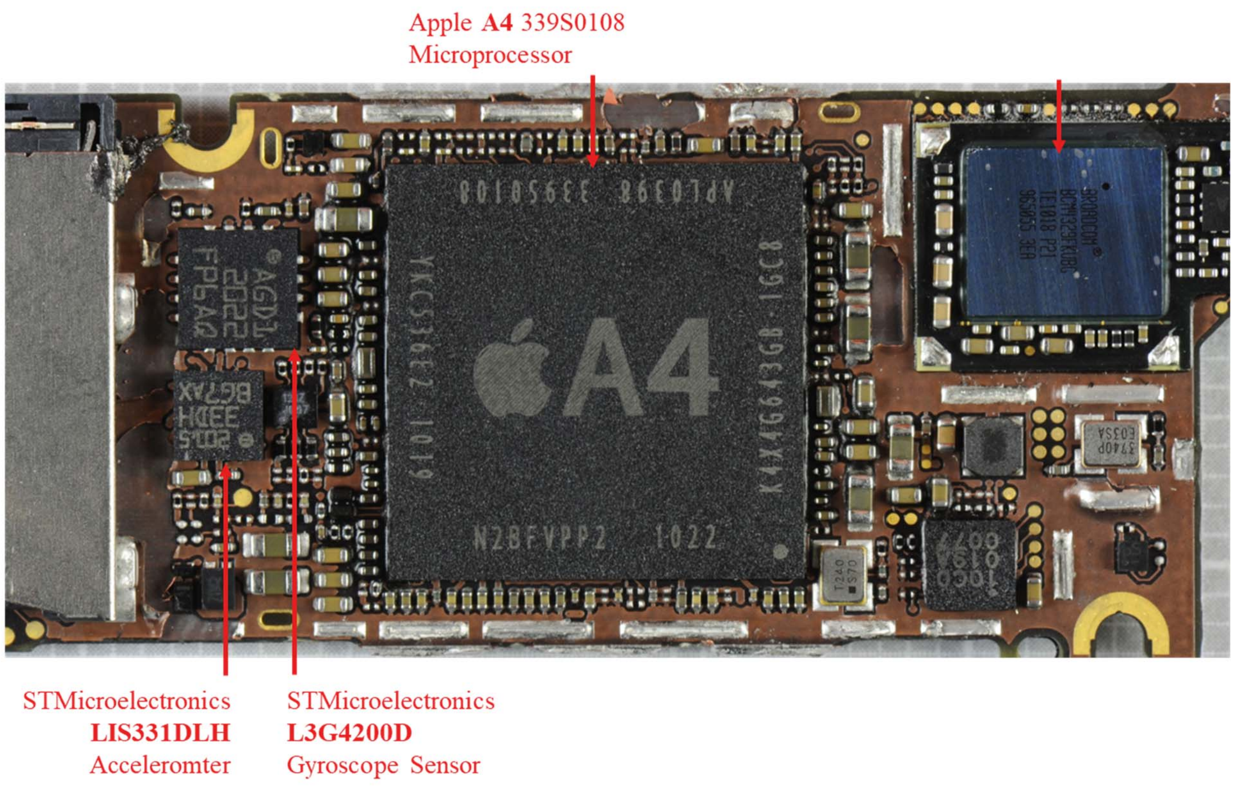


Figure 29: Side by side sensor placements (Chipworks)

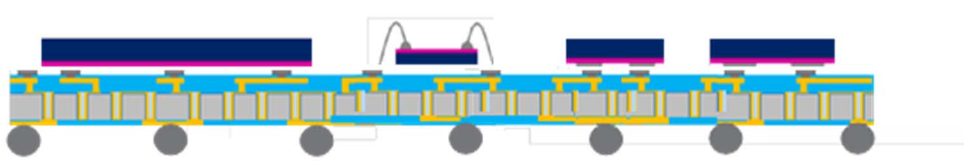


Figure 30: Multiple chips on an interposer

Wafer-level packaging is also being used as an integration method for multiple chips with diverse technologies, as in the conceptual process shown from Fraunhofer in Figure 31.

