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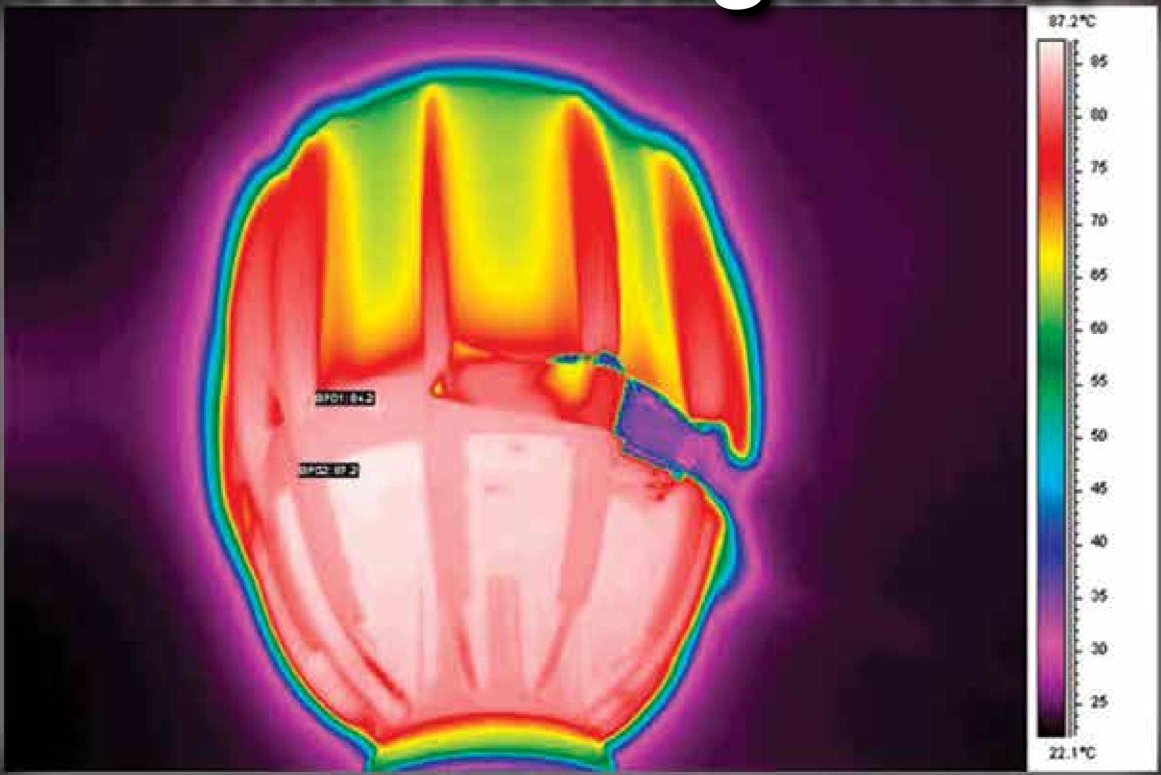

INSIDE THIS ISSUE

- Die Attach Film...
- Passive Thermal Management...
- MEMS Packaging...
- High Temperature Electronics for LED...
- Metal Inter-Diffusion and Eutectic Wafer...
- Wafer-Level Packaging...

Thermal Management Keynote Confirmed page 48

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Wafer-Level Packaging for Microsystems: From Automotive to Mobile Electronics and Beyond

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1. Abstract.

Microsystem devices have traditionally leveraged both wafer fabrication and packaging technologies born in the IC industry to implement sensing and actuation functions at microscopic scales. The inherent needs unique to microsystems motivated the development of the first products with wafer-level packages (WLPs) in the 1980s. The development of products that utilized WLP technology continued into the 1990s and on into the turn of the century due in large part to the needs of the automotive and later mobile electronics industries.

The relentless drive to miniaturize and cost reduce electronic devices has caused the IC industry, in a reversal of the flow of technology, to look to the microsystems industry as a source of technology. Thus, in recent years, the IC industry has begun adopting on a wide scale, some of the WLP technologies that have been mature in the microsystem industry for many decades. These technologies include: through wafer vias, CMP, wafer bonding as well as multi-die assemblies and die stacking.

This paper looks at the evolution of wafer-level packaging for microsystem products across many different markets and across the packaging hierarchy. While many technology demonstrations have been published prior to the devices highlighted in this paper, the emphasis in this paper is on WLP devices that have successfully navigated all of the possible pitfalls while traversing the challenging road to commercialization. Examples of WLP products that have been driven by market needs will be used to illustrate some of the advantages and challenges that are common to all successful wafer-level packages. The common threads found in these wafer-level packaged devices will provide insight into the technological challenges that will be encountered in the coming decades as microsystem technologies are used in ever increasingly diverse markets.

2. Introduction.

Microsystems technology has been the cornerstone for the creation of many of the amazing products that we take for granted today. The market pull that created the financial incentives to develop products based on these technologies has evolved over the last three decades from automotive to consumer markets. In the coming decades we will see further expansion of these technologies into new applications with potentially even greater volumes and technological challenges associated with medical and diagnostic applications as well as areas such as environmental monitoring.

Microsystem devices are transducers that convert information signals from one or more energy domains to the electrical domain and/or visa versa. These energy domains can be mechanical, thermal, magnetic, chemical, nuclear, fluidic, gaseous, or from any portion of the electromagnetic spectrum: infrared through visible light to gamma and x-rays. Many microsystems work across many energy domains. For example, display devices are actuation transducers that convert electrical energy into mechanical motion, which is then used to modulate incoming light. Medical diagnostic devices can incorporate chemically reactive cells on the surface of a chip and use an optical subsystem send the output to the user. The entire package hierarchy of a microsystem device must be designed with these signals in mind.

