MEMS PACKAGING ISSUES and MATERIALS

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Abstract

MEMS, Micro-Electro-Mechanical Systems, is the ultimate enabling technology for integration of almost any phenomena - motion, light, sound, chemical detection, radio waves and computation, but on a single chip. New commercial products send and receive light beams, others detect specific molecules and some mimic several "senses" simultaneously. If the logic device is the brain, MEMS adds the eyes, noise, ears and other sensory input. But MEMS is also control, the hands and fingers since these devices can move their own elements and also nearby objects. The ***merging of motion, sensing and computation*** *represents a significant new level in technology. But there are major challenges, especially in packaging, and MEMS probably represents the greatest challenge ever for our industry.*

This paper will review the status of MEMS fabrication, highlight problems and described some of the packaging strategies that are being suggested. Does MEMS and the optical version, MOEMS (add "optic" to MEMS) require a high quality hermetic seal? Should we remove specific impurities like water vapor and oxygen in situ? Can getters, molecular-specific scavengers, solve some of the hermetic atmosphere problems? Getters can remove micro-particles, moisture, oxygen, hydrogen (poison to GaAs) and other contaminants. What about "stiction", the plague that is "locking up" the microworld? Is new "zero-level" packaging the cost-effective replacement for the traditional hermetic package. These problems, issues and solutions will be discussed.

Keywords: getters, MEMS, MOEMS, packaging, parylene, stiction

Introduction

MEMS is about high-level integration of many different categories of functions. MEMS represents the ultimate for integration and it will enable System on a Chip (SOP). This unification of functions encompasses motion, light, sound, radio waves and much more. And if that were not enough, the additional features of computation and control centralize all of these actions as a fully integrated system that can deliver surprisingly versatile new products. MEMS is also about *technology convergence* where miniature devices including gears, mirrors, motors, radio elements, detectors and other assemblages are synergistically united in a new microworld. MEMS combines and integrates complete systems and this is the key. MEMS places systems together on a fully integrated and self-contained single piece of silicon that previously could only exist in the macroworld. It is remarkable that these previously isolated technologies can converge onto a tiny single chip of silicon.

But there are major challenges! Experts, and they are few, insist that MicroElecroMechancial Systems (MEMS) fabrication and packaging represent the greatest challenge our industry has ever faced. Not only are the advanced MEMS devices small and highly complex, many must communicate with the outside world by methods other than electronic signals. And MEMS devices are so specific that each new one can represent a novel problem to solve.

Some MEMS devices send and receive light beams, others detect specific molecules and a new system can even identify defective DNA. If the traditional IC is the *brain*, MEMS adds the *eyes, noise, ears* and some senses that humans don't even possess. But MEMS also can exert control using tireless electrically powered muscles that move and manipulate objects in this nanoworld. The merging of motion, sensing and computation most certainly represents a new level in technology that is still embryonic. Yet this ostensibly new technology has been around for nearly three decades. The recent high levels of success have pushed MEMS into the media's limelight. New markets that didn't exist a 5-years ago are creating extraordinary demands for MEMS, especially devices with opticals. Just during year 2000, the Internet giants spent billions of dollars to acquire MEMS companies. In fact, this business success could hold back MEMS technology since almost all the independents have been seized to become a sort of *road gang to work on the new Internet highway*. The modern Internet is really a glass highway and light control is the master key to efficient photonics! And MEMS will more than meet expectations for but only if packaging and assembly problems can be solved.

Fabrication

Techniques have been mostly borrowed from IC fabrication but with appropriate modifications. Standard semiconductor bulk fabrication processes are used to create traditional electronic circuits that are typically included. Subtractive etching produces the numerous mechanical devices. Silicon dioxide or nitride can be formed and used as the etching mask. These durable silicon compounds later become the mechanical and optical elements that remain after etching. Numerous subtractive methods can be used to remove the elemental silicon including wet chemical etching and reactive ion milling. A final chemical etching step is often used to free the movable mechanical elements. The "sacrificial holding structure" is sometimes etched away at the packaging foundry so that delicate parts are protected while wafer is transported. The fragile characteristics of these wafers and the need for foundry processes just before packaging are just two of the issues to be dealt with by the MEMS industry.

