MEMS PACKAGING & ASSEMBLY ISSUES [SMTAi_2000]

By Dr. Ken Gilleo
ET-Trend
Rhode Island
Ken@ET-Trends.com

MEMS, Micro-Electro-Mechanical Systems, may just be the ultimate enabling technology for the micro-level integration long sought for system-on-chip. MEMS manages many forms of energy and information. They include kinetic forces, light waves, sound waves, radio waves and conventional electrical energy. This technology has been applied to complex molecular detection, all kinds of analyzers, fluid pumping, radio signal manipulation, photonics and a host of medical applications. The most extraordinary feature of MEMS is that all of the diverse functions can be crafted into a single chip using specialized semiconductor fabrication techniques. While IC logic devices gave us the brain, MEMS adds the eyes, noise, ears and new senses beyond the limits of human range. And MEMS has output in the form of information. But more important, MEMS also produces control functions. This adds the muscle, the hands and fingers allowing MEMS devices to move internal elements and to affect the external environment. The ***merging of motion, sensing, computation and control*** *appears to represent the highest level of technology yet achieved.*

While packaging the versatile MEMS and it's optical kin, MOEMS (Micro-Opto-Electro-Mechanical Systems), is a major challenge, old and new solutions are being deployed. Most devices are housed in costly hermetic packages, especially the optical systems. Perhaps we can move to more traditional type packaging by using atmosphere control agents such as getters (molecule-specific scavengers). Wafer-level hermetic packaging, now under development, may also be an answer, bringing reduce cost, enabling high volume manufacturing and delivering the high level of protection needed. Some popular MEMS and MOEMS packaging strategies will be discussed.

But we also face the challenge of MEMS assembly. While many packages are hand assembled, will we standardize on SMT? Moving to SMT assembly appears to be a given for the high volume markets. But there will be new rules for MEMS primarily because of the need to sense the external environment. MEMS motion-sensing products like automotive accelerometers for air bags must be correctly oriented because they are directional. How important is package skew and tilt and can the solder fillet even change MEMS sensitivity? We will briefly examine MEMS packaging and then focus on assembly issues in an audience-interactive session. There may be more questions than answers at this early stage of MEMS.

Keywords: accelerometers, getters, MEMS, MOEMS, hermetic packaging, wafer-level packaging

INTRODUCTION

MEMS is about high-level integration of many dissimilar kinds of functions. This unification of functions includes motion, light, sound, electromagnetic radiation and high level analysis of external input. Computation, analysis and central control of these input/output functions results in a fully integrated system of incredible versatility. MEMS is the convergence point of many diverse technologies. Mechanics adds gears, optics brings mirrors, the electrical field delivers motors, chemistry adds molecular detection and general electronics adds radio computation and power to this new microworld. And we can expect biotechnology to enter the MEMS arena soon. MEMS blends and integrates complete functional systems and this is the key. This technology synergistically merges subsystems into a fully integrated, self-contained microcosm that once only existed in the macroworld. How remarkable that these once isolated technologies can converge into the microscopic world of silicon using wafer-level mass processes.

But there are major challenges! Specialists in this field insist that microelectromechancial systems fabrication, packaging and assembly are the greatest challenges our industry has ever faced. Not only are the advanced MEMS devices small and highly complex, many must communicate with the outside world by direct-path non-electronic signals. The burden placed on assembly is to provide electromechanical connections that do not interfere with or alter sensing and control function. Later, fiberoptic connections will be added. This challenge is new since assembly has mostly dealt with electrical signals. The additional input/output of motion, photonic and molecular "signals" adds a new twist.

Some MEMS devices send and receive light beams, others detect specific molecules, including biological analysis such as DNA. The merging of motion, sensing and computation most certainly represents a new level in technology that is still embryonic. Surprisingly, this new technology has been around for nearly three decades but at a simple level such as motion sensing. But more recently, optical MEMS, also called MOEMS, has become a hot area. The Internet is the new and powerful driving force. The solid and durable opportunities are in hardware, not in the present domain of "heretoday.gonetomorrow" dot coms. It's probably better to enable dot coms than to be one. The modern Internet is really a glass highway, a system of photonic light pipes. Light control is the master key to efficient photonics – the technology of communication using photons and MEMS is poised to be the winner here. Just during year 2000, the Internet giants spent billions of dollars to acquire MEMS companies. So as the light wave highway moves from the present long haul or backbone, closer to the home, we can expect the volume for MOEMS assemblies to increase and move out to the contract assemblers. The future wave may be light, not solder!