At the die level, microsystem devices have historically leveraged the tremendous technology investments made in the IC industry. Virtually all microsystems leverage the power of microelectronics through the incorporation of interface circuits that amplify, calibrate and condition the signals as well as through the material, fabrication, metrology, packaging, test and manufacturing infrastructures developed for ICs.

At the package level, however, microsystem devices have been a key driver of technological advances. Some microsystems have been packaged at the wafer level since the 1980s and through the 1990s wafer-level packaging has expanded to a multitude of microsystem applications. It is only recently that WLP technology been widely incorporated into IC products.

3. Electronic Package Hierarchy.

The packaging of electronic products is often discussed in terms of a hierarchy [1]. For purely electronic devices, this hierarchy is straightforward and clearly defined. For microsystem devices, the package hierarchy is more blurred as the overall package requirements become distributed over the hierarchy. As size, volume and cost pressures increase and as microelectronic technologies evolve, the opportunity to push microsystem package functions down the hierarchy increases.

At the top of the microsystem hierarchy is the third or system-level package. It is the package that the consumer or systems integrator interacts with. It includes an outer shell or case that has an interface to the outside world and it often supports some form of human interaction. System-level packages must typically be very robust, and often must be ergonomically designed for visual and market appeal. In addition to supporting second level packaging, the system-level package must have the appropriate ports or I/O channels that allow signal energies to pass to and from the outside world to the enclosed electronic components at the lower levels of the hierarchy.

Assemblies of components on printed wiring boards (PWB) or other substrates are referred to as the second level in the package hierarchy. These substrates provide mechanical support and electrical interconnections for the microsystems, ICs and passive components and are most commonly made from materials such as FR4 or flex materials with copper conductors, or from thick film ceramic materials. Because of physical limitations of these materials, some microsystems need to use more exotic substrate materials such as aluminum nitride, high performance organics or composite materials where electrical, thermal or mechanical considerations are important. The second-level of the package hierarchy often relies on solder interconnect to attach components to the substrate. Many WLP microsystems are assembled directly on a second-level substrate.

Microsystem and integrated circuit die are housed in and protected by the first-level or component package. This level of the package hierarchy includes conventional JEDEC outline packages such as PGAs, QFNs and BGAs, as well as more complex and custom packages for microsystem die assemblies. Component-level package assembly usually involves processes such as die attach, wire bond and flip chip along with a transfer molding, encapsulation or sealing method to protect the die. This level of the package hierarchy must also transmit signal energy into the die while still protecting the die from undesired forces.

The lowest level of the electronic packaging hierarchy is the wafer-level and as market demands for smaller and less expensive products continues, the importance of this level of the package hierarchy becomes more important. The growing demand for wafer-level microsystem packages is due to several factors: the opportunity to reduce component size; yield increases due to microsystem die protection before the wafer leaves the cleanroom; and the potential for improved testability. Wafer-level packages are batch fabricated and can therefore offer lower cost when the volumes are sufficiently high. However, the attraction of wafer-level packaging can quickly be offset by the added fabrication complexity and the more difficult engineering challenges of scaling package functions to the micro scale. Often a strategy that delays wafer-level packaging until after the initial component-level version of the package is qualified and in production is a good trade-off between technical complexity and time to market vs. overall product cost and size.

4. Materials for Microsystem Packages.

Microsystem packages utilize a much wider range of materials than do traditional microelectronic packages. These materials are used for package bodies and substrates, package sealing and encapsulation, die attach and interconnect. Specialized materials are often needed to provide the necessary media and stress isolation and to provide signal paths for non-electronic signals. Optical windows, gas-tight enclosures, fluidic interfaces, and the ability to survive extreme environments all require the use of specialized materials. WLP microsystems have driven the adaptation of solder, glass frit and organic adhesive technologies to the sealing of die at the wafer level. The cost of a microsystem product is often dominated by the cost of the package materials and the complexity and equipment investment that is required to assemble such devices.

Regardless of where they are used in the package hierarchy, microsystem package materials can be classified into two broad categories: hermetic and non-hermetic. Hermetic materials are limited to metals, glasses, ceramics and semiconductors: materials with very low gas permeability. Organic materials, silicones and other polymers have higher levels of gas permeability and are therefore classified as non-hermetic.

Hermetic packages can of course only be made from hermetic materials. These materials are often more expensive and the assembly processes associated with them are also more expensive. The requirement for hermeticity can be either due to the need to protect the die from the outside environment, or to keep the microstructure on the die in a controlled environment.

In applications where a microsystem requires a hermetic package, the designer has a choice of where to implement the hermetic sealing function. This can happen at the system, board, component or wafer-level. The trend in many applications has been to drive the hermeticity function to the wafer level, but some applications such as 3D fiber optic switches often must use a hermetic system-level package, due to the alignment, scaling and assembly complexity.

Hermetic packages are essential in applications where the microsystem must be in a harsh environment. Metal diaphragms can be used to transmit pressure signals to the die, and in imager and IR sensor applications for example, optical windows sealed to a metal package can allow incident light into the device while maintaining hermeticity. Inertial sensors along with resonant devices, switches and fuel cells typically require fully hermetic packages.

Hermetic packages are usually sealed with welding, or direct bonding processes such as fusion or anodic bonding. Hermetic sealing materials such as solders or glass frits are also used at various levels of the package hierarchy, especially in wafer-level packages. The needs of hermetic packages often drives the use of special assembly materials and processes such as low-outgassing die attach and extensive vacuum bake schedules. These packages often seal vacuum, controlled pressures or specialty gases inside that can further drive the incorporation of getter materials. Vacuum packaging is used for resonant devices as well as devices that need thermal isolation such as IR sensors and miniaturized fuel cell components. Specialty gases at controlled pressures are sealed inside packages to manage thermal conductivity, increase electric field breakdown strength or to dampen mechanical motions. Outgassing and partial pressure considerations must be given careful attention in these applications [2].

