"MEMS & MOEMS PACKAGING CHALLENGES"

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INTRODUCTION

MEMS (Micro-Electro-Mechanical Systems) is centered around the high-level integration of dissimilar functions from the most important domains of science. This extraordinary *unification of functions* includes both energy and matter; motion, sound, atoms, molecules, light, radio and other electromagnetic radiation. The blending of attributes from so many diverse fields of science into a single structure is what gives MEMS such incredible power and wide-ranging potential. But those who do not understand the awesome power of synergistically melding effectively all the areas of technology into a micro- or even nano-device, will not appreciate what MEMS really portends. We can also add one more extremely important science and technology to MEMS, and that is optics. We can call the result optical MEMS or MOEMS (Micro-Opto-Electro-Mechanical Systems). Now, we have combined essentially every region of science onto and into a single microcosm. Highly complex devices that can be built by familiar semiconductor mass processes to produce the long-sought System on a Chip (SoC). The most complex machine today is not the Space Shuttle or the Boeing 777, but a commercial MOEMS module with 1.6 million mirrors on a 1-inch square.

Some products, like Texas Instruments DMD™ (Digital Mirror Device), send and receive light beams, others detect specific molecules and some deal with several "senses" all at once. 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* because these devices can move their own parts but also nearby objects and materials. MEMS, while hyped by the media, can more than meet expectations for marvelous micro-machines during the next decade. **The *merging of motion, sensing and computation* represents a major leap in technology.** But the MEMS devices can be designed to serve the fields of chemistry, physics, biology and medicine. We are really just at the threshold of understanding and applying this technology from the man-made nano-world. This is certainly the most important "technology cluster" that has emerged as we move further into the new millenium and will likely bet the hallmark of the 21st century since it can interact with and enable all so many other technologies.

Computation, analysis and central control of these input/output functions results in a fully integrated system of incredible versatility. MEMS is the convergence site for so many dissimilar technologies that its importance is hard to overstate. Mechanics adds gears, pivots, hinges, sliders and elevators. Optics brings mirrors, filters, prisms, sensors, analyzers, converters and modulators. The electrical field delivers motors, propulsion, heat and other energy. General electronics delivers radio, computation and control to this new microworld. Chemistry adds molecular detection and manipulation. Biology and medicine add an entire field of functions and actions ranging from diagnosis and treatment to DNA analysis. And we can expect more biotechnology to enter the MEMS arena soon as indicated by IBM's recent announcement of a DNA detector. MEMS synergistically merges subsystems into a fully integrated, self-contained microcosm that once existed only in the macroworld and this is the essence. How remarkable that these once isolated technologies can converge into the microscopic world of solid state using wafer-level mass processes.

MEMS/MOEMS PRODUCTS

Let's first briefly review just what MEMS is and look at the types of structures that have been fabricated. Sandia National Laboratories and other research organizations around the world are building truly remarkable devices. One example of a fascinating device is a chip-size spectrophotometer that can detect and measure atmospheric gases from miles away. Microscopic pumps and valves have also been built that may be used for medical applications including drug delivery. Texas Instruments has commercialized micro-mirror array modules and IBM has developed a MEMS DNA detector that can even sense a when DNA strand is defective. Many devices are so small that they could be injected into the human body. The day may come when micro-robots, or "nanobots", travel through the body to clear arteries and make repairs borrowing a scene from the classic 1960's science fiction movie "**Fantastic Journey**".

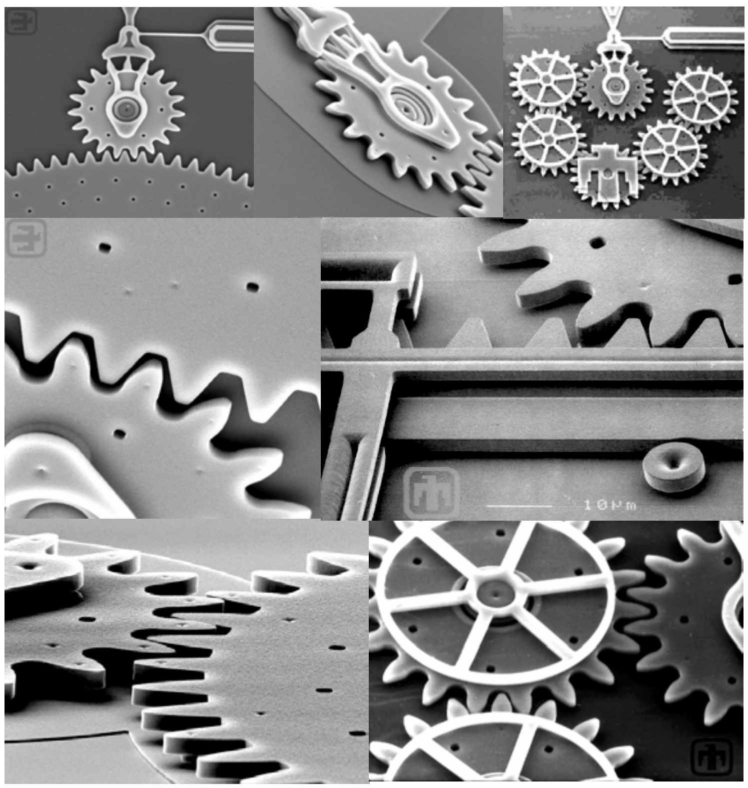


Figure 1 – MEMS Structures from Sandia National Laboratories

Before moving into the details of the packaging issues, a summary of the products that have been built and are anticipated, will be valuable. Most of the nearly three decades of MEMS has involved simple "bending motion" devices like pressure transducers and accelerometers. We will spend some time in the MOEMS area because this possesses the greatest challenge but solutions can be applied to simpler devices. Table 1 lists MEMS/MOEMS devices with relevant information relating to packaging.

TABLE 1

MEMS Device	Packaging	Input	Output
Accelerometer	EMC (Epoxy Mold. Comp.)	Motion	Electrical
2D and 3D Motion Detection	EMC	Motion	Electrical
Ink jet*	Selective encapsulation	Electrical	Motion
Digital Mirror Array	Hermetic with window	Electrical & light	Controlled light
Micro-Spectrophotometer	Hermetic with window/port	"Light"	Electrical
DNA Analyzer	Liquid access	Biological samples	Electrical
Disk Drive Heads	Sealed enclosure	Magnetic	Electrical
Optical Switches	Hermetic with 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, one-time use	Electrical, samples	Electrical
Infrared Imagers	Hermetic/window	IR, Electrical	Electrical
Micro-Relay	EMC	Electrical	Electrical
Pressure Sensors	Sealed thin wall is OK	Force directly/indirectly	Electrical

Some inkjets use thermal heaters with have no moving parts and may not fit a precise MEMS definition.

We can note that there are many classes of mechanical motion applied in MEMS and a simple classification is provided in Table 2.

