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Sensor fusion and MEMS technology for 10-DoF solutions

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Until recently the discussions about smartphones and tablets usually have focused on the latest generation of application processors, quality of the displays, the number of megapixels in cameras, or the newest version of operating systems. Now, sensors and particularly MEMS (micro-electro-mechanical-systems) sensors are becoming a part of that discussion thanks to their proliferation in both smartphones and tablets. As an illustration, ***Table 1*** shows the number of sensors incorporated into some of the newest smartphones.

	iPhone 4s	Galaxy S3	HTC One X	Droid 4	Lava Xolo 900
Sensor Type					
Accelerometer	*	*	*	*	*
Gyro	*	*	*	*	*
Dig. Compass	*	*	*	*	*
Proximity Sensor	*	*	*	*	*
ALS	*	*		*	*
Barometer		*			

Note: ALS – Ambient Light Sensor

Table 1 – Number of sensors in some recently launched smartphones

In high-end smartphones, the number of sensors has already reached a half dozen and is rapidly marching towards a dozen per smartphone. Sensors are not only essential to bringing new smart features to products such as smartphones and tablets but also to ultrabooks, laptops, and PCs. Moreover, sensors are becoming ubiquitous and are found in many different applications besides mobile devices such as industrial control, automotive industry, smart highway infrastructure, smart grid infrastructure, smart homes, health care, oil exploration, petro industry, and climate monitoring. This proliferation of sensors into all spheres of our lives is mainly due to MEMS technology that is finally entering a stage of maturity and becoming a main stream. MEMS maturity has brought new products to life with its low cost of under a dollar, which is in turn fueling further penetration of sensors and new applications. One can say that MEMS sensors are everywhere. Petrov group estimates that the sensor market specific to smartphones and tablets alone will pass 15 billion units by 2015.

Sensor fusion

One of the hottest developments in sensor applications is multidimensional sensing. Taking a closer look at the type of sensors used in mobile devices, it is easy to see that the 3D-accelerometer, 3D-gyroscope, and 3D-magnetometers are becoming standard features. Why the need for multidimensional sensing? The short answer: enhanced user experience. The interesting part about these sensors is that each one of them performs some basic sensing: accelerometer provides x, y, and z linear motion sensing, gyroscope provides pitch, roll, and yaw rotational sensing, and magnetometer provides x, y, and z axis magnetic field sensing. While all of these are powerful capabilities, each one of these sensors also shows some limitations which impact accuracy in applications. For example, accelerometers are sensitive to vibrations and can generate a signal even when smartphones or tablets are at rest; gyroscopes suffer from zero bias drift; similarly, magnetometers are sensitive to magnetic interference which can also create an undesired signal.

Can shortcomings of the individual sensors be compensated? This is where sensor fusion comes into play. Sensor fusion is intelligent and simultaneous sensor data processing (from multiple sensors) whereby the output is greater than the sum of individual parts. In other words, if the signals from an accelerometer, gyro, and magnetometer are taken at the same time and processed in an intelligent way, the deficiencies of separate devices can be eliminated and a synthesized smart output can be obtained. Typically, clever algorithms and special filtering techniques such as Quaternion based extended Kalman Filtering are used to produce more sophisticated results and precision. It should be noted that there are already several companies specifically dedicated to the creation of proprietary algorithms and firmware/software solutions for sensor fusion such as Sensor Platforms, Hillcrest Labs, and Movea. Also, some ODM companies are offering full solutions including STM, Freescale, InvenSense, and Kionix, to mention a few.

Microsoft considers sensor fusion to be so critical that it made it mandatory for Windows 8 to support sensors. To achieve that Microsoft has created a sensor class driver and also worked with industry partners to define the standard for sensors. This led to the introduction of standard for sensors in the Human Interface Device (HID) specification in 2011. They also looked for optimization of a sensor fusion solution by architecting an interface to enable sensor processing at the hardware level. In addition, they implemented a filtering mechanism for sending sensor data up the software stack only at the rate data needs (not faster). All of this is integrated in a programming module called Windows Runtime. Microsoft certainly did not want to make the same omission with Windows 8 that Google had made with the Android by simply creating a place holder for sensors, and leaving it up to the sensor companies to plug in their proprietary solutions.