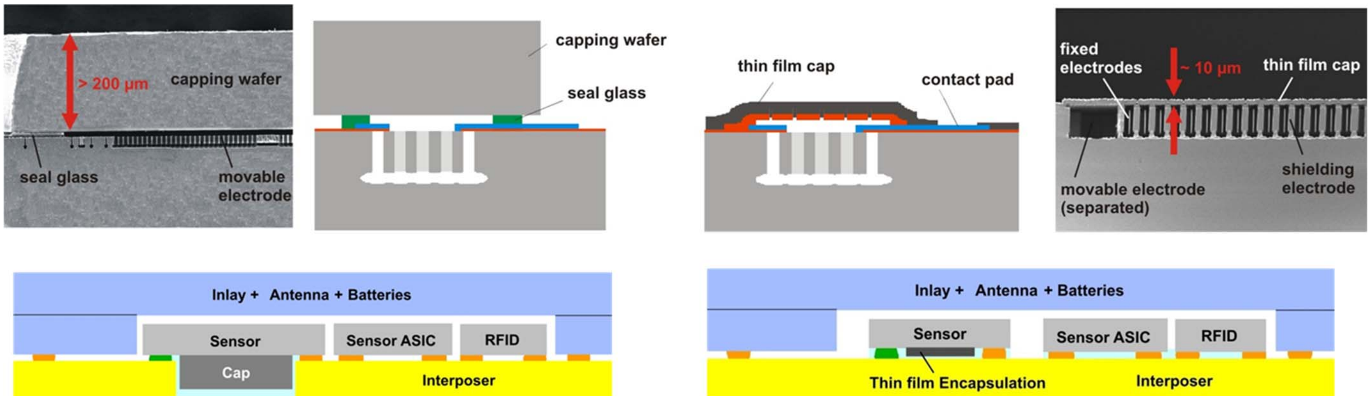


Figure 31: Fraunhofer WLP concepts

Flexible substrates and printed interconnect

Many applications require the use of MEMS on a flexible substrate so that the form factor for the assembled product can be achieved. Consumer wearables and medical devices often have this requirement. So, we see rigid MEMS dies being mounted, often after thinning, on flexible substrates. A natural combination is to use printed inks to create interconnects on the flexible substrates.

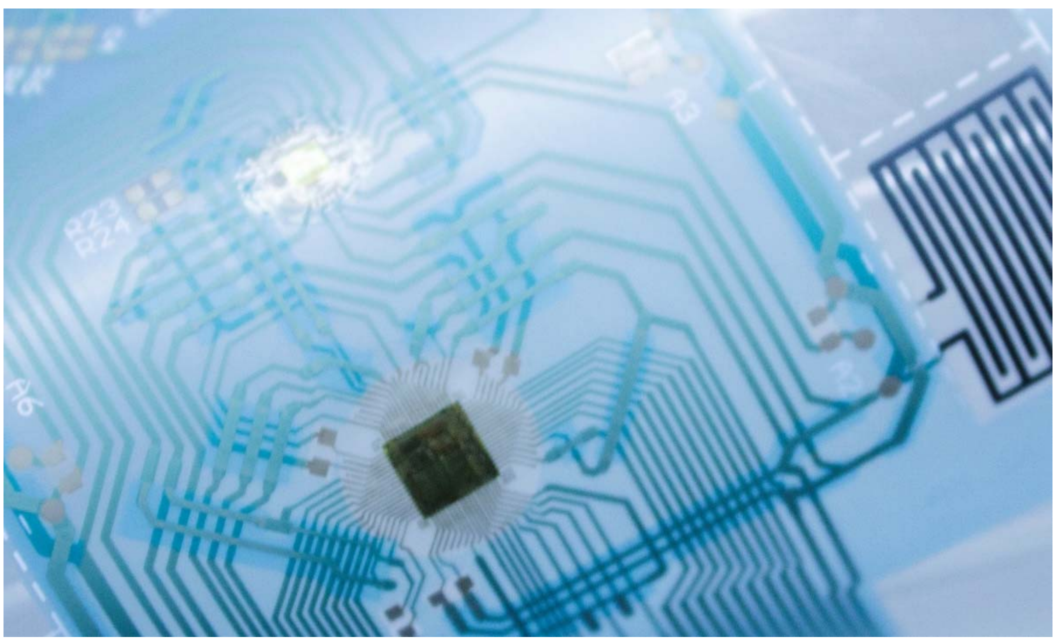


Figure 32: Rigid die on flexible substrate- used with permission Semi and American Semiconductor

Multiple dies from various sources can then be mounted on flexible substrates for wearables. Figure 33 shows a biosensor application with packaging using flexible substrates. It features multiple rigid components on multiple layers of flexible substrate. Components include sensors, processing, power and communication modules. The package is folded for space conservation and easy access to input signals. Some of the design issues for such systems include characterization of new packaging materials for their material properties, capturing physics in systems models including failure mechanisms and modeling of off-the-shelf chips, as well as testing access. Flexible substrates must often be combined with flexible interconnect to achieve wearable form factors as well.