TABLE 2

1. No moving parts but material movement; e.g.; ink jet. Is this still MEMS?
2. Non-contact motion, twisting or bending beams (as in simple accelerometers)
3. Moving parts but with no rubbing/abrasion type contact
4. Moving parts with impact, no rubbing/abrasion
5. Moving parts with rubbing/abrasion but no impact; gears, wheels, rollers, etc.
6. Moving parts with rubbing/abrasion and impact
7. Moving parts, interaction with non-electronic energy and/or matter; e.g., MOEMS

The commercial MEMS industry has focused mainly on level 2 where the package can be somewhat conventional. Level 1, found in the very high-volume ink jet printer cartridge, requires a more specialized package but a method has been developed that taps into the packaging infrastructure. Note that while the popular ink jet from HP has no moving parts, others use piezo pumps and are clearly MEMS devices. Let's examine the packaging solutions that have evolved for the two most common MEMS products, the accelerometer and the ink jet printer cartridge.

The accelerometer, one of the earliest MEMS devices, is the easiest to package. While many accelerometers are packaged in ceramic enclosures, the industry is moving to lower cost plastic. Traditional transfer molding can be used provided that the enclosure does not interfere with motion detection. But there are specific obstacles to overcome for this simplest MEMS device. The package must either be low stress or the stress-induced affects on the device must be predictable so that allowances can be made. Low warp, low stress epoxy molding compounds like Plaskon's (now part of Alpha-Fry Technologies) low stress series of molding compounds have become available in recent years for the Plastic Ball Grid Array (PBGA) and may help here. Figure 2 shows a MEMS IC and the mechanism for motion detection. Note that the motion detectors deal with inertial forces that do not require a special interface to the package, but the motion beams shown in Figure 2 must not be covered by encapsulant. Only electrical input and output is needed just like any common electrical package.

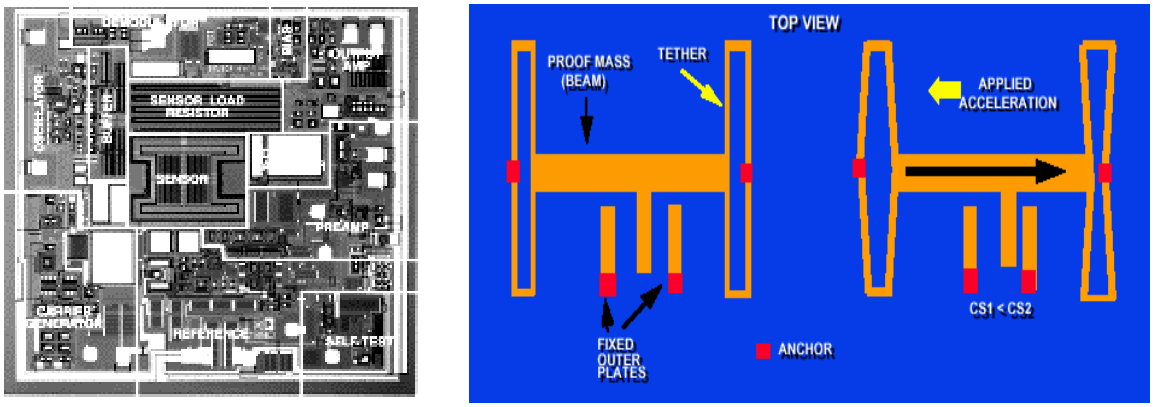


Figure 2 – MEMS Accelerometer – Analog Devices

The common ink jet chip that is attached to ink cartridges probably represents an equal level of packaging difficulty. The microscopic jet nozzles must be free to propel droplets of ink but the package-to-chip interconnect region needs to be protected and made robust for handling by end-users. This can be accomplished by "selective packaging". The ink-propelling IC is commonly packaged in a TAB (Tape Automated Bonding) tape system where cantilevered "wire" beams are bonded to the IC pads. The IC interconnect system is actually incorporated into a flex circuit that also provides a 3D cable and interface to the printer carriage [1]. The IC connection zone is then selectively encapsulated using robotic needle dispensing. Today's needle dispensing equipment allows the selective encapsulation process to be accomplished accurately and efficiently. Figure 3 shows an ink jet cartridge with a MEMS "gun" or multiple orifice pump. Figure 4 shows an automatic programmable dispensing machine similar to one used for ink jet cartridge encapsulation by a major printer manufacturer. This selective packaging concept may have applications for other MEMS products that interface with matter.

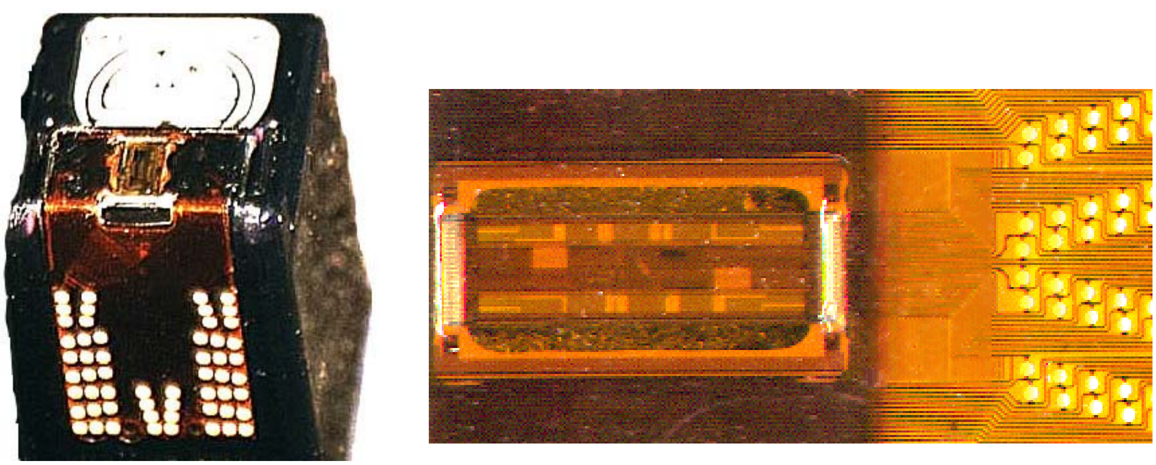


Figure 3 – Ink Jet Printer Cartridge with MEMS IC

Figure 4 – Needle Dispensing Machine - Speedline

OPPORTUNITIES & CHALLENGES

Some MEMS devices send and receive light beams, others detect specific molecules, including pathogens and even such complex structures as DNA. The merging of motion, sensing and computation most certainly represents a new level in technology that is still embryonic. But MEMS represents a chronology paradox. This “new” technology has been around for nearly three decades yet is said to be emerging. But the early products were simple level 2 classes such as motion sensors and perhaps we can refer to them as “traditional MEMS”. The newest products are orders of magnitude more complex and they are the new emerging class of MEMS. For example, optical MEMS, called MOEMS, has become the hot area in just the past year or two. The Internet is the new and powerful market force. The solid and durable opportunities are in hardware, not in the present domain of “dot-coms” and it is better to enable them than become one. The modern Internet is really *a fiber glass intercontinental highway* system, a system of photonic light pipes. In the US and Europe, over 90% of long haul is on fiber and the fiber moves ever closer to the home. Light control will be the master key that opens up efficient photonics. MOEMS appears poised to be the winner in the realm of light switching and routing. So as the light wave highway moves from the present long haul, or backbone, and approaches fiber-to-home (FTH), we can expect the volume of MOEMS assemblies to increase geometrically. We will emphasize the challenges for optical MEMS packaging since solutions will fit all the other devices but the added parameters of light transmission and gas-sensitive components makes this the most significant challenge in the MEMS field.