MEMS Packaging

Packaging foundry technologists have told us that MEMS presents the greatest set of problems yet faced by their industry. Worse yet, the issues are so application-specific that hard-earned solutions don't necessarily translate to other products. The different MEMS classes often determine the level of packaging difficulty. MEMS products include accelerometers, gyroscopes, ink jets, movable mirrors, microspectrophotometers, chemical analyzers, optical switches, tunable capacitors, infrared imagers, microrelays and pressure sensors[1]. The following examples with help appreciate the packaging concerns.

Air Bag Electronics

We'll begin with the accelerometer, 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. 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 1 shows the accelerometer diagram from Analog Devices.

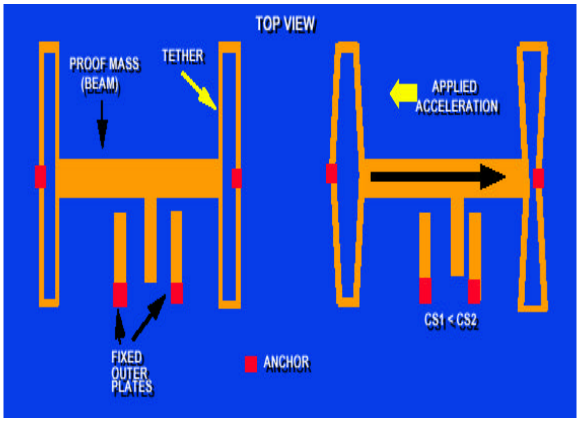

Figure 1 – Accelerometer Design – Analog Devices

Unique Assembly Issues

Analog Devices has used a cerdip 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 control 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°, the forward direction sensing would be reduced by half. 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.

Ink Jets and MEMS

The popular ink jet chip that can you see attached to most ink cartridges represents innovative packaging and assembly of a MEMS device with the HP products representing a good example. While at least one manufacturer uses true piezoelectric designs, most employ simpler micro-heater elements to form a microscopic vapor bubble that instantly ejects a droplet of ink. Arrays of micro jet nozzles propel droplets of ink at the paper and the package cannot restrict the line of fire. But the MEMS chip interconnection zone must be protected from the environment, especially the ink, and made robust for handling by you the end-user. A bare die assembly process is employed – a form of Chip-on-Cap. The ink-jetting chip is typically assembled using TAB (Tape Automated Bonding) packaging that is actually a flex-circuit with cantilevered wire beams protruding into the chip bonding window. The gold-plated leads, suspended over this access window are aligned to the chip bonding pads and a TAB inner-lead bonder provides the required heat and force to form strong metal-to-metal bonds. Normally, TAB packages have outer leads that are bonded to the circuit board, but the ink jet package-circuit eliminates them. The chip connection leads are integrated into the flex circuit in format that could be called TAB-featured flex. Instead of outer bond leads, termination is a connector that electrically mates to the printer cable when the cartridge is installed[1]. Figure 2 shows the MEMS device and package.