Non-hermetic microsystem packages are used in applications such as genome sequencing, cell analysis, chromatography, water quality, chemical and environmental sensing and other applications where the die must be directly exposed to the environment. These devices often incorporate a fluidic port with a sealing mechanism to allow the fluid of interest to be directed to the surface of the microsystem die [3]. These types of packages must often be very low cost since they could house die that are intended for a single use and then are to be disposed of.

continued on page 40

continued from page 39

Non-hermetic packages are also extremely useful in applications where the hermetic sealing requirement is provided at the wafer-level and the overmolded first-level package facilitates other packaging functions. Many inertial sensors incorporate this strategy.

Packages that rely on non-hermetic materials for sealing hermetic package body components might have very low total gas permeability, but they still cannot be considered to be hermetic. While their "as fabricated" performance can often meet product requirements, it is much more challenging for these types of assemblies to maintain the required environments inside the package after a rigorous qualification schedule or over the full lifetime of the product.

5. Microsystem Package Requirements.

In general, the package requirements for any electronic device are similar, but in microsystem applications, these requirements take on significantly different meaning and the package functions can be partitioned in different manners across the hierarchy.

All successful electronic packages must satisfy at least four functional requirements: 1) provide necessary I/O ports for signals; 2) manage power; 3) manage environmental factors from both inside and outside the package; and 4) facilitate in an aesthetic way, handling, marking and labeling of the device. Meeting these requirements for a microsystem package is especially challenging due to the limitations of the non-electronic interconnects and the need to often locate these devices directly in the environment to be sensed. For these reasons, microsystem designers often divide the package functions across several layers of the hierarchy.

6. Microsystem Package Requirements: Signal I/O.

The most fundamental requirement of a microsystem package is to manage the inputs and outputs of the device. The device I/O can be present in many different forms: electrical, optical, mechanical, fluidic, etc. Electrical signals are usually transferred into the device from pins or pads that interface with the other levels of the hierarchy through conductive paths in the package and then through wire bonds or flip chip pads to the microsystem die.

Optical I/O refers to signal transmission across the electromagnetic spectrum from infrared and visible light through high-energy radiation such as gamma and x-rays. This type of I/O can be broken down into free-space and direct interconnection. Free-space connection typically involves the use of a lens or transparent window through which the optical energy can pass. Cameras and display devices have this type of optical I/O. Direct optical I/O implies the use of a waveguide or optical fiber to direct the optical energy directly into the microsystem. Many telecom microsystem devices use this type of optical I/O. The package must not introduce distortions, dispersions or reflections that lower the signal to noise ratio of the optical signal. The integration of passive optical components with active die in a microsystem package can yield tremendous advantages.

Mechanical signals are typically transmitted into the microsystem device through the package that is mounted to a substrate. In applications such as inertial sensors, in addition to the need for mechanically-rigid mounting, the package must be designed to facilitate precise orientation on the mounting surface. Package resonance issues must be carefully controlled.

The interfaces that are used in microfluidic devices typically take on one of three forms: integrated connection; a system-level connection; or an open connection. Integrated connections use features built directly into the package to physically connect to a hose or tube that interfaces with the system. These integrated connections can be press fit or can involve a mechanical coupling that directs the fluid to the die surface. This is often seen in diagnostic applications and in pressure sensors where the device is remotely located from the fluid to be measured. System-level connections use a gasketing mechanism to seal around a surface on the microfluidic package. The flat surface can be on the top of the silicon die, or the device package. These gaskets are either incorporated into a fluidic connector that is external to the device, or are part of a clamshell housing that is integrated into the external system. In either case, open fluidic interfaces are commonly seen in pressure and chemical sensors where the die is directly exposed to the fluid that is being sensed. These include medical diagnostic devices as well as sensors that are immersed in a fluid such as those used in testing for contamination or water quality.

7. Microsystem Package Requirements: Environmental Management.

More than almost any other class of electronics, microsystem devices must be designed with environmental consideration in mind. This takes on two forms: environment internal to the package and the external environment. All microsystems must have packages that protect the die from external damaging forces, particulates, corrosive materials, undesired contact, etc. In other words, since the microsystem must interface with the outside world, the package must be designed to allow that to happen in a manner that does not damage the die but still allows the desired signal into the device and to the sense element. In devices such as pressure sensors, this challenge is called the media isolation problem. Stress sensitive die must also be isolated from external forces that can be transmitted through the package. A change in the output due to external package stress is referred to as "base-strain sensitivity" for example in accelerometers.

Second, the microsystem package must often create and maintain an environment around the microsystem die that is necessary for proper device operation. As examples, many inertial sensors and resonant devices must be packaged in a vacuum or low-pressure environment. Accelerometers are often packaged with a specific gas at a specified pressure to provide the appropriate level of damping. IR sensors often require an environment that minimizes thermal conductivity, and switch arrays often designed with a gas environment that increases the dielectric breakdown strength of the contacts. These internal environments must be maintained for the lifetime of the device and are dependent on both desired gases not leaking out, and undesired gases not leaking in.

8. Microsystem Package Requirements: Power Management.

Package considerations for power management must consider three different factors: methods of energizing the electrical circuits; dissipating waste heat; and containing desired internal thermal energy. Microsystems that have electrical circuits and/or incorporate electrical electrodes must have a way for those circuits to be energized. Typically these nodes will be implemented in the same physical connector as the electrical I/O, but unique factors associated with multiple die, different metallization schemes and noise should be considered.

