The Internet of Things and MEMS packaging

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Many experts regard the Internet of Things (IoT) as the third wave of technology. The personal computer (PC) created the first wave in the late 80s and early 90s. The cell phone initiated the second wave. It is widely believed that the IoT will be the third wave of technology where engineers use the experience and infrastructure of the first two waves to make day-to-day chores more connected for increased comfort, convenience and safety.

The transition of PCs from large desktop items with large under-the-desk boxes to highly portable laptops, and the transition from brick-sized, single-function cell phones to pocket-sized, multifunction smartphones resulted from an equally dramatic, but not as visible, transition from discrete packaged semiconductors to complex flip-chip integrated circuits (ICs) and multi-chip modules. Similarly, the IoT will require substantial IC packaging changes to achieve its expected growth potential.

Background on IoT growth and pervasiveness

"Smart" is a term commonly associated with products targeting the IoT. Any smart system is built with some basic building blocks. The most commonly used building blocks in an IoT system are: 1) Sensors and actuators; 2) Analog and mixed-signal translators; 3) Microcontrollers or embedded processors; 4) RF connectivity; and 5) Power management.

Sensors provide the changes in environment or status to a microcontroller or embedded processor, that in turn performs necessary calculations or makes decisions. This information is communicated through RF connectivity to the cloud or a local network, and once the necessary actions are determined, the response can be communicated back to a receiving node where an actuator can take appropriate actions. This initial IoT implementation is becoming smarter in terms of taking actions once a threshold is observed. In applications where action is required, greater capabilities can be found both on the sensor, as well as on the actuator side.

Microelectromechanical systems (MEMS) sensors play a significant role in the IoT. The other aspects include embedded processors and RF connectivity. MEMS sensors with other IC technologies are rapidly becoming highly integrated sensing nodes that process the sensor data and then communicate it to a local or remote location either directly, or through the IoT. While the embedded processors and RF connectivity have been adopted over time, MEMS is relatively new. However, the MEMS adoption rate is quite high and as a result, system designers expect the cost reductions to be high. Based on the use of MEMS technology, sensors for the IoT are projected to reach a trillion units in the next decade [1]. However, lack of standardization (i.e., one product – one ASIC – one package – one test system) will delay this monumental growth.

Packaging issues

While people are increasingly aware of the IoT and the promise of connecting billions of things together, many system designers are not aware of the packaging changes that are required to achieve this growth. On the other hand, the semiconductor industry is well known for meeting the packaging needs of innovative new products based on available package technologies, and then optimizing the packaging to achieve cost reductions. This trend is also occurring in the IoT area.

Today's designs must transition to more advanced solutions that combine more and more functionality into a single semiconductor package. With the high level of integration, concerns for EMI, package stress, and testing complexity are just a few of the issues that arise. Historically, packaging has always been the last, or among the last issues that is addressed in system design. In many cases, packaging has been an afterthought. While this has been changing, progress still needs to be made in many design circles to provide optimum system design advantages.

Solving the packaging issues for consumer products is difficult enough, but providing industrial packaging solutions means even more challenges. While designers working on the IoT are well aware of the building blocks, they usually are not prepared to address the challenges that result when these building blocks are packaged together in a single IC-style package. Common requirements for an IoT package are low cost, low power dissipation for silicon, and very good power dissipation characteristics for the package, and good RF shielding in packages that support multiple RF standards including Bluetooth® Low Energy (BLE), Wi-Fi, or ZigBee®, and others. With MEMS sensors in the IoT package, stimulus delivery is another important aspect, therefore cavity-based solutions are popular. Another requirement is a production-ready package to meet market timing. Waiting for a new custom package is usually not an option. A small footprint, whether it is a discrete solution or an integrated solution, is necessary in any case.