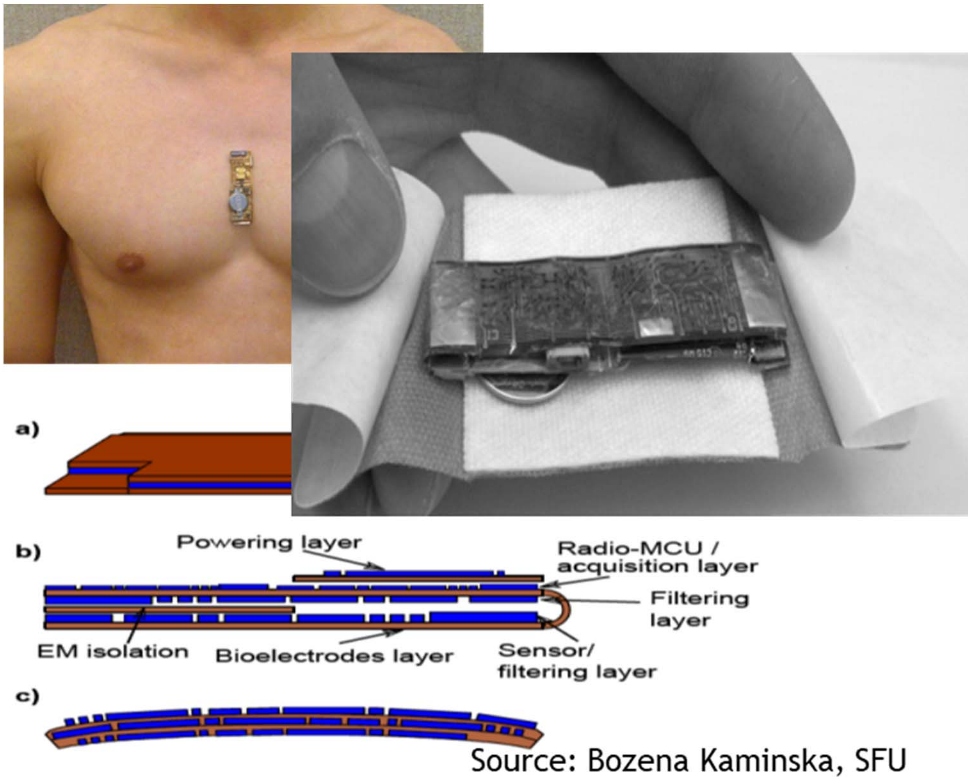


Figure 33: Multiple chips on flexible substrate for Biosensor applications

Application Specific Integration Structures

Because they must interact with the environment, MEMS devices may have specialized requirements on their packaging that often affects the heterogeneous integration. For example, speakers, microphones, and pressure sensors must have sound or pressure inlets. Optical devices may require certain types of materials be used so that the desired optical wavelengths may be sensed. Figure 34 shows some of these devices.