Specialists in the MEMS field insist that microelectromechanical systems fabrication, packaging and assembly will require the greatest effort our industry has ever deployed [2, 3]. Not only are the advanced MEMS devices small and highly complex, many, like MOEMS, communicate with the outside world by direct-path non-electronic signals. A high burden is placed on packaging and assembly to provide electromechanical connections that do not interfere with or alter sensing, receiving, transmission and control functions. Fiberoptic connections are starting to be added. These tasks are new since MEMS has previously dealt mostly with electrical signals of motion devices. The additional input/output photonic “signals” with extreme control and precision adds considerable complexity and perplexity.

Packaging and device fabrication become increasingly difficult as we move down the list in Table 2. Researchers at Sandia [4] have discovered interesting phenomena that become significant at extreme miniaturization. It may seem at first as if the laws of physics are transmuted when we get below certain dimensions – almost as if analog motion is trying to assume digital characteristics. Friction may answer to a new set of rules. "Stiction", for example, is a phenomenon that is prevalent in the MEMS micro-world. A micromechanical device appears to be stuck when force is first applied. However, once in motion, the resistance drops off substantially. This is reminiscent of the yield point in liquids where there is an initial higher resistance to flow. This problem must be solved in order to avoid building much larger "motors" and several groups are studying the phenomenon. But please note that stiction is a normal phenomenon of attraction between surfaces but goes unnoticed in the macro-world. The high surface area/mass ratio of nanoscale dimensions found in MEMS makes stiction forces significantly large since the force is directly related to area and also smoothness. We will go into detail, with proposed solutions, later.

The mechanical MEMS devices, with all types of sliding and rotational motion, also experience wear and this area is just starting to be understood and quantified. We cannot 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 lubricating anti-wear agent. Others indicate that water is a problem contaminant. Both findings are probably correct. According to Sandia, the relative humidity is the key. Too low a humidity value and resistance goes up. 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? There may be simple solutions. Later, we will look at both atmosphere control agents and surface treatments.

We can divide MEMS technology into primary segments such as fabrication, packaging and assembly. Each has subcategories. Implicit within fabrication is design, for example and assembly typically includes test. Our focus will be on packaging and the present issues associated with housing and protecting devices that must receive and transmit much more than electronic signals. The problem of sealing a semiconductor device while permitting electrical connections to be made has been solved by a number of means that range from hermetic to mold plastic packages and many can be applied to MEMS. However, we need to enable our devices to interact with light, radio signals and matter. Additionally, most of the MEMS devices must have move without interference. Even the simplest MEMS accelerometers have moving parts and any stress from the packaging or assembly processes will change the response of the device. MOEMS is probably the toughest challenge since a very clear two-way light path is often required. But one additional requirement is added for nearly all MOEMS and many MEMS devices and that is protection control of the atmosphere around the device. Electronics devices can tolerate some moisture or plastic packaging could not be used. All polymers are imperfect gas barriers and both H_2O and O_2 will invade the plastic package. But water vapor causes problems for optics and negatively affects friction for moving devices. Stiction is affected by package relative humidity. Oxygen can degrade lasers and other optical devices. The simple pat answer, "Just use hermetic packaging", is not the solution that we seek for reasons of cost and high volume manufacturability. This is the time for packaging innovation.

PHOTONICS

Distance communications began in ancient prehistoric times. Early civilizations used only light and sound waves. About 3,000 years ago the Greek victory in the Trojan War was communicated by lighting hilltop bonfires one after the other. But when did technology-based communications begin? Many would suggest the telegraph or telephone started the communications revolution. Some would consider the Marconi wireless radio as the beginning of sophisticated technology. While both copper wire and radio frequency communications are important and remain the basic modes today, this is changing. Photonics, the use of photons as a communications messenger, is rapidly becoming the most important terrestrial and submarine system. In fact, most long-distance telecom and Internet communications use photonics. New system installations are typically photonic and some new homes are fiber –ready. The long-haul Internet is about nearly all glass fiber, not copper. Several submarine fiberoptic lines have been laid recently and more are planned. Long-distance telephone service began moving to fiber about three decades ago and the newer Internet simply followed along. Photonics has quietly moved in and now dominates long-haul communications. And we are just starting to see new free-space photonics deployed for "last mile" links. But photonics, or more specifically, optoelectronics (OE) has also been used for many decades in the short-range market, such as TV controllers. So when did photonics really begin?

We need to step back all the way to the 1800's and examine the fundamental breakthroughs of the communications revolution. Alexander Graham Bell received his famous telephone patent in March of 1876. This patent would make him richer in today's dollars than the Internet barons. Yet Bell was dissatisfied. The telephone and Morse's telegraph were *land locked* and of little value to ships that were often in desperate need of communications. Bell realized that transmitting voice on a beam of light could be the answer. He reasoned correctly that the photoelectric effect demonstrated with selenium could be used to modulate an electrical signal for the receiver. The transmitter was a greater challenge. Bell hit upon the idea of using sound vibrations to modulate a sunbeam directed by a pivoting mirror although glass gratings were also tested. The voice-modulated beam of sunlight was detected by the selenium photocell – and telecom photonics was born. Bell had heard a sunbeam laugh. The year was 1880 and Bell's first wireless had been demonstrated well before Marconi's radio wave version. Bell considered the Photophone to be his most important invention and perhaps he was right. However, the photophone and optical communications were not a business success in that early era. Many other inventions would be needed to make photonics of practical value, but they would not come until the next century.

In 1958, Charles Townes and Arthur Schawlow of Bell Laboratories proposed the laser as a source of intense and coherent light for photonics. In 1960, a laser system was operated by Theodore Maiman of Hughes Research Laboratory. By 1962, lasing phenomenon was observed in a semiconductor chip heralding solid state laser technology. In 1970, Robert Maurer and colleagues at Corning announced an ultra-pure silica fiber with losses reduced to 4db/km. So this is how photonics was launched and while we might be tempted to say, "And the rest is history", a more meaningful statement is, "And the rest is the future". MOEMS appears to be the final "invention", the block of technology, needed to orchestrate and control the total system.

INTERNET HARDWARE

The key to Internet "speed" is bandwidth – total amount of data per unit of time per link. Light has a much higher frequency than radio or any type of electronic signals. Since data capacity is directly related to frequency, photonic signals can carry over a considerably more information than electronics. What's more, light can be readily split into numerous wavelengths (colors) with each wavelength carrying separate data on the same strand of glass fiber. We could, for example, use yellow light to send high-speed data along a fiber and than double our capacity by adding a green wavelength signal. Fiber cables, of course, carry many individual strands of glass fiber to provide nearly endless bandwidth.

The industry is already adopting multiple wavelengths and may use 100 different "channel colors" during 2001. This will increase single-fiber, single-color capacity to an astounding level but keep in mind that each signal color handles much more data than copper wire. Multiple colors is what high density multiplexing is all about, hence the market excitement. The fiberoptics Internet is just now reaching an amazing 10 gigabits/second (Gb/s), but soon moves to 40 Gb/s and maybe double again in 2002. The fastest single fiber rate in a lab exceeds 3 trillion bits/sec (terebits/sec). The year-2000 mega-mergers by Internet giants demonstrates that the carriers and hardware makers are betting their companies on light and are determined to catch the *photonic wave*! There is a furious pace of consolidation within the industry that is accelerated by the ongoing photonics revolution. Nearly all MEMS companies were acquired in 2000, but new start-ups are filling the void.