MEMS FABRICATION

Techniques have been mostly borrowed from IC fabrication with appropriate modifications to produce movable parts. Standard semiconductor bulk fabrication processes create the traditional electronic circuit portion. Subtractive etching produces the movable mechanical elements. Silicon dioxide can be formed for use as the etching mask. The etch-resistant silicon oxide or nitride will later become the mechanical or optical elements in a final step. Subtractive methods are used to remove the elemental silicon such as wet chemical etching or reactive ion milling. Other fabrication methods etch SiO_2 leaving silicon. A final chemical etching step can be used to free the movable mechanical elements. A "sacrificial holding structure" is sometimes etched away at the packaging foundry so that delicate parts are protected while the wafer is transported. Although initially fragile, MEMS parts are more robust after packaging. However, many need more careful handling by the assembler than conventional electronic packages.

MEMS PACKAGES

Most packages are hermetically sealed to keep out particles and gases that would interfere with mechanical movement or fog and degrade optical systems[1]. The package complexity that can add assembly restrictions is highly dependent on the type of MEMS product, its functions and the need for external access. All MEMS devices move, but their mode and the purpose of motion determine the packaging requirements. List 1 indicates some of the basic modes of motion. Table 1 gives applications, input/output and possible package type. Products with motion input and electrical output would appear to be the easiest to assembly.

LIST 1

1. Deformation of isolated parts; bending or twisting, no friction (accelerometers)
2. Rotating parts; friction
3. Sliding parts, friction and stiction
4. Impact, wear
5. Moving optical elements
6. Combinations of the above

TABLE 1

MEMS Device	Packaging	Input	Output
Accelerometer	EMC (Epoxy Mold. Com'd.	Motion	Electrical
2D and 3D Motion Detection	EMC	Motion	Electrical
Ink jet	Selective	Electrical	Motion
Digital Mirror Array	Hermetic/window	Electrical & light	Controlled light
Micro-Spectrophotometer	Hermetic/window	"Light"	Electrical
DNA Analyzer	Liquid access	Biological samples	Electrical
Disk Drive Heads	None	Magnetic	Electrical
Optical Switches	Hermetic/window	Electrical and light	Electrical & light
Capacitors, Tunable	EMC	Electrical/RF	RF
RF Tuners	EMC	Electrical/RF	RF
Gyroscopes	EMC	Electrical/motion	Electrical
Diagnostics (in vitro)	Open	Electrical, liquid	Electrical
Infrared Imagers	Hermetic/window	IR, Electrical	Electrical
Micro-Relay	EMC	Electrical	Electrical
Pressure Sensors	Sealed thin wall is OK	Force directly/indirectly	Electrical

The commercial MEMS industry has dealt primarily with type 1 motion devices such as accelerometers. The industry is scaling up for 2- and 3-axis gyroscopes that will be used for high volume input devices for computers, games and all kinds of handheld products. These products are easier to handle since the package can be sealed from the outside environment. The contract assembler is likely to encounter a MEMS motion package as one of the first. Packages will be both ceramic and plastic but both will be in SMT format. Let's look at some of the old and new MEMS packaging.

MEMS-SPECIFIC PACKAGE DESIGNS

Most MEMS packages started off as the standard Cerdip (ceramic Dual In-Line) package since a ceramic or metal hermetic package offers a high level of protection, but at a cost penalty. High volume accelerometer manufacturers like Analog Devices then converted the same packages to SMTs called Cerpacks®. Figure 1 shows some of the accelerometer chip. We will look at this package later to gain insight into assembling of MEMS.

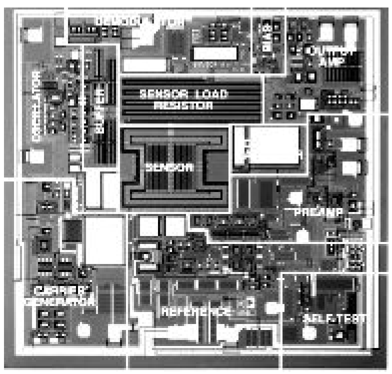

Figure 1 – Accelerometer Package
Analog Devices

Now we will examine some newer packaging concepts that could eventually become standard packages that assemblers will deal with[2]. Although the MEMS package can be very application-specific, some general design concepts are emerging. The MEMS devices have a universal requirement that the "motion zone" cannot be obstructed. A protective cap over the action area can permit the component to be overmolded while still allowing unrestricted movement within the device. Once the cap is in place, standard transfer molding can be used. In some cases, liquid encapsulants may produce less stress. Liquids may be applied by automated needle dispensing equipment commonly used for some BGAs.