Today's packaging solutions

Market analysts at Yole Développement have identified three sensor clusters that exist in today's smartphones—the sensors clusters include a closed package, an open

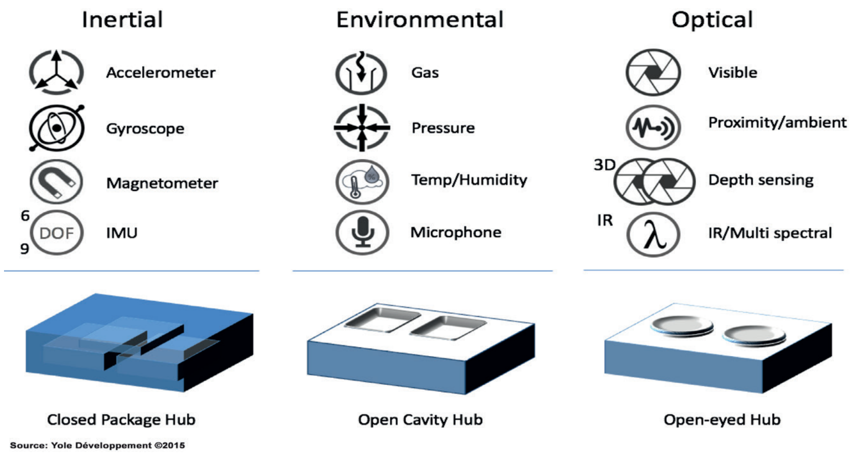

Figure 1: Integrated sensor clusters in smartphones vary based on sense parameters. SOURCE: Yole Développement.

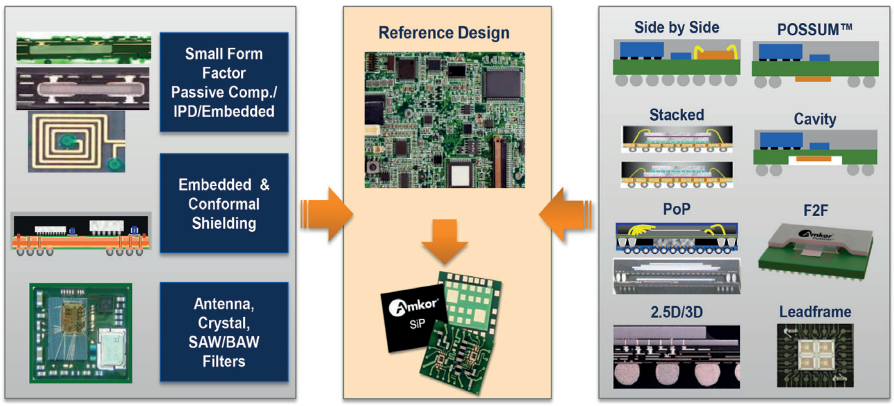

Figure 2: SiP module design options take many forms.

package and optical clusters. They expect these clusters to have increased integration in the future with system-in-package (SiP) technology as the primary means of achieving the increased integration. As shown in Figure 1, the different clusters target different sensing requirements. The closed package isolates inertial measurement unit (IMU) sensors from the environmental impact of torsion and humidity. These are typically overmolded plastic packages.

In contrast, the open-cavity cluster requires access to the environment for measurements such as pressure, humidity, gas, and more. The optical or open-eyed cluster also requires access to the external world and, in fact, a line of sight. Each of the packages in these clusters has unique design requirements.

SiPs are an ideal way to combine sensors, embedded processors, and RF connectivity together in a small form factor that meets both footprint and height constraints. With this packaging approach, manufacturers can combine different technologies very quickly without spending a lot of money on new mask sets.

In addition to quick time-to-market, a SiP allows manufacturers to use off-the-shelf components to build a system solution. Because all the building blocks are already in product form, it is relatively easy for packaging engineers to rearrange them to get optimal performance in terms of antenna location, power dissipation, and other critical design criteria.

As Figure 2 shows, a SiP can be a combination of several technologies including wafer-level packages, 2.5D or 3D structures, wire bonding, package-on-package (PoP), and more. SiPs can also include embedded passives, conformal shielding, filters and antennas. Combining all these technologies or components into a single package can be very beneficial for wearables where space and size are critical, as well as smart home and other smart applications, where space and size are also important.

While using some of the same foundry processes as CMOS devices, MEMS devices are different in many ways. For a MEMS sensor to interact with the environment, the package needs to deliver the stimulus to the chip. The stimulus can be in the form of vibration, humidity, pressure, light and more. Because the MEMS device is a mechanical structure with very small features, environmental contact must address particulates and the possibility of foreign matter contacting the structure. Figure 3 helps to visualize the challenges.