Dissipation of heat is usually not much of an issue in microsystems because they are usually designed to operate with very low power budgets. There are applications such as imaging arrays however where localized heating can cause non-uniformities in the output across the array. Thermal stability must often be considered to a much greater degree in devices such as chemical sensors and diagnostic bio-fluidic devices that depend on various reactions since the overall device performance is extremely dependent on temperature.

There are unique applications of microsystems where thermal energy must be contained inside the device for proper operation. Fuel reformers for fuel cells and ink jet print heads are two examples. Vacuum packaging, insulating materials and even thermal shields are used to keep the heat inside the device where it is needed and keep the heat away from other components or the external environment.

9. Microsystem Package Requirements: Handling, Marking and Labeling.

Microsystem packages must be designed to facilitate handling, marking and labeling. Handling topics are associated with simplifying and “mistake-proofing” the mounting installation and/or use of the device in the system or higher-level assembly. Designing insertion keys, ergonomic shapes and using form factors already standard in the industry aid in the usability of the device. Packages that fit standard JEDEC outlines can use standard trays, sockets and handlers thus reducing costs. Material selection, coloring, and surface texturing all influence a customer’s perception of the device and have a direct impact on the perceived value that a device offers a customer. These factors often require collaboration between the package engineer, industrial designers and material specialists.

The ability to affix a mark and/or label to a microsystem package is often an over-looked requirement. At a minimum, the device package must have room for a part and lot number to ensure some level of identification and traceability. Beyond that, many microsystems also incorporate company logos, branding features, use disclaimers, and operating instructions. Devices that are used primarily in a more controlled environment can have more generic marking and labeling schemes while devices that are sold commercially typically have much more elaborate labeling requirements helping to create value for the product in the market.

10. Functional Partitioning of Requirements.

The most successful microsystem packages distribute the package functions across the package hierarchy in a manner that optimizes the entire system. A common approach is to use the wafer-level package to provide environmental protection along with the necessary microsystem I/O. This can take the form for example of a wafer-level hermetic package with electrical feedthroughs. This component can then be mounted into a first-level transfer molded package to facilitate handling, marking and labeling. This paper will consider devices that use wafer-level packaging at any level of the package hierarchy even though the final device might be sold in a first-level package.

11. The Evolution of Microsystems WLPs.

Microsystem products have been the driving force behind wafer-scale packaging for many decades. More recently the integrated circuit industry has leveraged these developments in higher volume applications such as memory devices and complex systems-in-a-package devices. As with any technology development, market need pulls these technologies into products. The market drivers for WLPs are primarily improved performance, expanded function at a lower cost and smaller size.

Many microsystem devices are dependent on wafer-scale packaging for their basic function at a lower cost than conventional packaging technologies. Wafer-scale packaging introduces enough challenges and unique capabilities, that often only the highest volume applications can justify the investment.

12. The Evolution of Microsystems WLPs: First Decade of Wafer-Level Packaging (1980-1989).

The first wafer-level packaged device of any kind to enter volume production was the Silicon Capacitive Absolute Pressure (SCAP) sensor (Figure 1), patented by Ford Motor Company in 1981 [4-5]. The market pull that drove the creation of this device was the Clean Air Act of 1970, which required the adoption of closed loop controls for internal combustion engines. A focus on smaller size, lower cost and higher precision pressure sensor resulted in the wafer-level packaged device that supplanted macro-scale ceramic sensors from the aerospace industry that had been in widespread use.

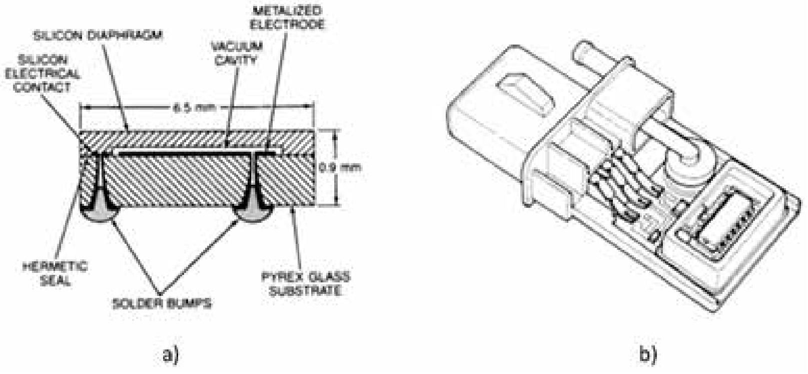

Figure 1. (a) Cross-section of the Ford SCAP device showing thru-wafer vias; (b) Drawing of the final assembly with the SCAP WLP mounted directly to the substrate.

The SCAP device used laser-etched, through-wafer-vias to create a WLP die that mounted directly to the second level substrate, thus eliminating any form of first-level package. The laser drilled vias were metallized, and after the sensor diaphragm was anodically bonded to the glass wafer, solder bumps were reflowed in the vias to seal vacuum inside the pressure sensor cavity. The solder bumps were arranged in a simple BGA configuration to allow electrical connection to the thick-film substrate that also contained interface circuits. This second-level package was placed in a third-level plastic housing that had an integral connector shell and port configuration to allow the device to be exposed to the engine manifold pressure. Many millions of SCAP sensors were manufactured for a variety of auto manufacturers well into the 1990s.

continued on page 42

continued from page 41

13. The Evolution of Microsystems WLPs: Second Decade of Wafer-Level Packaging (1990-1999).

Automotive applications continued driving the development of wafer-level packaging in the 1990s. The improved crash survivability offered by automotive passive restraint systems (airbags) created market pull that drove the development of wafer-level packaged accelerometers. Initially airbag systems received their crash information from macroscopic sensors that were located near the front of the vehicle. The cost and complexity of mounting the sensors in this location drove the development of microsystem-based accelerometers that were significantly smaller and lower cost while offering greater precision and the ability to directly interface with a microprocessor that ran the algorithm to determine “if and when” the airbag should be deployed.