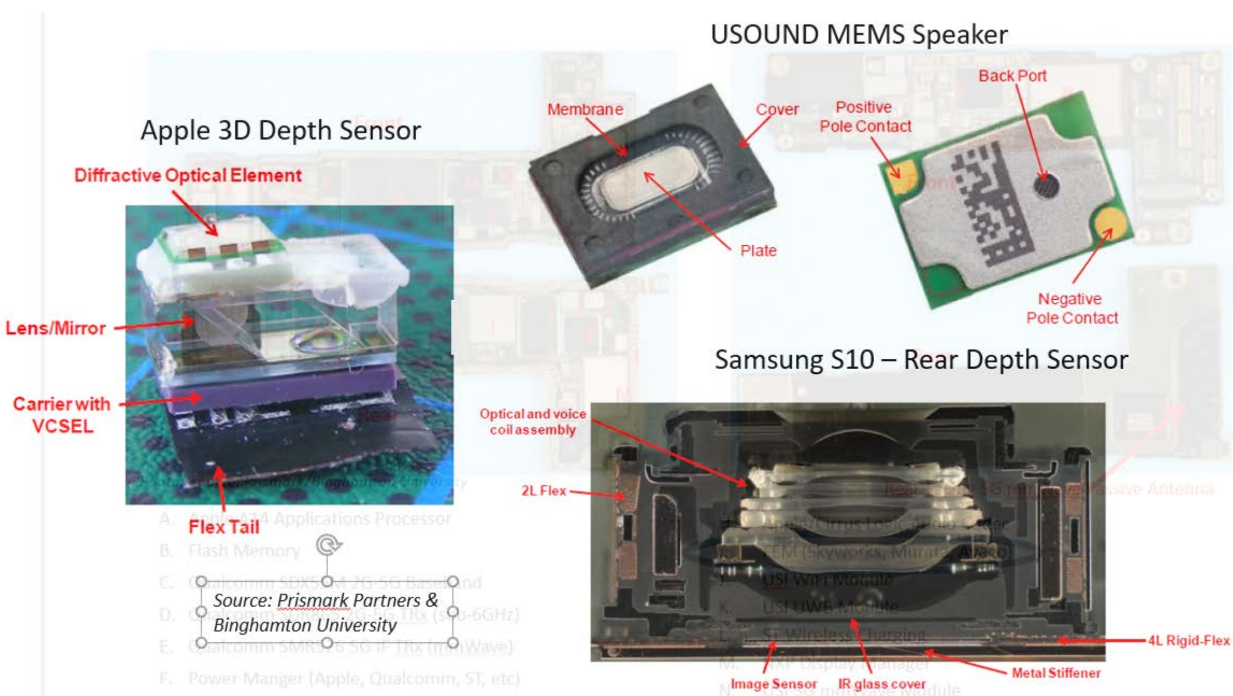


Figure 34: Application specific MEMS packaging examples

MEMS used in implantable medical devices have unique packaging requirements due to the need to put the device in the body. In 2014, a new technology was proposed to integrate a MEMS accelerometer and an ASIC inside a hermetic silicon box that could be embedded in a cardiac lead in order to monitor the endocardial acceleration signal. In brief, electronic components are attached and wire-bonded on a silicon interposer and a silicon lid is bonded using a eutectic AuSi ring to isolate them from the human body. The originality of the approach consists in using an interposer and a lid, both made of conductive doped silicon (0.1 to 5 mΩ-cm), to connect the device. The silicon box is connected to the electrical generator outside the heart through two conductor wires. A schematic view of the package is presented in Figure 35. The system integration is performed at the wafer level on 200 mm wafers.

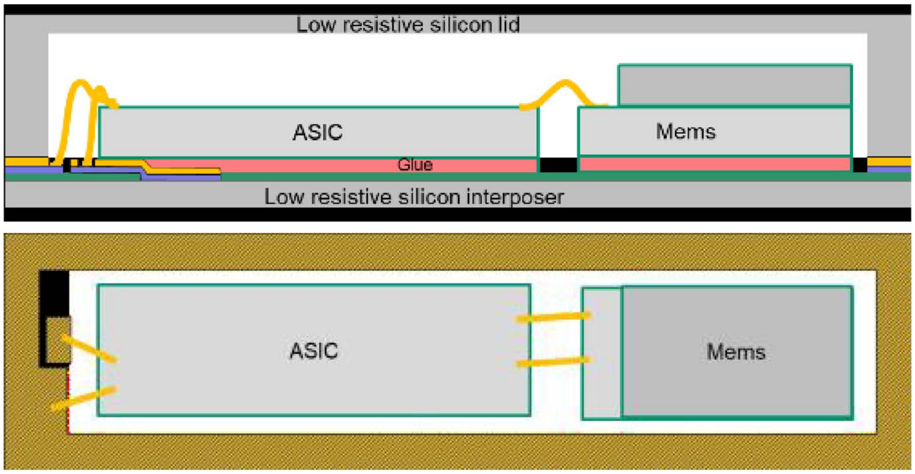


Figure 35: Hermetic silicon package schematic: a) cross section view; b) top view (with permission of CEA LETI)

Figure 36: Silicon box device (with permission of CEA LETI)

1.9 MEMS Device and Package Materials

Innovation in materials is driving performance enhancements in MEMS. The materials used in a particular MEMS product depend heavily on the working principle of the MEMS device, the device function and its end application. We survey in the next sections the types of materials used in typical MEMS devices based on their function. We present the materials currently used in fabricating the devices and discuss the future needs for each. We discuss the materials used for heterogeneous integration packaging and the future needs for these materials.