A typical sensor fusion solution that combines a 3D-accelerometer + 3D-gyro + 3D-magnetometer is called a 9-DoF (nine degrees of freedom) or 9-SFA (nine sensor fusion axis) solution. The best way to understand how such a system works is to take a look at the inputs and outputs, as shown in ***Figure 1***. It is easy to see that the 9-DoF solution allows for two sets of data, one being the pass-through data path that sends raw data directly to an application, and the other being the sensor fusion data path whereby initial raw sensor data is processed and synthesized into a more intelligent data output. An example of the pass-through sensor data is a pedometer application (counting someone's steps as they walk), while examples of sensor fusion data include compass applications, enhanced navigation, and 3D-games.

Sensor fusion is not limited to a 9-DoF solution. For example, if we include one additional sensing quantity, it becomes a 10-DoF (or 10-ASF) solution. A good example of this would be adding a location sensing inside buildings to the 9-DoF solution. That can be done by adding barometric sensing for altitude. Having a barometer enables altitude detection between floors since pressure changes with altitude at the rate of about 10 Pa/m (in average there is about 3.5 meters between floors). So, the 10-DoF includes a 3D-accelerometer, 3D-gyro, 3D-magnetometer and barometer.

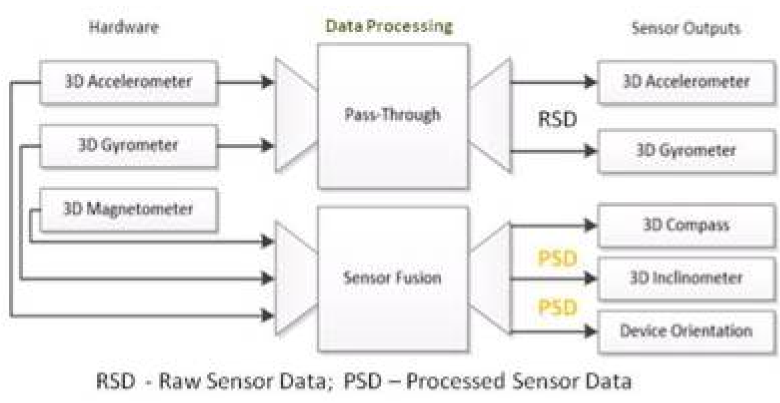

Figure 1: 9-Axis Sensor Fusion System (Microsoft – Supporting Sensors in Windows 8)

Why stop there? Even more sensing quantities can be added in which case the sensor fusion solution becomes an m-DoF solution, where 'm' stands for 'multiple' and it can be greater than 10. Why not have your own private lab at you fingertips and check the level of your blood sugar or cholesterol when you need it? It is not unfeasible anymore to see new smartphones, tablets, ultrabooks and PCs with universal sensor hubs that can accommodate many applications. Freescale has already demonstrated a 12-DoF solution that includes a 3D-accelerometer, 3D-gyro, 3D-magnetometer, a barometer, a thermometer, and an ambient light sensor. The m-DoF solutions will be the way of the future.

It is evident that sensor fusion requires substantial MCU power. There is currently a healthy debate about the most efficient way to do sensor data computing. Many industry experts think the way to go is a dedicated sensor processor (co-processor), while alternatives are also being considered such as doing sensor computing on an application processor. Interestingly, firmware/software companies are hedging their risk by providing solutions fully compatible with both - embedded processor and application processor. For example, Sensor Platforms has announced its Free Motion Library of software algorithms that supports both 32-bit embedded processors and 64-bit application processors including both architectures, ARM and x86. Free Motion Solution also supports all accelerometers, gyroscopes, magnetometers, and barometers independent of vendors. This independence from processor instruction set and sensors will allow mobile device manufacturers freedom in choosing a supplier and optimizing performance and cost.