Another possibility is to use Flip Chip. Since the active surface of the device with moving parts is placed downward toward the substrate, a natural protective zone can be formed. The standoff distance, or chip gap, can be accurately controlled by the chip bump height. High melting alloys or even non-fusible bumps can be used to insure a specific minimum gap between the chip and board. The next step is to selectively dispense underfill. Normally, underfill is applied to completely fill the chip gap, but this would interfere with MEMS movement or sensing. A more viscous encapsulant, resembling damming compound, could be applied to all four edges of the chip. This sealing encapsulant, a fillet without the underfill, would then thermally hardened. Now the package can be fully encapsulated by conventional transfer molding or by needle dispensing a liquid encapsulant. A chip access port could be added to the packaging substrate if the device must communicate with the outside atmosphere such as with a gas analyzer. A filter or semi-permeable membrane could possibly be used to limit entry to only the intended molecules. Figures 2 shows the Flip Chip designs.

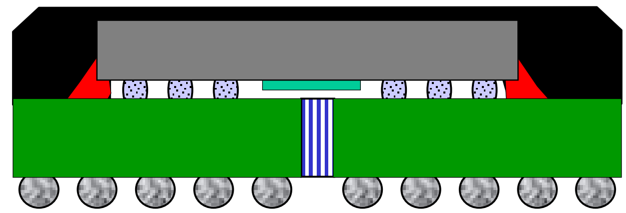

Figure 2 – Flip Chip MEMS Package

A more elegant concept is to apply a microcap at the device level or more preferably at wafer level and then proceed to standard packaging. Several groups, including AMKOR, IMEC (Belgium) and Georgia Institute of Technology are working on or have already developed "Cap-on-Chip" sometimes-called 0-Level packaging. The cap essentially produces a silicon micro-hermetic package well suited for accelerometers, gyroscopes or any other motion detectors. The present caps are made of silicon to achieve a perfect match of materials. However, the thin, flexible silicon cap may require a pre-molding step to prevent cave in due to high molding pressures. Perhaps low expansion metal caps can eliminate this problem. The alternative may be liquid encapsulation. Figure 3 shows the Cap-on-Chip concept. The final package, if successfully implemented, will be outwardly similar to the common SMT plastic packages although it is too early to know exactly what the form factors will be.

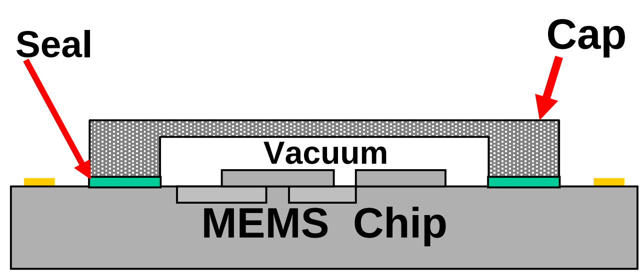

Figure 3 – Zero-Level Hermetic Package

Atmosphere Control

The MEMS package can also consume (absorb) and emit materials (outgas), but the atmosphere needs to be controlled within certain ranges. The atmosphere maintenance approach must be simple but effective and a class of materials called, getters, may be the best answer. Getters are agents true to their name and "get" things – primarily contaminants. Today's getters for electronic packages are very selective. Products are available that absorb gases, liquids and solids. While the present list of commercial getters only includes moisture, particle and hydrogen, additional getters can be designed as the need arises. Moisture getters use compounds that absorb and tightly bind water molecules. Zeolites and certain metal oxides are very effective. A special polymer matrix can be used as the "breathable" binder. Particle getters are made with permanently sticky polymers. This is not simply a "fly paper" material. The getter must be easy to use, maintain performance of extended time and not produce contamination. Hydrogen getters, used to prevent poisoning of GaAs devices, are more complex. We may see the use of GaAs devices in the optical MEMS area later. Getters could simply be "printed" on inside of the chip cap.