The substantially optical Internet backbone uses relatively few switches/routers since nodes (switch points) can be 500 miles or more apart. These nodes connect to cities, or metros. The metro network requires many more switches per length of cable. Many think that the Metros, or MAN (metropolitan area networks), will be well on their way to optical conversion by 2001. The next level for optical is enterprises and then the end user. These markets could generate 100 or even 10,000 times more hardware business. But there's a "Catch 22" since cost must drop substantially for each of the more hardware-intensive steps.

Photonics is well advanced in terms of discrete devices, but systems are not really integrated like electronics. The optical transistor could already be here, but the optical IC will be the big breakthrough. The photonics pace will be much faster than electronics because of powerful drivers, confidence in this approach and the availability of high technology that can be tapped from other fields. The winners will move at "Internet speed", take bigger risks and bet on strategies while waiting for implementation. Government support can help with high-risk strategies.

Here are some of the present components for photonics in general communications and the Internet. Note that even those, like the laser, that are not MEMS devices can benefit by integrating them into the system. In fact, one of the future challenges of photonics is device-level integration and MEMS may just be the key.

Fiber: Fiber became the long-haul backbone of telecom by the mid-1980's while a few links were operating as early as the 1970's. It was the obvious choice for Internet and glass rapidly displacing copper. Single mode fiber, with a core of only 8 – 10 microns in diameter, has become the preferred new fiber for long distance. One limitation is the difficulty and cost of connecting these hair-thin fibers together. Often, a high-powered microscope must be used and the ends are joined by fusion under high temperature. Could a MEMS alignment device solve the problem to enable low-loss, low-cost plug-in connections? MEMS fiber aligners have already been built and demonstrated by the University of Colorado [5] The MEMS alignment device moves the fiber until detected loss is minimized.

Lasers: These are the "light" transmitters and modulators that send signals along the optical fibers. There are dozens of types, but for now, the laser diode is the workhorse. But tunable lasers have recently been commercialized that will transmit different wavelengths (colors) on demand. The key to very high bandwidth will be the use of multiple wavelengths, with more than one hundred colors. The tunable laser, while not essential to this strategy, would produce major cost reductions and go a long way in simplifying the system. Several tunable mechanisms rely on mechanics and MEMS appears to be a viable approach. But lasers also interface with waveguides, filters, shutters, modulators, attenuators, equalizers and all kinds of devices that could be built with MEMS and nanotechnology. The source laser (transmitter) is a likely starting point for photonics integration using MEMS. The Vertical Cavity Surface Emitting Laser (VCSEL) that is fabricated in wafer form, may be an ideal class for MEMS integration especially since the power levels have recently reached a level where they can be used for Internet transmission, at least for metros that need less power.

Multiplexers/Demultiplexers: A multiplexer encodes information from separate modulated light beams of various wavelengths into a single, complex composite beam that is sent along optical fiber. A demultiplexer at the other end, or at a node point, separates signals and extracts the information. This is a key technology for very high bandwidth. The latest approach is called Dense Wave Division Multiplexing (DWDM) and it simply means using many colors of light with each carrying separate information to maximize the amount of information sent on a fiber. Optical gratings made with wafer-level processes are becoming popular and MEMS processes that may also combine other functions can be used. Numerous methods have been developed to add and separate optical signals. Arrayed Waveguide Grating (AWG) is emerging as the most popular method. The AWG is an array of optical waveguides with different lengths made of silica (SiO_2) on a silicon chip (Si), that can be employed for both multiplexing and demultiplexing. This device is essentially an array of optical waveguides of different lengths where input beams are fed into a micro-lens array that refocuses the beams to produce an output. The multiple inputs are fed into a cavity or coupler region that acts as a lens to equally divide the inputs to each of the waveguides. The output cavity acts as a lens to refocus the beams from all of the grating waveguides onto the output waveguide array.

Amplifiers: Very long optical fiber runs, like trans-oceanic (submarine), require signal boosts. Erobium-doped fiber amplifier (EDFA) types are the present favorite. They are assembled in a very labor-intensive and expensive manual process. Amplification is a function of frequency and this means that a set of incoming wavelengths will not be amplified equally. The job of balancing is assigned to a device called an equalizer. Lucent and others have already build MEMS-based equalizers and it makes sense to integrate them with amplifiers.

Routers/Switches: Internet and telephone information must obviously be sent to the proper locations and this is the task of the routers and switches. There is a tremendous effort to develop all-optical switches/routers that can direct photonic signals to the proper location at hubs along the Internet without converting back to electrons. Breakthroughs seem to occur nearly every week. This is the area where MOEMS is the star and will almost certainly become the key technology for all-optical switching. We should note that although electrical power is generally required for MOEMS devices, photonic energy can easily be converted to electrical. Lucent has demonstrated opto-generators that use light sent down a fiber and convert it to electrical for use with optical switches. Here are 4 basic approaches:

1. MOEMS micro-mirrors using electrical signals to move individual mirrors can be used to switch wavelengths off and on; "on" mirrors send the light to an output fiber while "off" deflects the beam. A more complex mirror could direct the light beam to any number of output fibers for very efficient signal routing. Many of the big companies have either developed prototypes or acquired companies.

2. Agilent Technologies has announced a very clever and simpler optical switch based on bubble jet principles after five years of development. A micro-drop of liquid that is "pumped" into the path of a light beam to refract and thus divert it from point A to B. The approach leverages HP's MEMS ink jet technology that has been so successful for ink jet cartridges.

3. Oak Ridge National Laboratories appears to have made a major breakthrough with a light wave switch requiring NO ELECTRICITY. Their **optical transistor** is switched on and off by photons at a speed of 1 microsecond. This device appears to be the true equivalent of the electronic solid state switch used in electronic routers/switches. However, the device is very rudimentary at this stage.

4. Add/drop filters can filter out (drop) specific wavelengths and also add to them composite signals as required by traffic demand. The add/drop capability is used for switching and is now considered conventional technology that may be replaced by MOEMS.

Shedding light on MOEMS

MOEMS products add a high level of complexity. The chip may need to be hermetically sealed and 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 photonic products. Figure 5 shows the Digital Micro-mirror Device™ (DMD) [6].