MEMS technology for 10-DoF solutions

There is a general expectation that 10-DoF solutions will be a high point of sensor fusion implementation in the next couple of years. So, let us focus on the 10-DoF solution and discuss the role of MEMS sensors in it. Three out of four sensors to be used in the 10-DoF solution (accelerometers, gyroscopes, and pressure sensors) are manufactured by using MEMS technology; thus it can be stated that MEMS technology is critical to sensor fusion. Magnetic field sensors typically do not use MEMS (although they could); therefore they will not be discussed here.

MEMS technology has matured in the last decade. It can now deliver reliable, and more importantly, cost effective sensors that are used in mobile devices without having a significant impact on the total cost of BOM. The same is true for other consumer products. There are two key features pertinent to MEMS technology that stand out. The first key feature of many MEMS devices is the creation of movable structures (dynamic MEMS structures). Often for a MEMS device to function something has to move (up and down, or left and right, or back and forth, or tilt) and then that movement is translated into a corresponding signal. The movable structures are diaphragms, cantilevers, beams, proof mass, or some type of combination of these basic micromechanical structures. The second key feature is hermetical sealing or capping. The movable MEMS structures need to function reliably; therefore they need to be protected. Typically, they are hermetically sealed (or capped), creating a controlled environment. Capping is usually done at the wafer level.

Naturally, there are variations in the MEMS process for making movable structures, as well as variations in the capping process, and often the process chosen for a specific device depends not only on the application but also on the vendor’s technology.

Motion and inertial sensing

Accelerometers and gyros are at the core of motion and inertial sensing. Most accelerometers and gyroscopes, when made by the same manufacturer, use the identical MEMS process. The only difference between these two sensors is basically in the geometry of MEMS structures. Movable MEMS structures for accelerometer and gyro are different (one is optimized for linear motion sensing and the other for rotational sensing) but the MEMS process itself, including the capping process, as well as the CMOS process for ASIC chips are the same for both. Today, the majority of 3D-accelerometers and 3D-gyroscopes are manufactured as separate MEMS chips although several companies have already introduced the integration of accelerometer and gyro on a single MEMS chip which leads to a 6-DoF combo solution.

The MEMS dynamic structures used in 3D-accelerometers and 3D-gyros are designed as high-aspect ratio structures. They are made from polysilicon or silicon using a deep reactive ion etching (DRIE) process. The high-aspect ratio approach prevails today in the industry because it provides shock resilient MEMS structures and it also makes use of a capacitive sensing possible. As already mentioned, there are variations in the MEMS process and they are typically associated with a vendor and proprietary technology. Here, we will discuss several examples of accelerometer/gyro products and point out some variations.

One common version of the accelerometer/gyro solution that is based on a combination of MEMS structure with a passive cap and a separate signal processing CMOS IC chip is shown in ***Figure 2***. The MEMS element is made of a thick polysilicon (up to 30 um) by use of DRIE and sacrificial etching. The sealing of MEMS is done by low-temperature frit-glass bonding. The CMOS IC chip in this case seats on the top of the cap. This approach is currently used by STM and Bosch. There are further variations of the passive capping approach whereby the CMOS IC chip is packaged side-by-side to the capped MEMS structure (ADI and Kionix/Rohm use this approach), or the capped MEMS device seats on the top of the CMOS IC chip (Freescale solution).