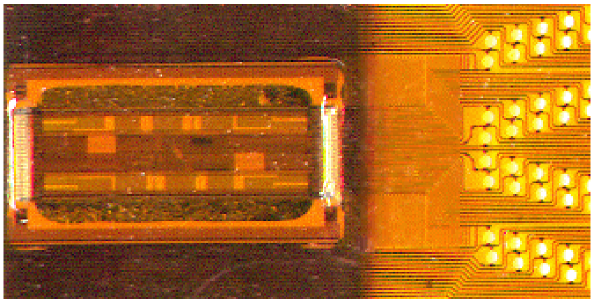

Figure 2 – HP InkJet Printer Cartridge

The chip pad connection zone is selectively encapsulated by applying liquid polymer using an automatic needle dispenser. The liquid material is then hardened with heat or UV. The action side of the die is not encapsulated so jetting is unimpeded. In a sense, the assembly process precedes packaging. The flex circuit, with its assembled and protected MEMS chip, is bonded to the ink jet housing that is also the ink container. The flex circuit wraps around the housing to become the interface to the printer. The MEMS chip is bonded in such a way that it is supplied with ink from the cartridge. The next time you replace an ink jet cartridge, take a look as this marvelous MEMS chip and package. Figure 3 shows the type of equipment used to automatically and selectively encapsulate the MEMS package.

Figure 3 – Speedline/Camalot Dispenser

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 4 shows the Digital Micromirror Device^{TM} (DMD).

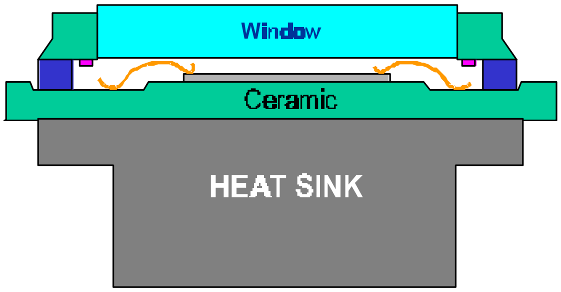

Figure 4 – TI's DMD Package Diagram

The Digital Micromirror 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 5 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[2].

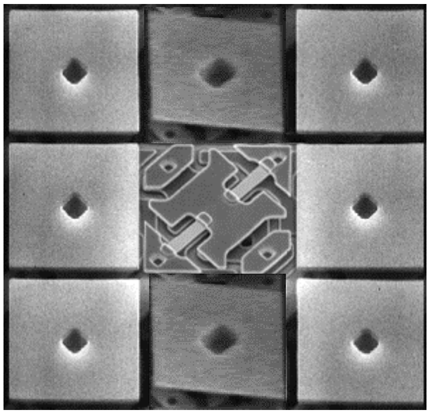

Figure 5 – TI Micro-Mirror Array Close Up

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 package is sealed and the product is in the field? The best solution appears to be "getters" that will be covered later.

Packaging Strategies and New Concepts

Now let's examine MEMS product classes and their different packaging requirements. All MEMS devices move, but the mode and the purpose of motion determine the packaging requirements. The list below indicates some of the basic modes of motion.

1. Deformation: no moving parts that touch; mostly bending or twisting (accelerometers)
2. Moving parts but with no rubbing
3. Moving parts with rubbing, no impact
4. Motion with impact
5. Moving parts with rubbing and impact

The commercial MEMS industry has dealt primarily with type 1 where the package can be somewhat conventional. Lucent, in their own micro-mirror work, has indicated that type 1 products will be emphasize because this eliminates all of the added problems from sliding and rolling mechanics. Packaging and device fabrication become increasingly difficult as we move down the list. Researchers at Sandia[2] and engineers at Analog Devices have described interesting phenomena that become significant at extreme miniaturization. Friction has one added problem called "stiction". Stiction, as implied by the name, is a friction problem where parts stick. The elements in a micromechanical device can be held together by relatively strong force. Sensor beams in accelerometers can stick together producing a "dead" device. Motors and gears can require high starting forces. The stiction problem must be solved in order to avoid building much larger "motors" and sensors go dead when handled.

MEMS devices with sliding and rotational motion also experience wear since speeds can approach 1 million RPMs in the microworld. We can't really "oil" a MEMS machine because of the high vacuum and extreme miniaturization although certain vacuum-deposited films may be beneficial. Some studies suggest that water molecules can act as a lubricant and anti-wear agent. Others indicate that water is a problem contaminant. Both findings may be correct. According to Sandia, the relative humidity is the key. Too low a humidity value may increase resistance. Too high, and corrosion and wear may climb dramatically. The ideal range appears to be somewhere between 20% and 60%. But is it practical to control water vapor at a specific range and one that will remain constant? We will revisit these problems later with some possible solutions.