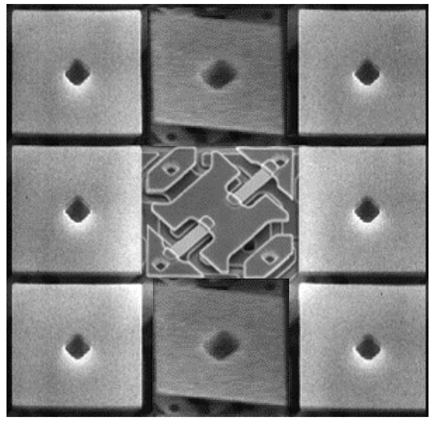


Figure 5 – TI Micro-Mirror Module - Ref. 6.
(One mirror is removed for structure visualization)

The Digital Micro-Mirror Device is presently the most sophisticated MOEMS product that has yet been commercialized and a preview of what lies ahead. The 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. The total parts count is much higher, so high, in fact, that the Digital Micro-Mirror Device from Texas Instruments, is now the most complex machine in the world with over about 1.5 million mirrors per module but many other parts for each mirror as can be seen in Figure 6. But a key feature is the manufacturing wizardry. All of the million-plus parts are crafted in sequence of mass processes producing over one hundred modules on a single wafer with a total count of about one-quarter of a billion mirrors per wafer. In the macroworld, a MEMS equivalent product would consist of countless sub-units made in many countries, by dozens of companies, by tens of thousands of workers. Figure 5 shows a section of the micro-mirrors with most pointed “on”. Large arrays are being used for digital projectors right now, but there are other applications such as digital video and optical switches.

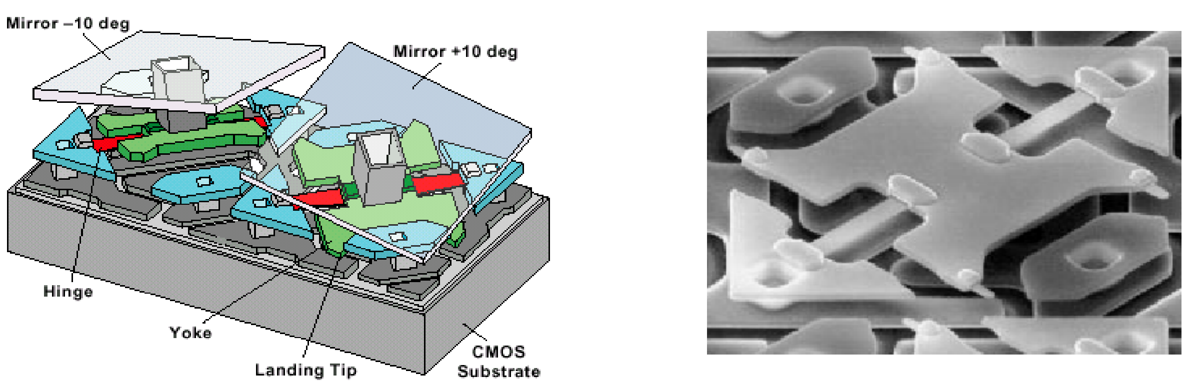


Figure 6 – TI Micro-Mirror Array Close Up, ref. 6

The movable mirror principle would appear to be a good fit for Internet routing of lightwave signals. An incoming beam could be directed toward the intended outbound fiber. A number of companies have announced products or plans for micro-mirror switches. Some pivot while others use a bending torsion beam action. Still others rotate and some even have multiple axis movement. Almost certainly, some moving reflector based optical routers will succeed and this has apparently already happening. Regardless of the specific director mechanism, the mirrors will probably need a similar type of high level package that is light-transmissive. The TI package is therefore a good model to explore the packaging issues for MOEMS.

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 clean, 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 will be discussed in more detail later. Figure 7 shows the TI package with getters attached to metal section of the lid assembly.

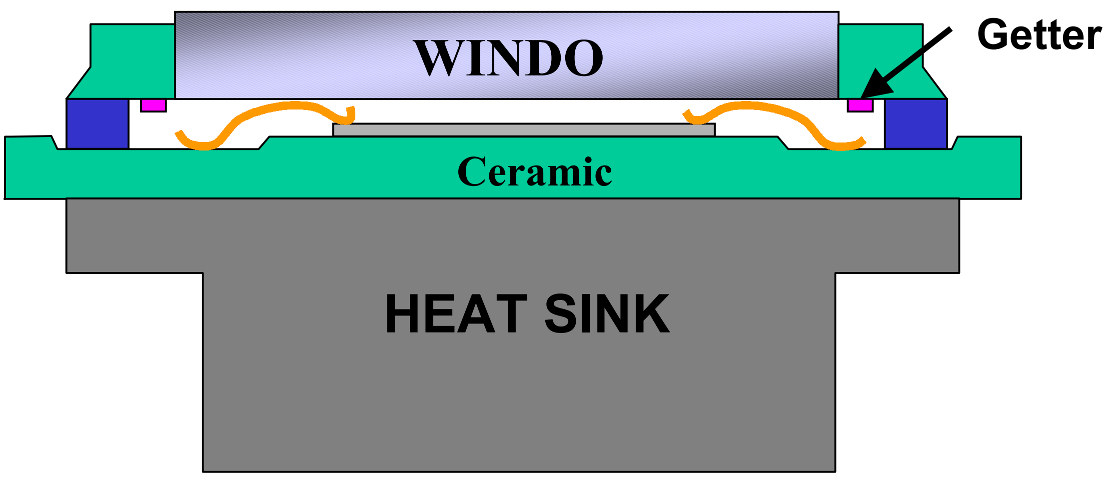


Figure 7 – TI's DMD Package Diagram

While significant fabrication issues remain, products, like TI's DMD, have successfully entered the market place with others products from dozens of companies also moving quickly to commercialization. The MOEMS products will control light, not just in projectors and displays, but also along the Internet Highway as photonics becomes the fundamental transmission technology. Modulated beams of laser light traverse the globe so quickly, that a message could circle the planet 7 times in just one heartbeat. But these broadband Internet data streams are optimally switched and routed directly as photons, not with electronic conversions that impose "speed bumps" on the Information Highway. MOEMS is the answer! Full photonics Internet switches are already in beta testing and begin limited service during 2001. The micro-mirrors and other opto control devices will catch multi-colored lamda waves and beam them to the desired fiber channels and out into cyberspace. Exceptional bandwidth has been gained by using a rainbow of colors sent along the same fibers and made possible by Wave Division Multiplexing (WDM). The more wavelengths, the greater the payoff in moving to MOEMS. Figure 8 shows a new MOEMS switch used in Lucent's Lamda Router^{TM}. Time will tell if the 2D, like the Texas Instruments structure or the 3D shown in Figure 8 will be the most efficient.

While 3D “point anywhere” MOEMS mirrors reduce the number of mirrors, the parts are more complex. Both will have a place with 2D serving the lower I/O market and 3D used for the truly large switches.