The world’s first WLP airbag accelerometer was the Ford Integrated Silicon Automotive Accelerometer (ISAAC) (see Figure 2). The initial version of the sensor, the ISAAC-2M [6], consisted of an exposed capacitive sense element on a glass substrate and interface chip that was packaged in a conventional hermetic ceramic package. Subsequent versions of the device (ISAAC-2S) utilized wafer-level packaging to create a hermetic enclosure over the sense element [7]. The glass substrate of the die had passivated electrical traces passing through the seal ring leading to wire bond pads. The hermetic silicon cap was anodically bonded to the substrate to maintain a gas environment around the sense element such that the microstructure was over damped. This function provided by the package was very important since higher frequency signal components in the crash signal are considered to be noise in the deployment algorithm.

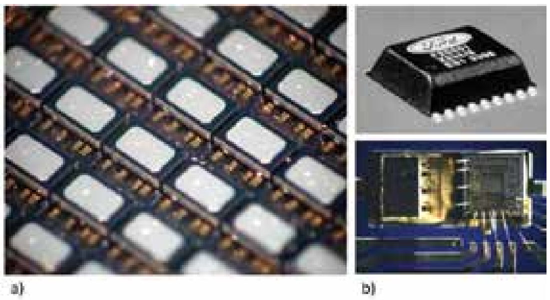

Figure 2. (a) Ford ISAAC crash sensor. The WLP sense element; (b) The WLP sense element and ASCI on a leadframe and in a transfer molded SOIC package.

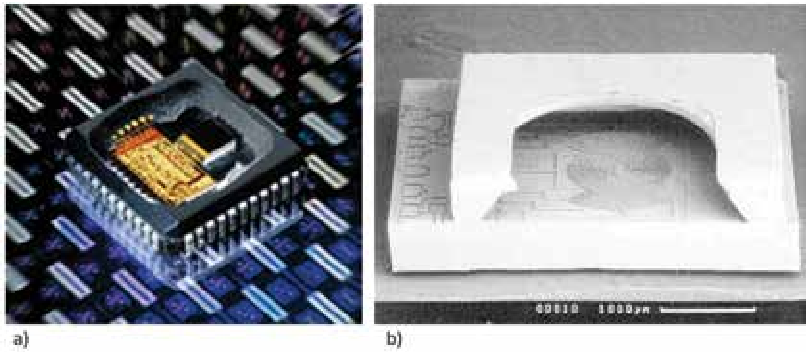

Figure 3. (a) Bosch WLP gyroscope showing the two die construction in a J-Lead plastic package; (b) The WLP sense element cut away to see the microstructure.

The WLP die and plastic package of the ISAAC-2S was qualified for volume production in 1997 in a SIP and SOIC configuration. The SOIC version remained in production until the late 2000 time frame with more than 10 million installed in vehicles in worldwide applications.

Freescale (at the time, Motorola) introduced a WLP airbag accelerometer in the late 1990s. Similarly, the sense element was fabricated on a substrate and a silicon cap was used to create a controlled hermetic environment for the sense element to operate in. The seal was made with a printed glass frit paste and external bond pads allowed the device to be electrically connected to a separate interface chip, both of which were mounted to a standard leadframe and then transfer molded. This device also went into high volume production and was later adapted to be one of the first accelerometers to be offered in a standard QFN.

14. The Evolution of Microsystems WLPs: Third Decade of Wafer-Level Packaging (2000-2009).

At the turn of the millennium, automotive applications were still the primary driving force for the development of wafer-level packages, but by the end of the decade, this would change [8]. These automotive applications expanded beyond accelerometers for passive restraint systems with electronic stability control and navigation systems driving the development of wafer-level packaged gyroscopes and magnetometers [9]. Bosch released the first wafer-level packaged gyroscope (Figure 3) in the 2004 time frame [10]. This device also used a silicon substrate and a surface micro machined structure to implement the angular rate sensing function. Like many other devices at the time, the WLP sense element die and the interface ASIC were mounted on the same lead frame and transfer molded. These automotive applications also pushed MEMS manufacturers to integrate more sensing axes in a single device such as the LSM303DLH 3-axis accelerometer/3-axis magnetometer from ST Microelectronics.

Later in the decade, mobile electronics and in particular the iPhone became an overwhelming market force that justified significant expansion in the investment in wafer-level packaging to support even smaller sizes, increased functionality and significantly higher volumes at lower cost. Specifically the strong need for very small, very low cost multi-axis accelerometers and gyroscopes, as well as low cost camera modules and later timing and RF devices became evident. The expansion of wafer-level packaged microsystems beyond automotive applications initially came from camera manufacturers, but this demand was quickly outpaced by the introduction of the iPhone and later other smart phones.

The first wafer-level package three-axis accelerometer for use in a consumer products was the LIS331DL from ST Microelectronics introduced in the original iPhone in 2007 [11]. With over 1 million units sold in the first week, it was a watershed moment for wafer-level packaged sensors, demonstrating the enormous size of the market as compared to the traditional market driver automotive.

Camera manufacturers implementing stability functions were the first consumer application to benefit from the small size of wafer-level packaged gyroscopes in the 2006 time frame [12]. This application as well as automotive applications were dwarfed however by the introduction of the iPhone 4 just after the turn of the decade. The iPhone 4 introduced the first three-axis wafer-level package gyroscope in the early 2010 time frame.