Motion Sensors

Typical materials used in motion sensors are shown in Table 4. Some of the drivers for motion sensor materials are to prevent the mechanical devices from sticking to the substrate, and materials that have a good CTE match to prevent unwanted bending and stress.

Table 4: Motion Sensor materials and future needs

Materials Currently Used Examples	Materials Future Needs Examples

• Polysilicon (doped and undoped), single crystal silicon
• Silicon nitride
• Low stress nitride
• Silicon oxide
• Single crystal silicon (SOI)
• Anti stiction coatings (siloxanes primarily)
• Wear coatings (MoS_2 for example)
	• Improved getter material and low-cost getter technology
	  • Reduce or eliminate activation required for getters
	• Low Stress Materials Needed
	  • Example: extremely low stress nitride deposited at very low temperature
	  • Low CTE mismatch materials sets
	• Coatings Needed
	  • Anti-stiction, anti-wear, anticorrosion, charge eliminating
	  • Example: thin monolayer or multiple monolayer coatings deposited at RT
	    • deposition of coatings at slightly reduced pressure <1 atm

Electro-Chemical Sensors

Typical materials used in chemical sensors are shown in Table 5. Some of the drivers for chemical sensor materials are to facilitate chemical reactions in a repeatable and stable way. Materials for creating heaters are also important.

Table 5: Materials and future needs for chemical Sensors

Materials Currently Used Examples	Materials Future Needs Examples
• Magnetoelastic • Potentiometric (Pt/PtO_2, W/W_2O_3, Pb/PbO_2, Ir/IrO_2) • ZnO • Silicon, Silicon oxide • Aluminum electrodes • Nickel heater, • Aluminum, alumina • Platinum, TiO_2	• Polyaniline • Boron-doped silicon nano-wires (SiNWs) • Nanoparticles for specific gas attraction • Increases surface sites for adsorption • Highly selective high sticking coefficient materials

Acoustics

Typical materials used in acoustic sensors/actuators are shown in Table 6. Some of the drivers for acoustic sensor/actuator materials such as speakers are to facilitate controlled motion to move/detect sound. Materials that do not fatigue are also important due to the large number of cycles the devices go through. Several different sensor/actuator types may be found – capacitive typically making use of silicon membranes, piezoelectric sensors make use of piezoelectric materials such as PZT and AlN, etc.

Table 6: Materials typically used in acoustic sensors/actuators and future needs

Materials Currently Used Examples	Materials Future Needs Examples

• Polysilicon
• Silicon oxides
• Silicon nitride
• Piezoelectrics
  • PZT
  • AlN
  • SiNx
	• Piezoelectrics that don't fatigue at low temperature
	• Lead free piezoelectrics (such as KNN)
	• Layer thickness increases for PZT (or KNN)
	  • 5 to 50µm with good performance and high throughput
	• Development of magnetostrictive actuator materials
	• Development of electroresistive low power materials

Optical

Typical materials used in optical sensors/actuators are shown in Table 7. Some of the drivers for optical sensor/actuator materials are to create flat and reflective surfaces that do not change their shape and that have the appropriate optical properties. Material coatings with the correct properties are also important in optical MEMS.

Table 7: Materials typically used in optical sensors/actuators and future needs

Materials Currently Used Examples	Materials Future Needs Examples

• Gold, platinum, palladium, titanium
• Silicon, optical glass, AR coatings, glass to metal bonding in packaging
• NiCr strain gage, Cr, Au, silicon nitride, silicon oxides
• Aluminum, aluminum alloys,
• SAW, BAW: piezo (LiTaO3 for example)
• FBAR ZnO or AlN
	• Thin film layers for adhesion and diffusion for mirror metal
	• Layers do not change mirror shape over temperature
	• Thin film layers for adhesion and diffusion for mirror metal
	• High quality LNO deposition
	• Lead free optical glass
	  • Develop new processes for this new material
	• Low outgassing materials for optical sensors
	• Electrets – low power
	• Piezoelectrics that don't fatigue at low temperature
	• Lead free piezoelectrics (such as KNN)
	• Layer thickness increases for PZT (or KNN)
	  • 5 to 50µm with good performance and high throughput

Ultrasonic and RF Devices

Typical materials used in ultrasonic/RF MEMS devices are shown in Table 8. Some of the drivers for these materials are to create structures that create/sense ultrasonic waves and have repeatable, optimized properties that are manufacturable. In piezoelectric devices, materials with a good piezoelectric transfer coefficient are prized. PZT has been routinely used but has been supplanted by AlN due to the need to refrain from creating devices using lead. AlN has been typically doped with Scandium to increase its performance. In RF MEMS switches, the development of reliable contact materials has increased the commercialization of certain types of switches.