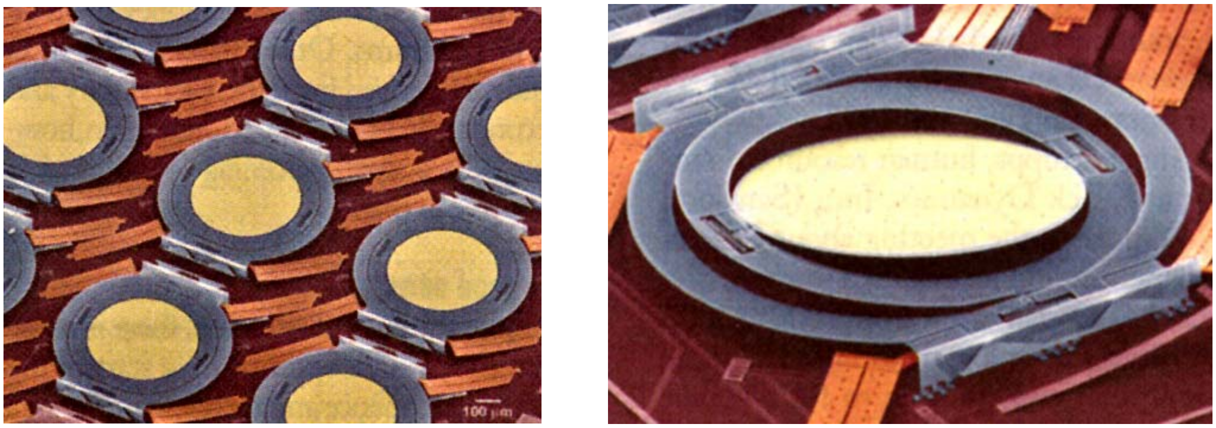


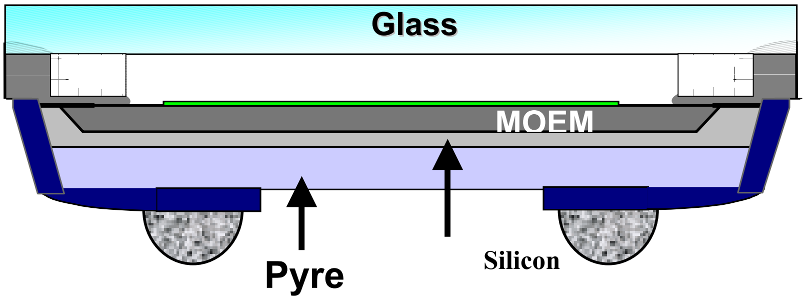
Figure 8 – Lamda Router Mirror Switch – Lucent

PACKAGING

The principal concern beyond fabrication is packaging. Nanoscale MEMS devices can be easily impaired or damaged by atmospheric contaminants such as submicroscopic particles and moisture. Particles will jam up the mechanical mechanism and immobilize components. Worse yet, particles can be produced inside the package as a by-product of wear as mentioned earlier. *But excess moisture is the real MEMS killer*.

Water vapor can fog and corrode delicate optics but it plays a more insidious role. Water increases the phenomenon called “stiction”. Stiction can “lock” surfaces together as if they were instantly glued. But as parts continue to get smaller, the surface area-to-mass ratio becomes excessive and this in turn multiplies surface-related3 stiction. Stiction can be a “show stopper” for MEMS when moving parts get permanently stuck. The “breaking force” can be up to a million times higher than the force that MEMS “engines” can generate. The topic will be covered in more detail in its own section.

The micropackaging industry is also offering novel packaging solutions for MOEMS. Some of these packages were initially designed for sensors and displays that have similar light I/O requirements, but not necessarily the high atmosphere control constraints as MOEMS. While such packages may not completely satisfy the requirements for MOEMS mirrors, it may be possible to modify and improve them. One new package from Chip Scale Package (CSP) maker ShellCase, is the ShellMEMS shown in figure 9. A glass cap is used in this wafer-level CSP.



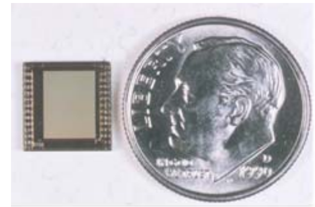


Figure 9 – Optical CSP - ShellCase

There are other photon-enabling potential solutions like glass substrate modules offered by Intarsia shown in Figure 10. While not designed specifically for MOEMS, the glass could let light pass in and out. A flip chip MOEMS device could be used to point the light through the glass substrate. Other flip chip constructions could possibly be used by with more conventional opaque substrate by using light ports or optical fiber and this will be discussed later. Now let's move into more detail.

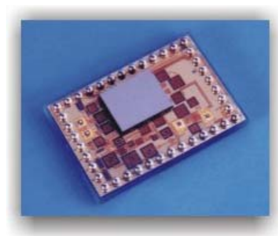


Figure 10 – Glass Substrate - Intarsia

Atmosphere Control

The MEMS package can both consume (absorb) but also generate materials (outgas), but apparently the optimum atmosphere needs to be controlled within certain ranges. Any 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. While the present list of commercial getters is small, other types are feasible. The common moisture getters use compounds that absorb and tightly bind water molecules. A special polymer matrix can be used as the "breathable" binder to hold the agent. Particle getters are made with permanently sticky polymers. The getter must be easy to use, maintain performance over extended time and not produce contamination. Getters could simply be "printed" on inside of the package. MOEMS devices often use moisture and particle getters as is the case with the TI mirror package.

Modern Getters [7]

Many may not have heard of getters, but they are important materials for many sealed packages. Getters have been around since the earliest era 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 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 designed to absorb and sometimes neutralize specific contaminants. Products are available that absorb gases, liquids and solids. While the present list in Table 3 is not that extensive, additional getters can be designed as the need arises.

TABLE 3

Getter	Form	Status
Moisture: H_2O	Film, paste	Commercial
Particle	Film, paste	Commercial
Hydrogen: H_2	Film, paste, thin film	Commercial
Oxygen: O_2	Film, paste, thin-film	feasible
Humidity range	Film, paste, fluid?	feasible

Moisture getters use compounds, like zeolites and metal oxides that absorb and tightly bind water molecules. A thermoplastic polymer binder is used that can be formed into film or pastes, such as Staystik 415 / 482 and StayDry SD1000 / SD800 from Alpha-Fry Technologies. Particle getters are made with permanently sticky polymers that maintain this characteristic over 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 particulate forming in the package. The Hydrogen Getter H2-3000, for example, utilizes palladium oxide (PdO) in combination with zeolites dispersed within a stable polymer matrix. The PdO converts H_2 gas to water that is then consumed by the zeolites 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 semiconductor structure of the GaAs devices reducing device performance over time.

Sandia and others suggest that a specific range of moisture is best since it can act as a lubricant. Can getters control humidity within a specific range? This is certainly feasible although the term getter may not be entirely accurate here and the term, "atmosphere stabilizer" is suggested. 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. Work is in progress at Alpha-Fry Technologies on such materials and intended for use with MEMS devices.

Surface Control

As you may have noted when 'stiction" was mentioned, MEMS has its own vocabulary. As mentioned earlier, stiction is related to friction but a much higher force is required to get things apart or 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 excessively high 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 will mean excessively large motors, or worse, disabled MEMS devices.

But stiction can be a crippling problem for even simple bending mode devices. What happens if the motion beams make contact? They stick! They stay stuck! We can't just pry the beams apart since the package is already sealed. But what made the beams come together? Jarring the parts or just moving them too quickly can cause the "floating" beam to move and make contact. So the assembler or user can unknowingly "lock up" the MEMS/MOEMS part just by handling. But the only evidence for stiction immobilization is testing or filed failure. Some mirror arrays have function for millions of cycles and suddenly got stuck according to Texas Instruments. The stiction problem applies to all moving devices where interfacial contact can occur. Mirror pivots, hinges, beams and sliders can all suffer the stiction-debilitating phenomenon.

A micro-machine with a potential to lock up or never get moving cannot be considered for high reliability Internet switching. The problem must be solved by design, materials or processing. But there are some surface chemistry complexities involved with silicon and its oxides that appear to make surface coating a logical option. Organic coatings with low surface energy and perhaps hydrophobic properties can probably help. The coating would need to be very thin and this is the realm for vacuum coating technology.