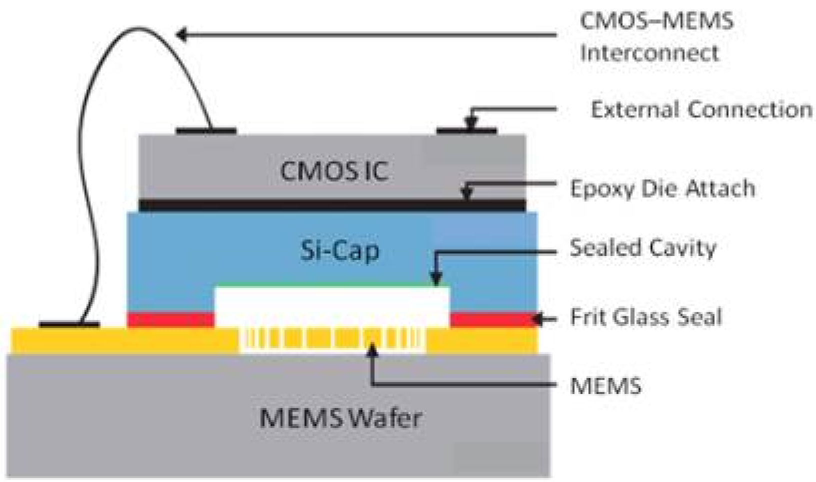

Figure 2: Accelerometer/Gyro solution with passive capping

There is another version of the accelerometer/gyro solution that involves active capping, as shown in ***Figure 3***. In this case, the MEMS structure is made of silicon crystal by using fusion bonding of two wafers, DRIE, and sacrificial etching. The capping wafer is the CMOS IC wafer; thus the passive cap has been eliminated completely. The sealing is done by low-temperature eutectic metal (different combinations of metals can be used including an AlGe, Au and Au/Sn combination). As is always the case, there are advantages and disadvantages in every approach. For example, a frit-glass sealing is a relatively simple process but it takes up more space on a die to make a good hermetic seal which leads to a larger die size. On the other hand, the metal seal approach requires additional photo steps for metal patterning but it enables the shrinking of a die. InvenSense is the leader in the active capping approach. Their accelerometers and gyros have been accepted enthusiastically by the smartphone OEMs (they are the dominant supplier to the Android OS camp while STM is a dominant supplier to Apple).

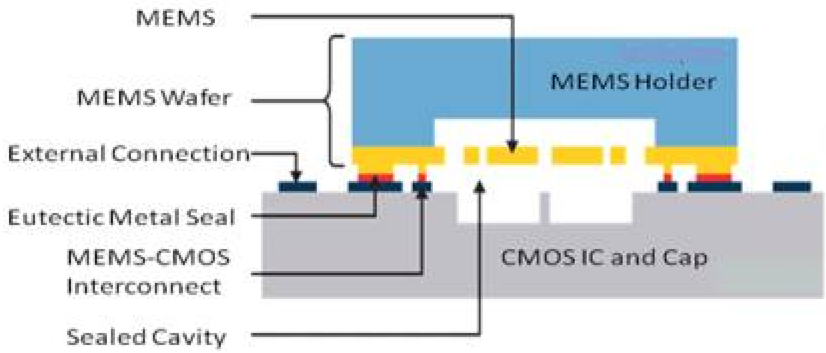

Figure 3: Accelerometer/Gyro Solution with Active Capping by InvenSense

The CMOS IC chip is an inevitable part of every accelerometer and gyroscope solution. It plays the crucial role and provides basic functions such as biasing and reference voltages, offset compensation, trimming, self-test, signal amplification, temperature compensation, driving MEMS structures to oscillation (as in gyros), filtering, and analog to digital conversion. The CMOS IC may also contain a DMP (Digital Motion Processor) as in the case of the integrated 6-DoF solution introduced by InvenSense (their series MPU-6000/6500). It should be stressed that the 3D-accelerometer and 3D-gyro, as well as the 6-DoF integrated solutions provide digital output that comply with either the I2C, or the PSI protocol, or both. The I2C and PSI are communications protocols commonly used in the industry.

The examples shown here are representatives of the current inertial sensing products on the market. If one starts looking into the next generation products things look even brighter. As already mentioned, a further integration is already taking place and the form factor is shifting from discrete accelerometer and gyro devices to 6-DoF combo products on a single MEMS chip. This is possible because of the advancements in MEMS technology and packaging. One excellent example of this is STM's announcement of the use of TSV (through silicon via) technology in MEMS packaging. Using TSV through the CMOS IC chip enables active capping and elimination of the bond wires at the same time, as shown in ***Figure 4***. That way the new 6-DoF combo solution (accelerometer + gyro) is scaled down in all three dimensions (true 3D-scaling down), reducing the cost and improving performance. Very impressive indeed!