MEMs devices do not scale in the way CMOS devices scale with different processes. This means that there are no roadmaps for the MEMS process nodes. As a result, planning and packaging pose even greater challenges for MEMS devices.

Figure 4 shows standard packages that exist today for IoT applications. Note that MEMS and sensor packages are typically modified versions of packages used for other technologies and the modifications are not standardized. Packaging designers tend to use the same packages, but the changes are typically not compatible for a given application. This situation increases packaging cost.

SiP design methodology and standardization are among the approaches for cost reduction. If the package is standardized, cost is reduced by spreading development, assembly and testing costs over higher volumes with economies of scale, rather than each company using a custom packaging design.

Standardizing the packages for MEMS sensors not only helps lower the cost, but also helps increase the adoption of MEMS solutions in the market. Standards build manufacturers' confidence to enter the market with the reliability data that allows them to stand behind their products. When the forms of packages are fragmented, the reliability or field experience data is limited and it delays the adoption by manufacturers. Figure 5 shows different package types that could be used, or at least proposed as goals for standardized packaging that match the three cluster classifications identified previously.

The size of an IoT design can be reduced through package-level integration as shown in Figure 6. The initial IoT solution was more than $10mm^2$ in area using discrete packages - a separate package for each technology.

With the integrated package solution, the final size is about 6mm^2. This reduction of 40% does not include the space saving in routing the signals. Expanded design capability to combine traditional layout expertise with digital and RF circuit design and system modeling is essential to achieve this advanced package-level integration.

Evolving packaging solutions and issues

The packaging for MEMS devices is transitioning from quad flat no-leads (QFN) packages to laminate-based packages. Packaging alternatives include cavity-based packages or hybrid cavity packages with half of the package molded and the other half with a cavity for the MEMS device (Figure 7). While the molded part is more robust and can handle harsh application conditions, many of the sensors need the cavity to interact with the environment as noted earlier.

Several advanced packaging design techniques will be involved in achieving the appropriate highly integrated, self-powered MEMS sensor node that senses, computes and communicates with the IoT. The 3D approach shown in Figure 6 will evolve based on PoP, chip-on-substrate, chip-on-wafer, advanced interconnects including interposers and thru-mold via (TMV®), advanced materials including inter-layer dielectric (ILD) materials, film-over wire (FOW), conformal shielding, and other techniques that are either being developed or being used for one of the other technologies today.

Conformal shielding provides an excellent example of a system-level solution for combining technologies, while avoiding electromagnetic radiation effects among electronic components within a SiP and with the surrounding environment. Using a sputtering shielding technology to replace bulky metal shielding has zero impact on package size and weight, with excellent electrical and magnetic shielding performances.

Other package-level issues that must be solved for an advanced multi-technology IoT device to pass rigorous quality testing include: chip-package interaction, warpage of thin high-density packages, delamination, and more.

When multiple-die in a single package are pushed to their highest performance capabilities, thermal stress is always a major consideration. Thermal enhancement options to ensure that each die operates within its thermal limits

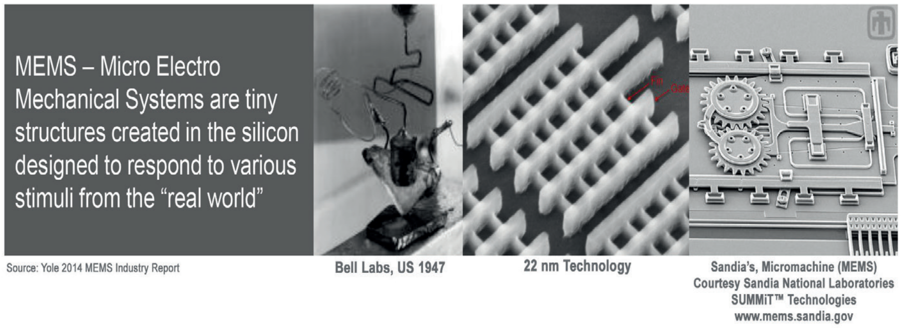

Figure 3: The packaging challenge: stimulus delivery. SOURCE: Yole Développement, 2014 MEMS Industry Report.