Surface Control - Friction, and Stiction

But stiction can be a greater problem for even simple bending mode devices like accelerometers. What happens if the motion sensing beams in the accelerometer make contact? They stick! They stay stuck! Figure 4 shows the stiction effect. The capacitor sensor is now a short circuit and the device is inoperable. We can't just pry the beams apart since the package is already sealed. But what made the beams come together? Dropping the parts or just moving them too quickly can cause the "floating" beam to move since it's designed to move with a change in motion. So the assembler can unknowingly "break" the part just by handling. Worse yet, the only evidence for stiction immobilization is electrical test.

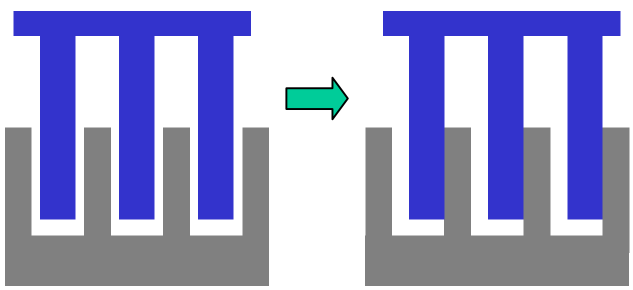

Figure 4 – Stiction of Accelerometer

A device that goes dead when the assembler moves it quickly is unfriendly indeed. So the accelerometer stiction problem is important to solve for assemblers. This will reduce handling restrictions and improve yield. There is still some debate as to what kind of atmosphere is best for reducing stiction since it can involve mechanical interlocking, atomic forces and even chemical reactions such as hydrogen bonding. Many advocate the highest vacuum possible while others suggest that a small amount of moisture can reduce wear and stiction[3] But there are some surface chemistry complexities involved with silicon and its oxides that appear to make surface coating a logical solution. Organic coatings with low surface energy and perhaps hydrophobic properties should help[4]. The coating would need to be very thin and this is the realm for vacuum coating technology.

Anti-Stiction Coatings

Many have heard of Parylene (poly-para-xylylene) as a special polymer film applied to substrates with a vacuum coater. The Parylenes are noted for high chemical inertness, strong barrier properties and perfect conformity. to the surface applied. The surface tension approaches that of As you can see, MEMS has its own vocabulary. So what's stiction and why should you care? Stiction is a form of friction where a much higher force is required to get things moving. Once the gear, wheel, slider or arm is unstuck, we are back to ordinary friction. Stiction goes unnoticed in the macroworld where it is a minor factor. The attractive forces in the microworld are relatively higher and stiction is a big deal. It can require a high initial force to start a mechanism moving if stiction can't be overcome and this means bigger motors.

Teflon. A new fluorinated, teflon-like version (Nova HT) has been recently developed for semiconductors that can handle over 500^{o}C. Nova HT could be ideal for anti-stiction. Hopefully, work in the near future will determine if this material is a good solution to stiction and wear to deliver assembler-friendly MEMS[5].

ASSEMBLY

Let's assume that the myriad of fab and packaging problems will get solved. The next challenge is MEMS assembly[2]. What kind special requirements and restrictions will be faced in assembly? The accelerometer and motion detectors, in general, are probably the best place to learn about MEMS assembly.

Accelerometers - Air Bag Electronics

The accelerometer is one of the earliest and most important MEMS devices. The chip typically uses a cantilevered silicon arm or a comb that bends slightly when there is a change in motion as shown earlier. Movement is detected and translated into an electrical response. Analog Devices, a leader in this field, uses a design where a movable beam and a stationary one form a capacitor. Motion changes the spacing and thus the capacitance to translate deceleration into an electrical signal. The system must accurately sense deceleration and send the signal that deploys your airbag. The deployment signal must only trigger under crash conditions. "Almost right" is not good enough in a life and death situation as has been shown in some unfortunate incidents. The packaged product can appear very ordinary since traditional methods can be used here. This is one of the few MEMS products that can be completely sealed since motion detection does not require an opening to the outside. Still, the packaging cannot interfere with mechanical movement and must have low stress. Package stress, if present, must be predictable so that allowances can be made. The critical factor for both the packaging and assembly is *stress*. Anything that increases package stress will change sensitivity.