In 2007, Tessera introduced the OptiML wafer-level packaged camera that reduced the size of the camera module by 50% and the cost by 30% as compared with competing devices of the time. Using some of the first silicon thru-wafer via technologies, combined with a unique method of laminating molded plastic lenses over the surface of the wafer were the hallmarks of this technology [13] that has since seen widespread adoption in mobile electronic devices (Figure 4).

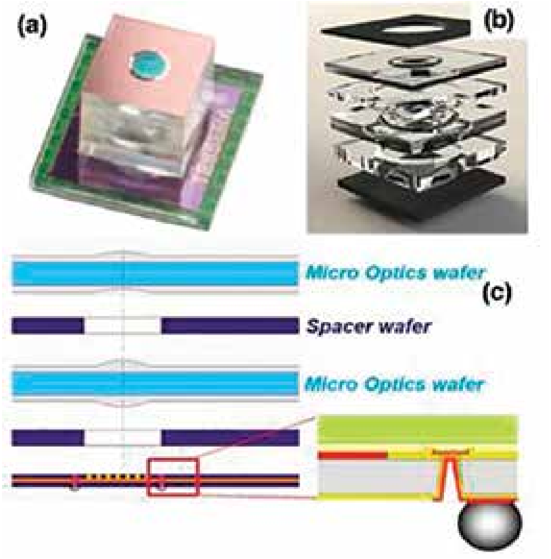

Figure 4. Elements of a typical wafer-level camera module include a CMOS image sensor, polymeric lenses molded onto glass carriers by UV imprint lithography, spacers and aperture layers. Source: EVG.

In 2008 SiTime introduced the SiT8002XT programmable clock oscillator as a replacement for traditional quartz oscillators [14]. Due to a unique wafer-level packaging process [15] that seals the resonator in a vacuum, the final device is one-third the height of a comparable quartz oscillator. In addition, the device is more robust and subsequent versions show significantly better long term stability. The packaging is based on silicon fusion bonding done at high temperatures, which reduces issues with outgassing while sealing the package in as closed an environment as possible.

Microsystems for telecom applications have often implemented hermetic packaging at the component and system level. Crossbar switch arrays were in production in a WLP at the end of the decade [16] using a silicon cap sealed to the substrate with a gold-based solder. The final device had a control ASIC mounted on top and the two die were wire bonded together in plastic cavity package (Figure 5).

WiSpry began sampling RF tuning and switch components in the 2008 time frame for use in cell phone front ends [17]. The devices originally were fabricated in a wafer-level package that was then overmolded into a surface mount package. More recently, the devices are being delivered in a WL-CSP.

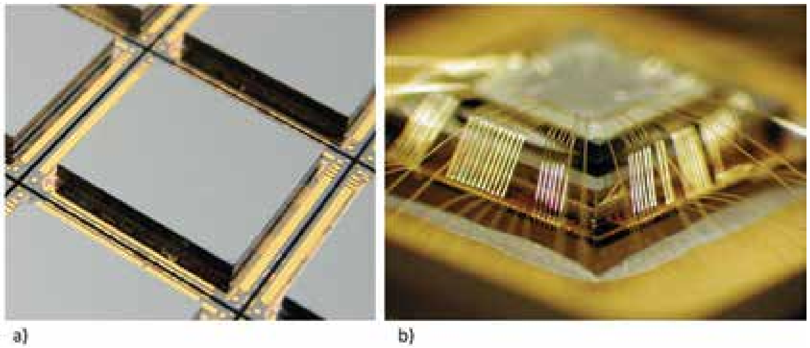

Figure 5. (a) WLP 8x8 crossbar switch array die; (b) The switch array packaged with a control chip in a cavity package.

15. The Evolution of Microsystems WLPs: Current Decade and Beyond.

The fourth and current decade of wafer-level packaging can be characterized in three ways: first, expansion of WLP technology for commercial ICs with major thrusts in die stacking and TSVs; second, the introduction of new wafer-level packaged products in the consumer, medical and environmental monitoring spaces; and third, continued cost and size reduction of microsystems along with the integration of more sensing functions including 9 and 10 degrees of freedom sensors, integrated front end RF components including timing circuits, etc., as driven by the mobile device markets.

Wafer-level package IC technology was initially focused around copper traces and redistribution layers on the surface of the IC to allow solder balls to be distributed over the surface of the IC [18]. In the current decade, mature microsystems technologies such as DRIE and CMP are leveraged more fully in the IC industry, facilitating advanced packaging techniques such as die stacking, and WLP with Through Silicon Vias (TSV) [19]. This packaging technology is now ubiquitous in memory devices and is rapidly gaining adoption in other types of ICs as well.

In the early 2010 timeframe, even more sensing functions became available in WLP. The first major three-axis magnetometer was the Honeywell AN203 used in the iPhone3GS in June of 2009. Although the device was not in a wafer-level package, it paved the way for subsequent wafer-level packaged magnetometers such as the Bosch 3-axis magnetometer in a WLP in the 2011 time frame (Figure 6). Devices such as this create component building blocks that can be integrated into systems-in-a-package (SIP) configurations that dramatically improve value for the end customer.

Figure 6. Bosch BMC 150 three axis magnetic sensor in a 2x2mm WLP.

continued on page 44

continued from page 43

Microsystems, driven by the demands of the cell phone markets, continue to evolve the use of WLP technology by integrating accelerometer, gyro and magnetic sensor WLP die into a larger subassembly to bring greater levels of functionality into a single package [20]. The availability of these inertial sensing components facilitates the development of products with almost every conceivable combination of inertial sensing capability including 10 degrees of freedom devices that add pressure and temperature sensing the 3-axis gyro, accelerometer and magnetic sensor products. As an example of how WLP has driven size and cost reduction in these devices, in 2007 3-axis accelerometers were in 12mm2 packages with production costs of greater than $0.10, yet just four years later, WLP allowed similar devices to be offered in a 2mm2 package for about half the price [21]. The use of TSV technology in the devices will drive the size even lower.