	Connectivity	Memory	Power Management	Microprocessor & Microcontroller	MEMS & Sensor
SOIC/TSSOP		✓		✓	✓*
QFN/TQFP	✓		✓	✓	✓*
Laminate CSP	✓	✓	✓	✓	✓*
WLCSP	✓		✓	✓	✓*

*Limited Compatibility

Figure 4: Current discrete (single-technology) packaging for the IoT.

	Overmolded	Exposed Die Surface	Cavity Package
SOIC			
QFN			
Laminate LGA/FPBGA			

Figure 5: Evolution towards standardization for MEMS/sensor packaging.

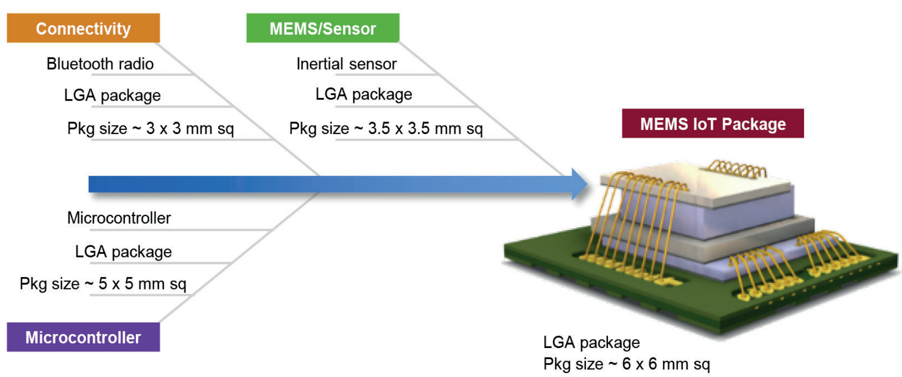

Figure 6: Adding IoT blocks to a MEMS/sensor package.

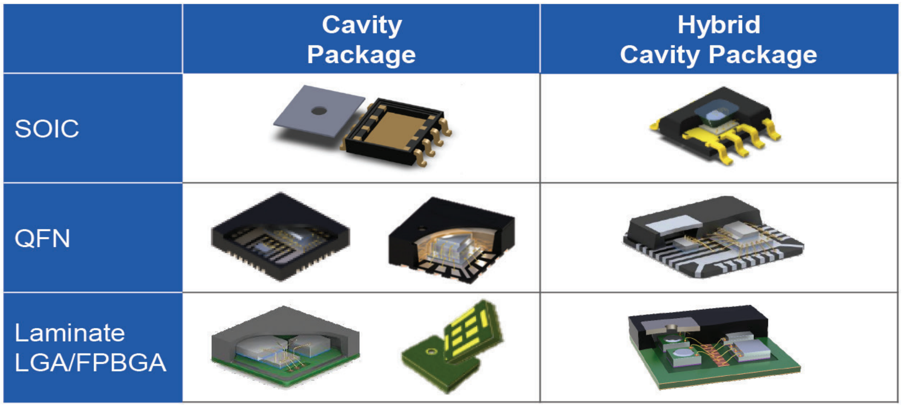

Figure 7: Alternatives for adding IoT blocks to MEMS/sensor package.

may require: 1) Thermal vias; 2) Stacked Cu-filled via structures; 3) Direct-to-metal die attach pad structure; 4) Enhanced thermal die attach compound; 5) Enhanced thermal mold compound; 6) Detailed mechanical test and simulations for mechanical SiP integrity including: warpage improvement, solder joint reliability, die strength and stress, flip-chip bump fatigue, substrate trace cracking, temperature cycling, and more.

System-level packaging technology

Similar to previous technology waves, the IoT will dramatically change people's lives in the 21st century and beyond. However, today's approach to system-level technology must change. Silicon design must take into account packaging capabilities, limitations and requirements from the beginning. When several ICs are mounted on a substrate, it is more important than ever that the interaction among the various signals and noise aspects are considered early in the design process.

To bring down system cost, achieve a more robust design and avoid some of the difficulties that others have encountered, packaging experts must be involved soon enough in the design integration process to address increasing packaging/system complexity in IoT-related applications and, in fact, most of the advanced systems that are expected to be developed in the future. Standardization for packaging and other aspects promises to play an important role in achieving design goals.

Reference

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Biographies

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