The accelerometer (decelerometer) must sense change in motion but not in all directions. The sensor must detect the rate of change primarily in the forward direction of the vehicle. We don't want the air bag activated if the vehicle is rear-ended or hit from the side or bounced by a pothole. Some cars are adding side air bags, but their separate sensors detect side-ways motion. Anything that interferes with sensing the direction or alters the ability to detect absolute deceleration will be a problem. Let's look at how circuit assembly can affect things. Figure 5 shows the accelerometer diagram from Analog Devices.

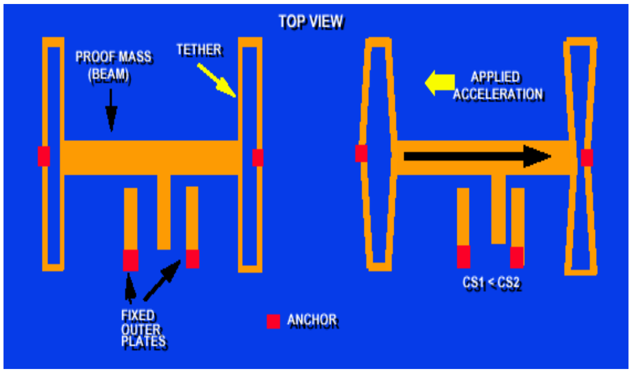

Figure 5 – Accelerometer; from Analog Devices

Unique Assembly Issues

Analog Devices has used a Cerpack® hermetic package successfully for a number of years although considerable development was required to build a durable and reliable product. Even with a good package, assembly must be well controlled with new rules applied. Package orientation must be correct. Skew will reduce sensitivity since the MEMS device will not point true. Hypothetically, if the package were to be skewed by 45^o, this would reduce the forward direction sensing by 50%. While it may be impossible to have that degree of skew, there is a potential for some. Component tilt is also undesirable since this would also change the effective direction of motion and reduce sensitivity. Even the solder fillet could be critical. A thicker fillet could reduce compliancy and the sensor would receive a stronger signal because less deformation would transmit more force. Other types of MEMS products may not be as critical. On the other hand, optical systems can have more complexities for the assembler.

These are some of the more obvious assembly concerns, but there are many more that involve a change in sensing. We asked if the solder fillet was critical and the answer is "Yes", but for mechanical not electrical reasons. Even the lead compliancy plays a role in determining what the sensor "feels" in a high impact crash. Stiffer leads will allow less deformation and this results in a stronger signal. The assembly challenge appears to be complex.

Even the laminate characteristics must not change, but because of yet another affect. We mentioned that stress on the device, while permitted within limits, must be predictable. While Cerdip packages are popular for MEMS, there is changeover to plastics that can increase stress and its sensitivity. The manufacturer may calibrate the device during packaging as part of test, but if the assembly processes later causes unexpected changes, there will be problems. For example, board warpage and twist could be devastating. Even a change in the CTE (Coefficient of Thermal Expansion) of the laminate would need to be taken into account. The more we delve into assembly, the more questions arise. We don't even know "what we don't know" at this point. The guiding principle comes from Amkor's Steve Anderson, "View the device, package and assembly as an interactive system".

OPTICAL MEMS – MOEMS

Optical MEMS products add one more level of complexity. The chip should be hermetically sealed but a light path is another obvious requirement. The solution is somewhat apparent, but implementation can be a Herculean task. A light-transmissive lid or "port hole" is designed into the package. Several materials can be used. The micro-mirror module from Texas Instruments is one of the best examples of the packaging of complex electrophotonic products. Figure 6 shows the Digital Micro-mirror Device™ (DMD)[3].