Figure 7 shows two different approaches taken to integrate WLP components into higher-level inertial sensing subassemblies also called systems in a package [22]. In Figure 7a, WLPs are mounted on a ceramic substrate along with ICs and passives, and in Figure 7b, wafer level packaged sense elements are packaged with interface chip in an overmolded LGA.

The current decade also marks the turning point for the widespread adoption of MEMS timing and RF components. Sand9 is introducing a combined oscillator and temp sensor in a sub-mm WLP that is half the size of competing quartz crystals. In keeping with the trend towards integrating WLP into higher-level subsystems, the device will be available in a form that supports SIP assembly [23].

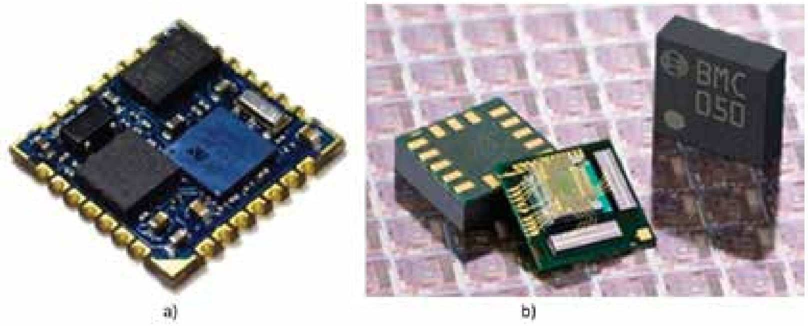

Figure 7. (a) WLP inertial sensor components integrated into multi-axis inertial sensing devices. Inertial sensor package from ST; (b) The BMC050 3 axis accelerometer, 3-axis magnetic sensor from Bosch.

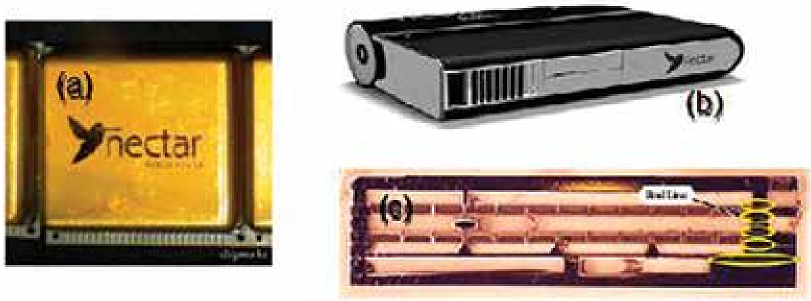

Figure 8. Micro fuel cell and reformer. (a) The packaged reformer; (b) The complete commercial package; (c) A cross section of the interior assembly of the reformer.

Miniaturized fuel cells and fuel cell reformers (Figure 8) are an emerging market opportunity that will require WLP to become successful. Reformers convert fuels such as butane into hydrogen that can be used in the fuel cell. This reaction typically requires process conditions of up to 800°C. Vacuum packaging is essential to isolate the reaction cell from the exterior walls of the device, as is the use of internal radiative shields.

Fluidic connections must be robust enough that they will not leak even through multiple fuel cartridge replacements. Lilliputian Systems has been developing a microfluidic butane reformer called the "Nectar." While initial versions of the device were packaged in conventional hermetic packaging, a wafer-level version will be required [24].

Another market that will provide the pull necessary for innovative wafer-level packaging development is in the medical implant and diagnostic areas. Cochlear and optical implants will continue to evolve and expand in the market along with implants for pain management [25]. New WLP devices that interface with the human body will emerge as the technology adapts to these market needs.

As an example, chronic pain can be mitigated through the use of wafer-level packages to create spinal cord stimulation arrays that allow unprecedented levels of electrode density and addressability. Figure 9 shows a 9x6 array of wafer level packages assembled on a Nitinol frame with thin film gold interconnects. Each of the 27 packages has two electrodes that are individually addressable and powered via an ASIC that is flip chip mounted inside the WLP. Each package is about 2x4x0.5mm and is both fully hermetic and biocompatible.

Another example of how wafer-level packaging is driving the implantable medical market is in the area of ocular pressure sensors. Using a wafer-level packaging process and custom circuits, a wireless device for chronic measurement of eye pressure has been demonstrated [26] (Figure 10). While not yet in production, the device demonstrates the unique capabilities of microsystem technology in meeting new and challenging market needs.

Wafer-level vacuum packaging will become more universal improving the performance of a variety of device applications such as infrared sensors and energy harvesting. Remote sensing devices such as IR imagers for human presence [27] can be used in smart home and office applications to manage room environments. By sealing a wafer-level package over the surface of the thermopile performance is improved because there is less radiative loss and the cold junctions have more thermal mass to maintain temperature difference. The WLP creates a smaller device that uses less power and is much more sensitive, thus broadening its application.

Environmental monitoring will become more common as technologies continue to develop that allow lower cost devices with the necessary functionality. Applications such a gas detection [28] and complex WLP to support multi-sensor devices will see continued growth in the coming decade [29].