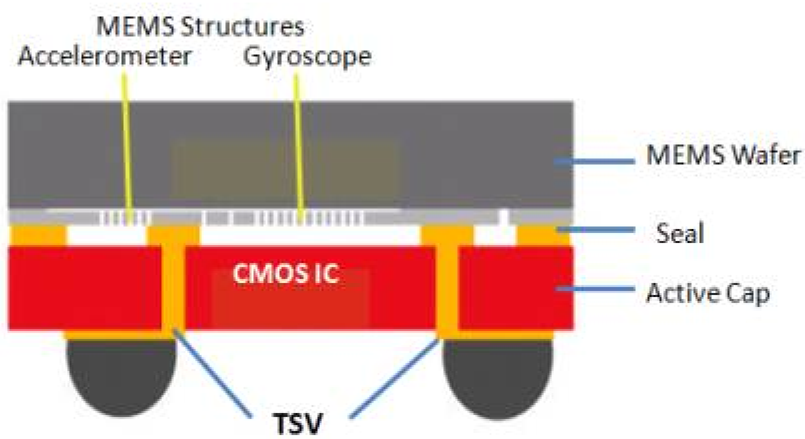

Figure 4: Active Capping and use of TSV by STM

Barometric sensing

Let us turn now to barometric sensing. The key part of a barometer is a pressure sensor. The crucial part of every pressure sensor is a diaphragm. There are several variations of MEMS technology on how to make a silicon diaphragm. In part, this is related to underlying principle of operations of pressure sensor. Generally, two basic principles are exploit: piezoresistive effect and capacitive method. In the case of the piezoresistive effect, there is a piezoresitor embedded into a diaphragm. When the diaphragm moves it creates a change in the piezoresistor, which in turn is correlated to pressure. In the case of capacitive sensing, the diaphragm itself represents one of the electrodes of the capacitor, and the change in capacitance is correlated to the change in pressure. Here, we will discuss several examples of pressure sensors that represent the main stream in barometric sensing.

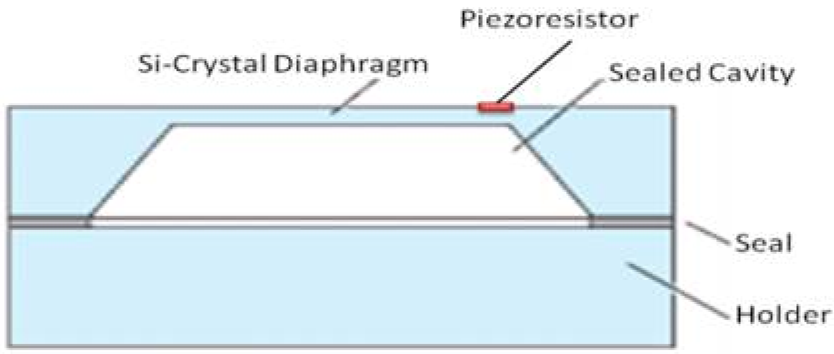

Figure 5: Piezoresitive pressure sensor made by using wet anisotropic etching

Figure 5 shows one of the pressure sensors and its diaphragm. The diaphragm is made of silicon crystal by using wet anisotropic etching of the silicon wafer with the (100) orientation. This approach is known as a bulk-micromachining. The etch rate of the silicon crystallographic planes with (111) orientation is much slower than the surface with (100) orientation which leads to the unique sloped truncated, and pyramidal shape beneath the diaphragm. The piezoresistive resistors are placed at the edge of diaphragm. The MEMS die is completed by bonding the MEMS wafer to the holder wafer whereby a sealed cavity (reference chamber) for absolute pressure sensor is created. This approach is used by Honeywell and Freescale.

Figure 6 shows another pressure sensor with a different diaphragm. In this case, a combination of dry and wet etching with monocrystaline silicon growth, CMP process, and sacrificial etching is used. It leads to the formation of a silicon diaphragm with a sealed cavity at the top of the wafer without the need for wafer-to-wafer bonding. This technique leads to a smaller MEMS die compared to the die made by using wet anisotropic etching. The piezoresitive elements are again placed at the edge of the diaphragm where the stress is the largest. This approach is used by STM – they call the process VENSENS.