MEMS-Specific Package Designs

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 over-molding while enabling unrestricted movement in the device. A generic cap could be designed. Once the cap is in place, transfer molding can be used. Wafer-level processing would be preferred and this appears to be the goal of those working on the concept. In some cases, liquid encapsulants may be less stressful and more tolerated by a cap. They may be applied by automated needle dispensing equipment as shown earlier in Figure 3.

Another possibility is to use Flip Chip. Since the active surface of the device is placed toward the substrate a natural protective zone can be formed. The standoff distance, or chip gap, can be accurately controlled by the 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, can be applied to all four edges of the chip. This sealing encapsulant, a fillet without the underfill, is 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 can 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 6 shows the Flip Chip designs.

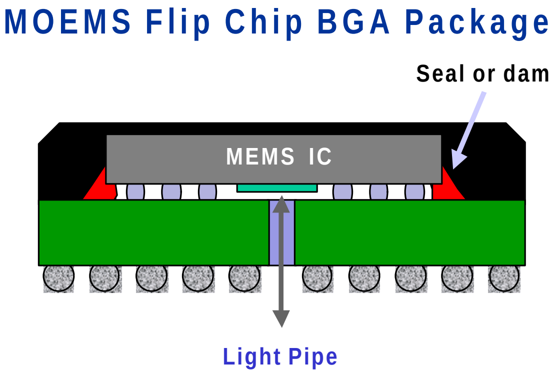

Figure 6 – Flip Chip MEMS Package

Another clever concept is to apply a microcap at device or even 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 Chip-on-Cap sometimes-called 0-Level packaging. The cap essentially produces a micro-hermetic package well suited for accelerometers and gyroscopes. 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. Figure 7 shows the Cap-on-Flex concept.

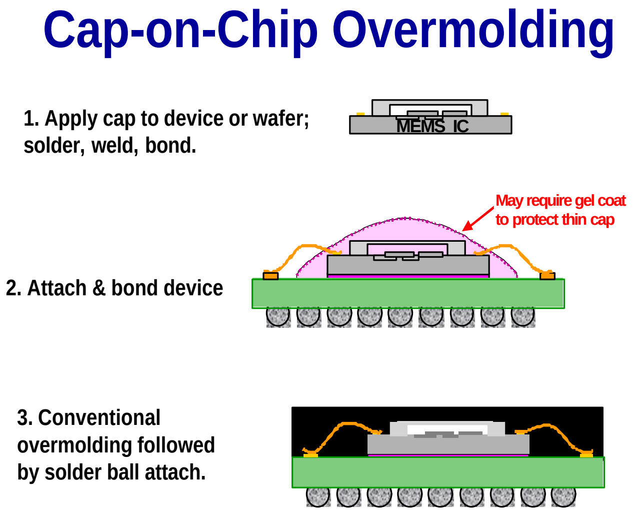

Figure 7 – Cap-on-Flex or Level 0 Packaging

Atmosphere Control

When a manned spacecraft is launched, life support requires that the “human package” atmosphere be constantly controlled since gases are constantly being consumed and generated. The MEMS package can also consume (absorb) and emit materials (outgas). While the space capsule atmosphere control system is complex, the package maintenance approach must be simple but effective. How can we add package interior atmospheric control in a cost-effective manner? Enter getters!

Modern Getters

Many may not have heard of getters, but they are agents true to their name – they “get” things. Getters have been around since the earliest phase of the electronics revolution. The early electronic vacuum tubes experienced unacceptably short lifetimes because of the oxidation of filaments and electrodes. Back in the early 1900’s, it was not practicable to produce a high and stable vacuum. But the life-limiting culprit was oxygen. The simple solution was to add an oxygen getter to the package. The getter was simply a metal or compound with a strong affinity for oxygen. The vacuum tube, even with a small leak, remained at a low oxygen level provided that some of the getter remained active. Now back to the 21st century.