Table 8: Materials typically used in ultrasonics and RF MEMS and future needs

Materials Currently Used Examples

Ultrasonic/Resonators	
PMUT--ultrasonic transducers	PZT, AlN, SiN, silicon
CMUT--ultrasonic transducers	SiN, silicon
MEMs Switch	Precious metals for contacts Au, Ag, Pt, Pd, Ru, Rh, Os

Materials Future Needs Examples

Ultrasonic/Resonators	

PMUT--ultrasonic transducers	• Doped-AlN with higher piezo performance
	• Piezos with
	  • higher process stability
	  • reproducibility
	  • homogeneity
	  • lower deposition cost

CMUT--ultrasonic transducers	• Low stress and excellent membrane thickness homogeneity control over the wafer
MEMs Switch	• RF MEMS switch materials for contacts

1.10 Simulation, Modeling and Co-design

Design flow

MEMS design, simulation and verification is challenging due to the 3D nature of the device motion, the varying time and length scales of the MEMS device behavior and the fact that the design involves multiple energy domains. MEMS products may require the use of new materials, new fabrication processes, new device designs, and custom packages. The "one-product, one-process, one-package" rule popularized by Yole development is still in force in MEMS.

Co-design is required at a number of levels in the MEMS design process, particularly: Material/Process, Process/Device, Device/Packaging, Device/Electronics. The MEMS design flow may vary ranging from a bottom-up approach for new sensor devices and new processes to a more IC-like top-down approach for mature technologies and next-generation devices. MEMS design also may encompass the IC design flow as companion ICs are designed to drive and sense MEMS device signals. Hence, the design flow considerations from this roadmap for ICs may be part of the MEMS product design flow. Many applications of interest require more than one sensor, and each sensor type may have a specialized process. Hence, design flows and tools targeting the heterogeneous integration of multiple sensors with electronics is an active area of research and commercialization. The following sections provide a perspective on trends on MEMS co-design and simulation.

Materials design

New materials such as Graphene, Scandium-doped AlN, and SiC are being utilized in MEMS devices and their packaging. Product requirements are driving the required materials properties. Materials design tools are starting to be deployed in the MEMS industry to help optimize materials for a given set of requirements. For example, design tools are being used to predict and optimize the Scandium doping levels of AlN in piezo-electric devices. The optimal doping is often device/product dependent, creating a challenge for materials suppliers to standardize.

Material/process/device/package co-design is important because as-processed stresses in materials can cause bowing of released structures, and TCE mismatches can cause stress as devices are packaged. The packaging issues are similar to those described elsewhere in this roadmap on IC packaging. Several modeling and simulation strategies are being developed to check for process compatibility, as temperatures used in subsequent processing can affect materials deposited in a previous step. In addition, more MEMS device design simulations are taking into account materials variations across a wafer.

The availability of accurate materials properties is critically important for obtaining correct device performance simulation results. As new materials are brought online, their characterization is important to simulation success. Current issues include characterizing new materials used in the packaging, chemical and biosensors. Materials properties in multiple energy domains must be available. CMOS MEMS may have well-characterized electrical properties but often other domains may not be represented. As MEMS are combined with flexible substrates, the effect of material bending on MEMS performance must be accounted for.

Device design

MEMS are moving 3D structures and operate in multiple energy domains, often transferring energy from one domain to another, and hence must be simulated in 3D with coupled physics solvers. Previously, 3D simulation tools were used to verify device concepts and optimize individual device performance or manufacturability, solving millions of DOF (degrees of freedom). Hardware limitations often forced simulation to be conducted on 2D or regions of devices. New requirements in 5G, ADAS, PMUT/CMUT transducers, combining multiple sensors and arrays, are requiring billions of DOFs to simulate their behavior. Engineers explore device geometric parameters such as device diameters and layer thicknesses, environment variables such as temperature and material properties, in evaluating candidate device designs. Now designers want to study design parameters such as device spacing in arrays and phasing between cells, as well as environment effects coupled into the device design. Previously, designers would do frequency or static sweeps, but designers also want to simulate transient analysis, which is much more time consuming.