It should be pointed out that the final barometer product includes two dies in a single package. One is the pressure sensor MEMS die and the other is the CMOS IC die. The two dies are typically packaged side-by-side. For example, STM and Freescale use the LGA package for their barometers. Naturally, there is a hole in the LGA package to allow ambient pressure to reach the pressure sensor. The CMOS IC is an ASIC that performs signal processing and also provides a digital output that is compatible with I2C and PSI protocols.

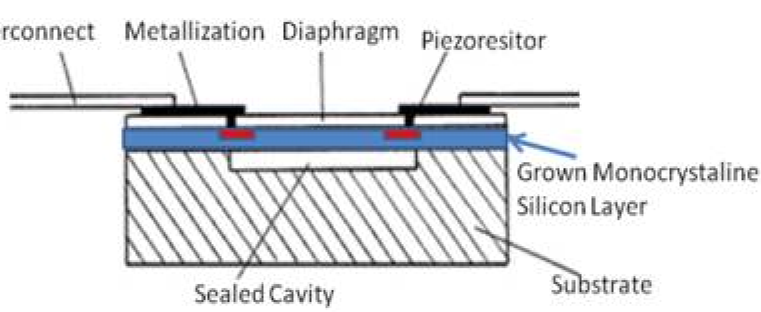

Figure 6: Piezoresistive pressure sensor made with a grown-monocrystalline Si-layer

Finally, an example of a pressure sensor based on capacitive sensing is shown in ***Figure 7***. In this case, a surface micromachining is used in combination with a thin polysilicon layer (about 2 um) and sacrificial etching. The sealed cavity and the thin diaphragm that also serves as one of the plates of the capacitor are seated at the top of the MEMS die. This technology is essential for high pressure sensors. The capacitive pressure sensor is at the core of sensing solutions for TPMS (tire pressure monitoring system). An excellent example of this type of product is a Freescale's TPMS solution that includes a capacitive pressure sensor and CMOS ASIC on a single chip, an RF-transmitter chip for wireless data transmission, and an MCU chip, all in a single package (all together three chips). This product is the darling of the automotive industry and is used in both cars and trucks for monitoring tire pressures.

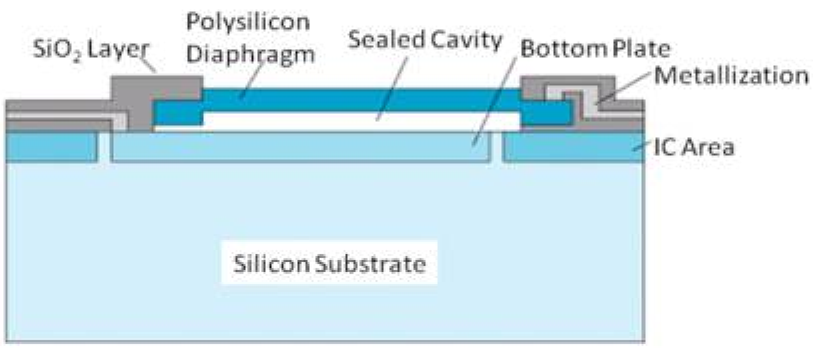

Figure 7: Capacitive MEMS pressure sensor

Conclusion

The basic aspects of sensor fusion have been described in this paper including the 10-DoF solution. Sensor fusion is a powerful concept that demonstrates how the whole is greater than the sum of its parts. Then, the focus turned to motion, inertial, and barometric sensing since they are the key components of 10-DoF solutions. The select MEMS sensor examples shown here are representatives of real products. They illustrate well that there is no lack of inventiveness when it comes to MEMS technology. Some MEMS solutions are cautious, some are more radical. Either way, they deserve our full attention because the products made by MEMS technology are reliable, and cheap, and they fuel new applications that were unthinkable only a few years ago. One can state with certainty that MEMS technology and MEMS sensors are essential to sensor fusion and the 10-DoF solutions as well as to the next generation of m-DoF solutions.

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