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.

How do getters work? 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, such as Staystik 415 and 482 (StayDry SD1000 and SD800 respectively). 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. Although hydrogen-adsorbing palladium (Pd) metal can be applied to lids, a better solution is to use a polymer-bound system. This is because the plated Palladium compound has a tendency to embrittle and flake over time, leaving the possibility of unwanted particulates forming in the package. The Hydrogen Getter H2-3000, for example, utilizes palladium oxide (PdO) in combination with zeolite dispersed within a stable polymer matrix. The PdO converts H_2 gas to water that is then consumed by the zeolite making the reaction irreversible. Incidentally, the H_2 sources include the electroplating on the metal package, die attach adhesives and RF absorbers. Released hydrogen degrades the wire bond interface of the GaAs devices reducing device performance.

Can getters control humidity within a specific range? This is certainly feasible although the term getter may not be entirely accurate here. Specific compounds or mixtures are known that can maintain moisture within specific limits inside a sealed container. Equilibrium levels are soon reached with atmospheric water to regulate humidity. The appropriate selection of such desiccants and polymer carriers could produce "atmospheric control agents" for specific humidity ranges.

Surface Control - Friction, Stiction and Solutions

There is still some debate as to what kind of atmosphere is best for reducing stiction since it may 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. The coating would need to be very thin and this is the realm for vacuum coating technology.

Analog Device was able to solve their stiction problem after years of work. One approach was to add a tiny drop of high boiling, thermally stable liquid such as a silicone just before the ceramic package was sealed. The heating process prior to sealing caused the liquid to boil and coat the MEMS combs. A later solution was to coat the MEMS device with a low surface energy reactive silane[4].

Polymer Vacuum Coatings

Specialty Coating Systems, a manufacturer of chemical vapor deposition (CVD) materials and equipment, suggested that a very thin organic parylene film could solve the stiction and wear problems. Parylene, a thermoplastic polymer, has been around for years and many are familiar with this organic CVD coating. Parylene (poly-para-xylylene) is a high temperature polymer film applied to substrates in a vacuum chamber by means of a gas phase polymerization that provides unusual electrical and environmental performance. This class of polymer has been used on a variety of applications especially those involving the protection of electronic devices and circuitry. CVD is used to form an insulating thermoplastic coating with a high degree of chemical inertness, absence of pinholes and perfect conformity to the topography of the surface applied. Coefficients of friction range from 0.25 to 0.33 so that the lubricity is close to that of Teflon.

A new fluorinated Parylene, Nova HT, has been recently developed for semiconductors. Nova HT shares the unique properties of the other Parylenes but offers properties that should be ideal for anti-stiction. The film is deposited in a molecule-by-molecule polymer process, with no cure-related stress that can occur with liquid polymers. There is no liquid phase, no hydraulic forces, and the coating conforms to substrate features rather than pooling or bridging in the manner of conventional liquid coatings. Free molecular dispersion of the monomer results in the development of an overlying film on all exposed surfaces, with equal thickness on inside and outside corners, flat surfaces, and in crevices. Parylene can effectively penetrate inside surfaces through small openings.

The new **Nova HT** has a crystalline melting point above 500°C, which is at least 250°C higher than the recommended continuous exposure level for the conventional Parylenes. Nova HT can be used for applications that require exposure to lasers and high intensity lamps such as MOEMS with its improved UV resistance. It is particularly resistant to yellowing and physical degradation under such conditions. This advanced coating has all of the useful properties of traditional Parylenes, including resistance to solvents, moisture, gases and other contaminants, high dielectric strength in very thin layers and favorable physical and electrical properties. Its superior properties are due in part to the integration of fluorine into the Parylene lattice, which results in improved polymer stability and a low dielectric constant. Hopefully, work in the near future will determine if this material is a good solution to stiction and wear.

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-effect solution today and for future generation MEMS products.

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