The use of cloud computing and multi-core machines is enabling larger simulations. As more 3D simulation vendors fully support these platforms, designers will truly be able to take advantage of massive parallelism on either private or public clouds. Previously, companies did not want to utilize cloud computing platforms due to security issues. Many of these issues have been resolved, with large companies adopting private clouds, and fabs have released their design kits on the cloud. Most EDA vendors have announced cloud initiatives. Finally, the increase of RF MEMS and Optical MEMS designs are driving a need to couple simulators in Photonics, RF or Computational Fluid Dynamics with traditional coupled physics solvers used in MEMS.

Electronics/MEMS co-design

One of the key challenges in the co-design of MEMS and electronics is the co-simulation of MEMS, analog, and digital components along with embedded software. Circuit designers need MEMS models for impedance and timing. Parasitics from MEMS devices may affect circuits and vice versa. Different simulation tools are used for electronics than are used for MEMS, along with different modeling languages and different levels of abstraction. Amplifiers or other analog components may use SPICE. ADCs combining analog and digital circuits are simulated with Verilog, and systems languages are used for embedded components, while MEMS are represented typically with finite element models. MEMS behavioral models are needed that can be used in electronics simulators. Previously, electronics designers used very simple models of MEMS devices as equivalent circuits and often neglected their mechanical behavior in circuit simulation. Simulation models of MEMS devices are not new but are not widely deployed; next-generation models for co-design incorporate impedance vs. motion, inertial and damping behavior affecting timing, as well as better noise and statistical information. As MEMS become more complex, better models are needed for regions when the MEMS behavior is strongly nonlinear or exhibits hysteresis, such as for modeling overpressure in microphones, or inertial devices hitting the stops due to large accelerations.

Packaging co-design

Packaging in MEMS is not just for protection against the environment; it is part of the device function. Often the first-level capping of the MEMS device is done in the MEMS fab before further packaging is done. The performance of the MEMS device often cannot be calculated until its packaging is known. For example, the Q factor is a function of hermeticity. MEMS/Package co-design is often needed. In MEMS energy harvesters, the vacuum level sets the air damping, which in turn sets the maximum displacement, and the package must be deep enough to accommodate this motion. In addition, MEMS device models often must be co-simulated with thermal and mechanical models of the package to predict temperature and stress effects on the sensor's performance. For microphones, models of the acoustic ports and paths need to be added to the sensor model for applying the correct sound pressure to the MEMS device model. The trend towards co-design and co-simulation of package and MEMS is increasing, where previously, MEMS packaging was sometimes an afterthought in the design process.

When MEMS/IC or multiple MEMS are packaged together, there are a variety of methods used including chip stacking, side by side, interposers and bare die packaged on flexible substrates. Use of interposers allows optimizing fab processes for each device separately. Interposers tend to have higher performance than PCBs due to improved signal integrity with smaller form factor and utilize TSVs made in wafer fabs.

Digital Twins

Digital twins were initially developed in automotive, industrial and aircraft applications – examples are Siemens for cars and GE for its engine model. Several important areas where MEMS Digital Twins are starting to be used are in designing control and calibration loops – for virtual testing and qualification, to train AI algorithms, or as part of a larger model such as a car. With the availability of high-performance hardware, the construction of Digital Twins became possible, as the computational load is enormous. Digital Twin models can also be used for testing and virtual qualification. They are helpful for debugging test setups and for understanding test results. Digital Twins can be used to pinpoint faults for devices where it is hard to probe physical points on the device. The model can be run under the same qualification test the final product will undergo so that design issues can be caught early.

Digital Twins can be used to optimize manufacturing processes and increase manufacturing yield. MEMS processes vary from machine to machine, across a wafer, and from wafer to wafer, leading to performance variations. Digital twins can be used to model these variants statistically and to understand which process parameters or outcomes need to be controlled or which affect device performance the most. They can also be used to develop design rules and help designers to optimize designs that will be robust to process variations.

Design Kits/Technology Transfer

Although we do see some standardization, with many MEMS fabs offering one or more platform fabrication processes and unit standard processes that can be combined, the majority of designs are continuing to have some process customization. We also see some standardization in packages for a given product type, such as accelerometers, but packages also tend to vary with sensor type. Standard processes allow the development of statistical models, programmable cells, IP and design kits. IP is often process-specific similar to analog IP in the semiconductor industry. In addition, MEMs IP may be application-specific. The market for MEMS IP is still unclear, and when and if MEMS IP will be as prevalent as IC IP remains to be seen. MEMS PDKs must include information about multiple-physics domain design rules and materials properties, packaging, wafer/bonding information, and fabrication. Current issues today are the ownership, distribution, and maintenance of the PDK, consensus of what is in a MEMS PDK, the ability to support both standard and custom processes, and how to merge or make it compatible with IC PDKs.