As a companion application, energy harvesting is an emerging market with potentially very large volumes that will require low-cost, controlled environment packaging. Often an energy harvesting device consists of a movable structure with a piezoelectric film that generates charge as the flexure moves [30]. Low-pressure packaging allows greater displacements and thus more charge to be generated. A WLP strategy that provides a large enough cavity

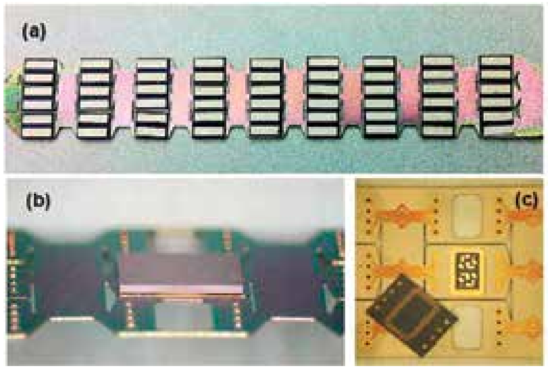

Figure 9. (a) An array of implantable WLPs mounted on a Nitinol frame for spinal cord stimulation; (b) A close-up of one package on the frame; (c) The base of the package under the frame and the package lid.

to accommodate motion while still maintaining environmental integrity over the life of the device will be essential to fulfill the market needs.

16. Conclusions.

Microsystem products have been the technology driver for wafer-level packaging since the 1980s. The demands of the automotive industry for engine controls and safety systems were the initial application, followed by the even greater demands of the mobile electronics industry. The IC industry has leveraged some of the WLP technology developed for microsystems to facilitate similar advantages in miniaturization by utilizing TSVs and die stacking. Further development of wafer-level packages for consumer and medical applications will drive even greater expansion of the technology to support an even broader set of market demands.

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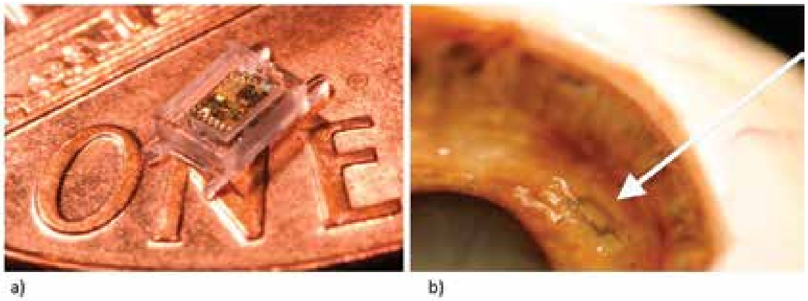

Figure 10. (a) An implantable wireless sensor for chronic eye pressure measurements; (b) The sensor implanted in the eye of a human cadaver.

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Biography

Dr. Spangler received his Ph.D. in electrical engineering from The University of Michigan in 1988 and is currently President of Aspen Microsystems, LLC, a microsystems product development and intellectual property company with specialization in semiconductor devices, packaging and assembly.

continued on page 46

continued from page 45

Chip was previously President and CTO of Aspen Technologies a semiconductor package design and assembly subcontracting company that provided services for customers in medical, industrial, telecom and mil-aero markets. Among these products were ultra high-resolution displays, several DNA analysis products, implantable devices for neuromodulation, and MEMS switch arrays for telecom applications. Prior to this, Chip was employed at Ford Microelectronics where he had responsibility for a number of microelectronic programs including analog IC design, pressure sensors, micro-machined fuel injectors, as well as airbag and chassis accelerometers. His work lead directly to the production of the world's first wafer-level packaged, plastic surface mount airbag accelerometer.

Dr. Spangler is the author of over 30 technical publications and 9 patents. He is currently an editor for IEEE Journal of Microelectromechanical Systems (JMEMS) and he serves on the board of directors of several organizations. He has also been active in organizing a number of technical conferences including the biannual Transducers Conference as well as the Hilton Head Solid State Sensor Workshop.

In Memoriam

Roger S. Benson

Our well-loved friend, Roger Benson, 58, passed away suddenly on Tuesday afternoon, July 15th, 2014.

An inspiring colleague, engineer, dad, husband, and fellow Board Member, Roger's passing is a great loss for our IMAPS community, yet pales in comparison to the exceptional family life he led. Those who knew Roger will never forget his warmth, generosity, sense of humor, and the immediate connection you felt with him.

A by-the-book task master, every role or interest Roger dealt with was accompanied by desire, organization, patience, and the ability to achieve the best results possible. Nothing better describes Roger than an event one morning in Upton, Massachusetts, when his second daughter was making an entrance into our world. With no time left on the clock for a hospital delivery, Roger called 911 and then calmly, with all his organizational skills and patience in check, cool-handedly delivered Ms. Marisa Benson at 10:20 AM.

Roger was employed by Hittite Microwave as a Project engineer and was excited to return to the world of microelectronic manufacturing. Past employers that were honored to have worked with Roger included Digital Equipment, Raytheon, IRC, Skyworks, and Conexant.

A graduate of Northeastern University, Roger held degrees in Biology and Chemistry. Roger also had the ability to make airplanes go and was an FAA-certified Airframe and Power Plant technician.

Roger's Memorial Service on Sunday afternoon, July 20th, was beautiful. The love from his family and friends was bright and strong. Kathy Benson performed a Bonnie Raitt love song and both daughters spoke candidly and humorously about their dad. One daughter sang "Somewhere over the Rainbow," *a cappella* style, which was both tearful and joyous. Another close friend sang "Heart of Gold" made famous by Neil Young. Roger now serves as the guiding light for his wife Kathy and daughters Rachel and Marisa.

I want to live
I want to give.
I've been a miner for a heart of gold
It's these expressions, I never give
That keep me searching for a heart of gold.

Keep searching, Roger, for all of us.

Vaya Con Dios

Your friends from IMAPS New England

Donations in Roger's memory can be made to The Trustees of Reservations.