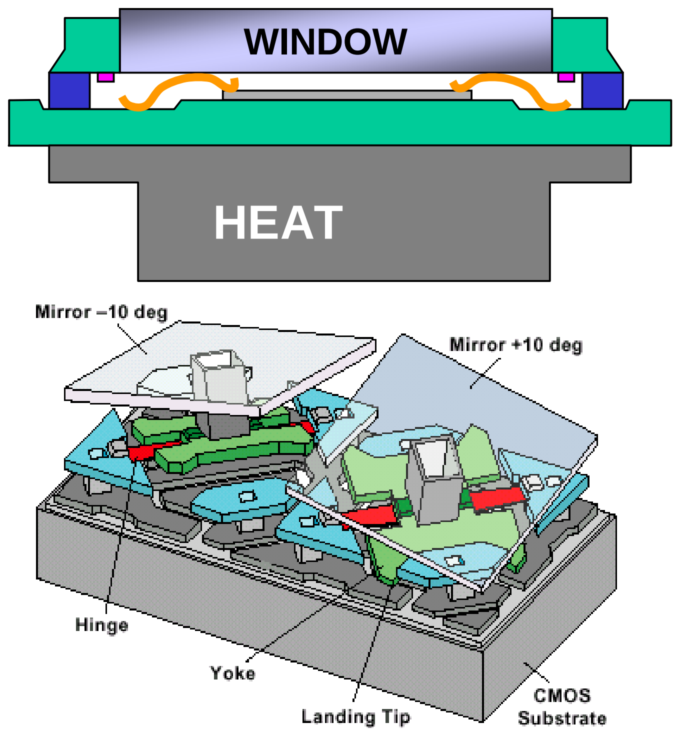

Figure 6 – TI's DMD & Package Diagram

The Digital Micro-mirror Device is very likely the most sophisticated MEMS product that has yet been commercialized and a preview of what lies ahead. The MEMS chip incorporates light beam-directing mirrors that move independently and almost instantaneously during operation. A pixel is turned "on" by pointing a mirror at a projection lens while turning "off" involves pointed away. Let's look more closely at the optical package. Figure 7 shows a section of the micro-mirrors with some pointed "on". Large arrays are being used for digital projectors right now, but there are other applications such as digital video and optical switches[6].

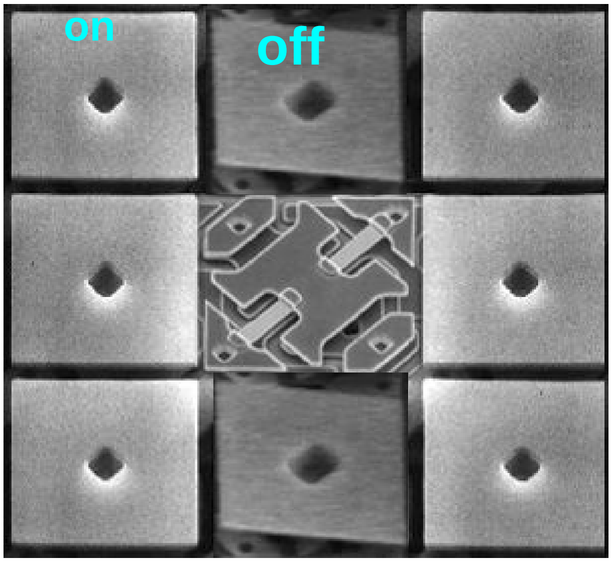

Figure 7 – TI Micro-Mirror Array Close Up

Most optical systems use a high-vacuum hermetically sealed package. Although many researchers recommend a high vacuum, others suggest a specific range for gases. Movable optical systems require that the package atmosphere not only start off clear, but that nothing within will later degrade lens clarity. One added problem is that materials can outgas to generate atmospheres that cause damage later, even though the initial package had a very high vacuum. Microscopic particles can also dislodge or even form during operation. How can we deal with gases and contaminants that are produced long after the package is sealed and the product is in the field? The best solution appears to be "getters" that where already discussed.

The Internet giants, like Cisco Systems, Nortel Networks, Lucent, Alactel and others, have bet billions of dollars on MOEMS. Right now, the network routers and switches run OEO – optical-electronic-optical. This means that an Internet light signal must be converted to electronic format, switched and then reconverted back to light. This adds cost and slows down the switch. The industry is intent on developing full optical switching where photons are routed without the double conversion. One way is to use micro-mirrors to catch and direct the light wave. While this is easier said than done, it will almost certainly happen. While movable mirrors are the most obvious, there are other technologies within MOEMS that may ultimately win a piece of the light show action. So stay tuned to see who will catch the light wave. And the good news is that you may get to assemble it. That may also be the bad news.

SUMMARY AND CONCLUSIONS

MEMS will be a hallmark technology for the 21st century. The capacity to sense, analyze, compute and control, all within a single chip, will provide new and wonderful products during this decade. While package challenges are substantial, progress is accelerating. The need to control and regulate the package atmosphere will be critical. Stiction and wear problems may be solved in the future with new vacuum-applied polymers. Getters and emerging control agents appear to offer a practical and cost-effective solution today and for future generation MEMS products. Assembly will have some different rules but they will be less restrictive if package sensitivity issues can be solved. Expect to see MEMS as a high volume component in the future – one that will usher in the new era – BEYOND ELECTRONICS!

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