Conclusions

Trends are leading both to some process standardization and IP re-use for MEMS devices to target new markets, and at the same time innovations in materials and fabrication process are driving focus on new tools for fabrication simulation and device modeling. Lack of standardization and technology transfer is still a major component of delays in bringing MEMS-based products to market. For well characterized processes and mature devices, simulations and experimental results often agree, but for modeling of new types of devices, the physics may not be well understood, as in some biodevices. Even in traditional MEMS, modeling of damping and stiction is still challenging.

1.11 Summary of Strategic Challenges for the next 5, 10, 15 years

This chapter has described heterogeneously integrating MEMS-based sensors along with other parts of the signal processing value chain as applied to automotive, handheld/consumer, and medical healthcare applications. We compare status and needs in 5 to 10 years of each area in terms of their packaging in the following table. We conclude that there are certainly some commonalities in needs but we also see application-specific differences.

	Current State-of-Art		5 to 10 years	
	Application Areas	**Packaging**	**Application Areas**	**Packaging**
Mobile / Consumer	• Tilt • Navigation • Gaming	• Traditional low density LGA • Thick sensors	• Tilt • Navigation • Gaming	• Size reduction, **WLP** • **Thin sensors** • Integration with µProcessor • **EMI shielding**
Medical & Health	Not pervasive	Traditional plastic on rigid organic substrates	• Implantable • Concussion monitoring • Vital Signs monitoring • Telemetry	• **Flexible substrates** • Thin profiles, **WLP** • **Biocompatibility**
Automotive	• Air bag crash sensors • Rollover • Stability control	• Traditional large body SOIC / QFN	• Navigation grade IMUs • ADAS • Audio noise cancellation • Adaptive headlights	• **SiP based modules** • Substrate technology • Integration of µProcessor for intelligent processing • **Integration of RF for communication**
Aerospace & Defense	Not pervasive	• FOG and/or RLG • Traditional ceramic substrate based modules	• Machine Health • Attitude & Heading • Navigation • Stability	• **SiP based modules** • Substrate technology • Integration of µProcessor for intelligent processing • **Integration of RF for communication**

In order to support the development of the needed technologies we see a need for advances in materials in the following areas:

- Additional photoresists that can be used as dielectrics
- Low-dielectric materials that can act as substrate and replace capacitors
- Low-temperature solders that are reliable and compatible with reflow of SAC (SnAgCu) solders
- Mold materials for packaging, low stress
- Need for virtuous materials (less rare and with reduced environmental footprint)
- Die attaches: low stress, low strain, low CTE
- Passive getters: porous nickel oxide, titanium oxide, aluminum oxide for example
- TSVs in glass substrates
- Flexible, stretchable substrate
- Stable in water and saline environment, biocompatible
- Plastic lids for optical sensing
- All-silicon packaging

HIR Cross-TWG Teams

It is often said that the world economy is undergoing digital transformation and data is the new oil. If data is the new oil, then MEMS and sensor integration is on the front line, facilitating the exploration, extraction and refining that is enabling the data revolution. Such integration technologies are a crucial part of the building blocks for electronic systems both today and tomorrow.

The MEMS and Sensor Integration TWG partners with the adjacent HIR building block TWGs in single- and multi-chip integration, integrated photonics, integrated power electronics, and 5G communication, to bring full functionalities to leading electronics system applications from IoT, Mobile, Automotive, Medical, Health and Wearables, Aerospace and Defense, High Performance Computing and Data Centers. Within the miniaturization and integration realm, there are commonalities in requirements for research and innovation in emerging devices and materials, test, security, thermal and supply chain. The ways in which we must develop and focus future integration technologies – SiP and Module, 2D and 3D, Wafer- and Panel-level Packaging – will challenge our knowledge base in co-design and simulation, from devices to package and to systems. The global COVID-19 pandemic has brought new awareness of the potential and power of electronic systems, from virus contagion tracking to vaccine development. Sensing and data collection technologies are proving critically important in enabling scientists to overcome tough challenges and potentially save lives today and in the future.

Edited by Paul Wesling