Friction, Stiction and Solutions

There is still some discussion 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. 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 [4]. There are some surface chemistry complexities involved with silicon and its oxides so the logical solution is a surface coating. Virtually all agree that the right coating 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 reduce the stiction problem after years of work. One approach was to coat the MEMS device with a low surface energy reactive silane. Although silanes have been suggested, their use had been limited by inadequate thermal stability required for the high temperature required for sealing the packages. Jack Martin, one of the most experienced technologists in the MEMS business, came up with several ideas. One solution 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. While this concept worked, a more precise method was sought. In late December 1997, Analog Devices was granted a patent covering anti-stiction that also proposed wafer-level coating [8].

Polymer Coatings

Specialty Coating Systems (SCS, Alpha-Fry Technologies), a manufacturer of chemical vapor deposition (CVD) materials and equipment, suggests that a very thin organic film could possibly help the problem. Only a limited amount of study has been done in this area, but SCS is ready to work with researchers to test several Parylenes including a newer fluorinated product. Parylenes, a thermoplastic polymer family of materials, have been used in electronics for years but many may not be familiar with this organic CVD coating system so let's briefly look at vacuum-deposited polymers.

The Parylenes for Anti-Stiction?

Parylene (poly-para-xylylene) is a special polymer film applied to substrates with a vacuum coater. The Parylenes are noted for high chemical inertness, strong barrier properties and near-perfect conformity. The surface energy is generally low due to the absence of functional groups. A new fluorinated, teflon-like version (Nova HT) has been recently developed by Specialty Coatings Systems 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 in MEMS [9]. The high optical clarity would also seem to make it a good candidate for MOEMS devices. Nova HT is also stable to UV radiation and high-intensity light in general.

Parylenes are 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 for decades 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. Table 4 summarizes the attributes of value to MEMS/MOEMS.

Table 4 - Parylene Attributes

Attribute	MEMS	MOEMS
Stress-free coatings	yes	yes
Thin contiguous film without pinholes	yes	yes
Inert	yes	yes
Even coating of sides and edges	yes	yes
Hydrophobic	yes	yes
Low surface energy, especially fluorinated Nova HT	yes	yes
High temp capability up to 500 degrees C	yes	yes
Low k down to 2.28	yes	
Optically clear, UV resistant		yes

Vacuum Coating of Parylene

The Parylene coating material starts off as a granular white powder that is used in a specialized vacuum coating chamber. The Parylenes are applied in a three-stage vacuum deposition process: (1) vaporization of the dimer at 150°C and 1.0 torr, (2) molecular cleavage, or pyrolysis to a reactive monomer (dimer) at about 680°C/0.5 torr and (3) polymerization of the thermally stable, kinetically unstable dimer on the cooler substrate at 0.1 torr. Figure 11 diagrams the process.

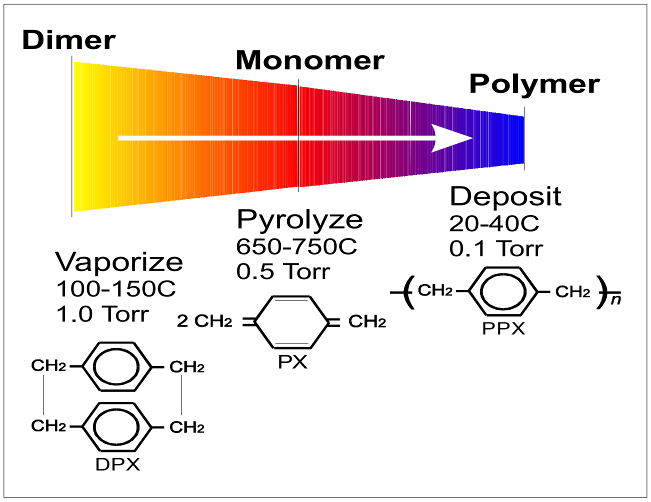


Figure 11 - Parylene Deposition.

The reactive gas polymerizes spontaneously on the surface of coated objects that are at ambient temperature with no stresses induced initially or subsequently. There are no cure-related hydraulic or liquid surface tension forces in the process. The mean free path is only about 0.1 cm so that sides and small openings are coated. A typical rate of 0.2µ or less provides precise thickness control. Polymerization occurs in crevices, under devices, and on exposed surfaces at about the same rate to give a very uniform film. The coating thickness can be as low as 100 Angstroms.

Types of Parylene

Parylene N has high dielectric strength that is independent of frequency and a low dissipation factor. **Parylene C**, with a chlorine atom on the benzene ring, has an excellent combination of electrical and physical properties, low permeability to moisture and corrosive gases and more rapid deposition than Parylene N. **Parylene D**, with two chlorine atoms on the ring, has higher thermal stability than the other two with superior physical and electrical value. More recently, Parylene HT with higher thermal stability and lower surface energy has become available. This product appears to be well suited for solving the stiction problem and so let's look more closely.

Fluorinated Parylene - Nova HT

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.

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. Nova HT polymer (Figure 6) is a fluorinated version of Parylene N. Its superior properties are due in part to the integration of fluorine into the Parylene lattice, which results in improved polymer stability. Nova HT has its origin in Specialty Coating Systems' Parylene VIP™ AF-4 - developed as an interlayer dielectric for the next-generation of very high-speed, fine-pitch integrated circuits. Its especially low dielectric constant minimizes the interlayer capacitance of ICs, and enhances operating speed by minimizing both power consumption and cross-talk. Like Parylene VIP AF-4, new Nova HT has a dielectric constant of only 2.28, and a crystalline melting point above 500 °C.

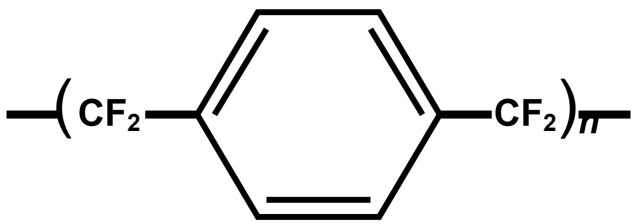


Figure 12 - The Nova HT Molecule

Nova HT film is applied to substrates in a similar vacuum process to conventional Parylenes. However, the required temperatures, pressures, dwell times, product preparation and fixturing are unique for this new material, and involve a proprietary process that has been developed by Specialty Coating Systems. Table 5 compares properties of the Parylenes.

Table 5 _ Parylene Properties

Parylene	50% Strength Temperature
D	150°C
C	100°C
N	75°C
HT	450°C

Parylene Issues

But there could be some issues with Parylene according to the few who have experimented with the organic coatings on MEMS. Thin coatings gave good anti-stiction results before packaging but deposition control may be difficult. Anti-stiction performance was apparently good using standard Parylene but sealing the hermetic package can cause degradation. Two recommendations were given for Parylene on MEMS devices:

1. A well-controlled deposition process for very thin coatings.

2. Higher temperature stability to withstand ceramic packaging processes.

The Nova HT appears to address the thermal issue. Perhaps different or more precision vacuum coaters in research organizations would permit a very thin, but pinhole free film to be applied.

DESIGNING MEMS PACKAGES

Many of the 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. Many Internet hardware packages are the hermetic metal type costing hundreds of dollars. New packaging may be needed as MEMS, MOEMS and photonics technologies expand.

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. In products like the ink jet where matter is ejected, the action zone must remain open to the outside. Other products need only have a protected area. 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 shown earlier that are commonly used for some BGAs. But overmolded packages would require modification for MOEMS.

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 harden. 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 glass port or fiber could possibly be used to limit entry to only the intended light. Figure 13 shows the Flip Chip designs with a light port. Optical underfill has been used experimentally. Another possibility is to use clear (no filler is used) "No Flow Underfill", NUF [10, 11].

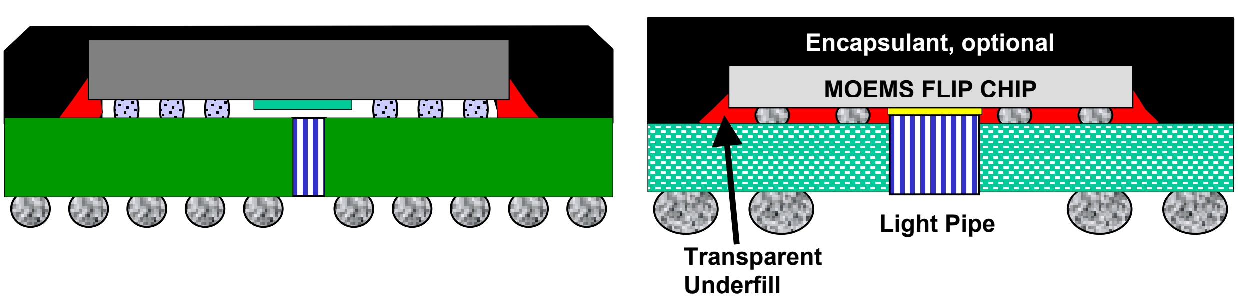


FIGURE 13 – FLIP CHIP MEMS PACKAGES

Another 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. One accelerometer maker is thought to be using thicker silicon caps to allow 2-axis motion sensors to be overmolded. The alternative may be liquid encapsulation. Figure 14 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. But can this concept work for MOEMS? The cap would have to be transparent, as would the molding compound. Quartz or some other "glass" could possibly be used for the cap. Molding compound specialist also think that a clear EMC (Epoxy Molding Compound) is possible since many epoxy resins and hardeners are transparent. The filler, required to reduce CTE (Coefficient of Thermal Expansion), could be the problem, however, since light scattering can result.

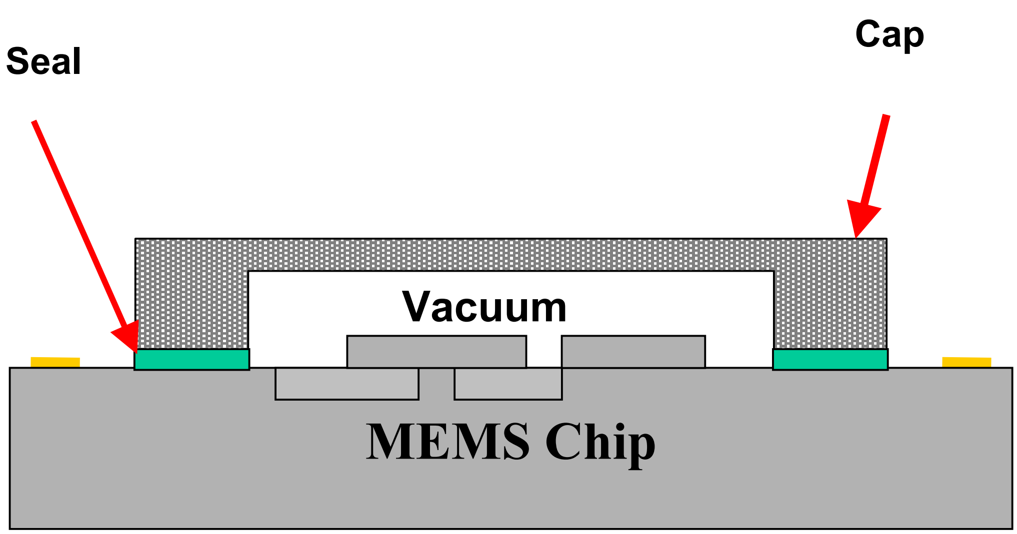


FIGURE 14 – 0-Level Hermetic Package

The cap principal is shown for MOEMS with a transparent cap and optical encapsulants were used. A quartz cap seems to be a logical starting point. While optically clear encapsulants may not be available, there is no reason whey they can't be developed. In fact, optical underfills, that contain similar ingredients to encapsulants, have been made and used on an experimental basis. Figure 15 depicts and optical cap-on-chip design that should be considered. Perhaps the mold cavity could be designed so that no molding occurs over the cap. Many designs are possible and need to be explored. This area appears to be a rewarding one for R&D but it probably falls into a high-risk category.

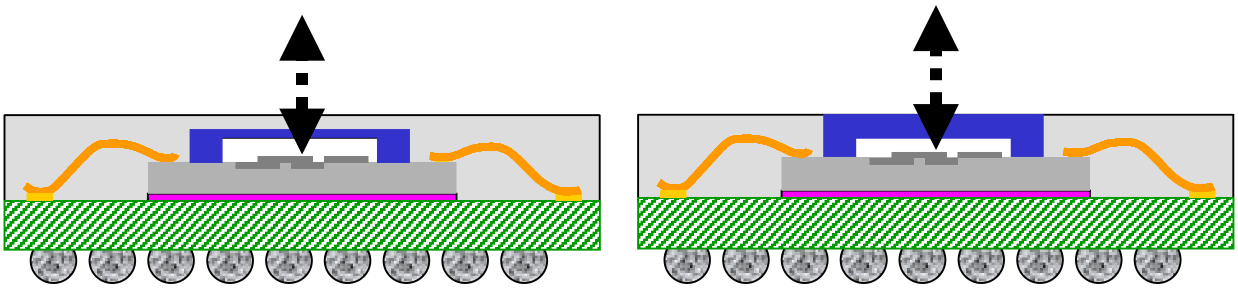


Figure 15 – Cap-on-Chip for Optical MEMS Devices

SUMMARY & 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. This technology is the convergence point of virtually all of the sciences and it will help enable many new concepts as it brings a science and technology synergy. Optical MEMS, or MOEMS, continues to gain strength as the photonics Internet and other segments of the telecom revolution gain momentum. While package challenges are substantial, progress is accelerating, but much work lies ahead. The need to control and regulate the package atmosphere will be critical. Fortunately, getters and emerging control agents appear to offer a practical and cost-effect solution today and for future generation MEMS products. New packaging designs will still be needed, especially for optical devices. A focused effort on MEMS packaging is needed now as a parallel effort to fabrication work. MOEMS packaging is more challenging due to the added requirement for light access, but new designs can solve problems. Considerable R&D will be needed in the packaging area that has been ignored while MEMS/MOEMS fabrication was emphasized. Now is the time to add thrust to packaging before it becomes the bottleneck that inhibits future growth in the MEMS arena.

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