Future Applications for MEMS/MOEMS Technology

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Abstract

Traditional MEMS (Micro-Electro-Mechanical Systems) devices have been with us for decades. A micromechanical motion sensor connected to the airbag electronics in your vehicle is always ready to send the message that may save your life. Sensing an abrupt change in motion indicative of a crash, the MEMS accelerometer sends the deployment signal to fire the airbag. MEMS technology is also used to rapidly fire a barrage of ink droplets out of tiny holes in an ink jet chip allowing you to print words and draw colorful pictures. MEMS chips, made by the millions, are part of the ink jet cartridge that enables low cost, reliable and high quality printing.

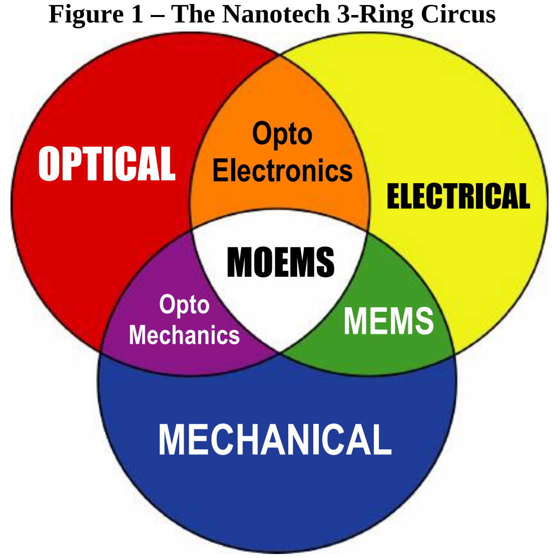
Emerging MEMS and MOEMS (MicroOptoElectroMechanical Systems) are ready to enable everything from sophisticated biomedical detectors to powerful, lightweight digital projectors. MOEMS optical switches are poised to take control of the photon-powered backbone of the Internet. MOEMS router switches will soon direct your e-mail to the correct address in cyberspace at the speed of light. But marvelous nanoworld devices can also detect specific molecules both near and far. Atmospheric gases can be measured by chip-level spectrophotometers. And lab-on-a-chip devices can detect pathogens or abnormal DNA quickly and accurately. We will highlight the most extraordinary applications but also describe the less exotic but essential ones. But let's first get better acquainted with the technology.

What is MEMS and MOEMS?

MEMS (MicroElectroMechanical Systems) combines electronics and mechanics on a single substrate. MEMS is centered around the high-level integration of dissimilar functions from the most vital realms of technology. This extraordinary *unification of functions* includes both energy and matter; motion, sound, atoms, molecules, light, radio and other electromagnetic radiation. The melding of attributes from so many diverse fields of science into a single structure is at the core of MEMS incredible power and wide-ranging potential. But those who do not understand the awesome power of synergistically merging essentially all the areas of technology into a micro- or even a nano-device will not appreciate what MEMS really portends[1].

We can add one more extremely important science and technology to MEMS and that is optics. This all-inclusive *technology bundle* is called optical MEMS or MOEMS (MicroOptoElectroMechanical Systems). Now, we have combined essentially every province of science onto and into a single microcosm. Highly complex devices can be mass-produced using proven processes of the $200-billion semiconductor industry. We can finally build the long-sought System on Chip (SoC). The most complex machine today is not the Space Shuttle or the Boeing 777, but a commercial MOEMS module with 1.5 million individually-controlled mirrors on 1 square inch of substrate. The latest MOEMS products have many more moving parts than anything ever built using all of the macro-world processes. MOEMS is at the center of the nano-universe where all other technologies converge. It is the new **3-ring circus of technology** where you'll find real action is and as depicted in Figure 1.

Figure 1 – The Nanotech 3-Ring Circus



Is MOEMS Really That Significant?

Some products, like Texas Instruments DMD™ (Digital Mirror Device), send and receive light beams, others precisely detect specific molecules and some deal with several "senses" simultaneously. If the logic device is the *brain*, MOEMS adds the *eyes, noise, ears* and other sensory input. But MOEMS is also control, the *hands and fingers*, because these devices doesn't just move their own parts, they can also manipulate 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 nanodevices can also bee designed to serve the fields of chemistry, physics, biology and medicine. We are really just at the threshold of understanding and applying this "alien world" 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 millennium. MOEMS will likely be the hallmark of the 21^{st} century since it can interact with and enable so many other technologies.

Computation, analysis and central control of these input/output functions results in a fully integrated system of incredible versatility. MOEMS 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 this arena soon as indicated by IBM's recent announcement of a DNA detector. MOEMS 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.

How Do We Build MEMS and MOEMS?

The real key to the technology is the ability to tap into the world's largest industry – electronics! The basic raw material is silicon, the same element used to make most of the nearly trillion-parts-per-year semiconductors. Photolithography, vacuum deposition, etching and all the others used to make ICs, are employed here. Design architecture, of course, is different for the mechanical components that must be free to move. Designs must enable 3D structures to be built and micro-channels are often added to allow liquid etchant to flow under surfaces. A final etch step is typically used to release the components that will move. The moving parts can be wheels, gears, beams and twisting bars with no rubbing parts. Just about any structure from the macroworld can be produced in the brave new nanoworld. Figure 2 shows some of the structures that have been built. The components are too small to be seen without a microscope.

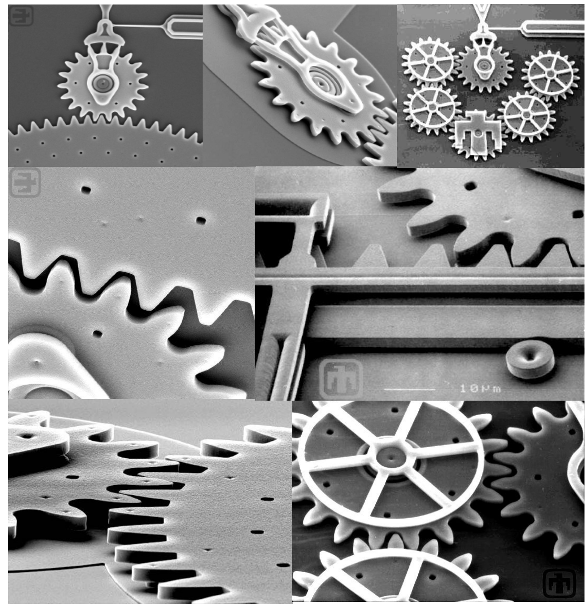


Figure 2 – MEMS from Sandia National Labs

Adding Optics = MOEMS

Now let's move on to optical MEMS so that we can later investigate the full range of applications for this fascinating *arena of technologies*. A large variety of optical devices have already been built and some are being used in products today. All of the structures incorporate some optical elements that may be as simple as a shutter. Others are more complex like two-axis mirrors that can be precisely aimed to direct light exactly where desired. Adding bright metal finishes to the silicon produces efficient mirrors at wafer-level. Aluminum, gold or other metals can be vacuum-deposited using semiconductor equipment. Non-mirror products include optical waveguides and even automatic beam aligners. Someday, we will have optical integration much like we have achieved in electronics. Silicon dioxide, the common IC insulator, can be used for its light-transmission characteristics. Figure 3 shows just a few of the MOEMS structures. Mirrors are made by adding bright metal and waveguides can be made from readily-formed silicon dioxide or other inorganic compounds.

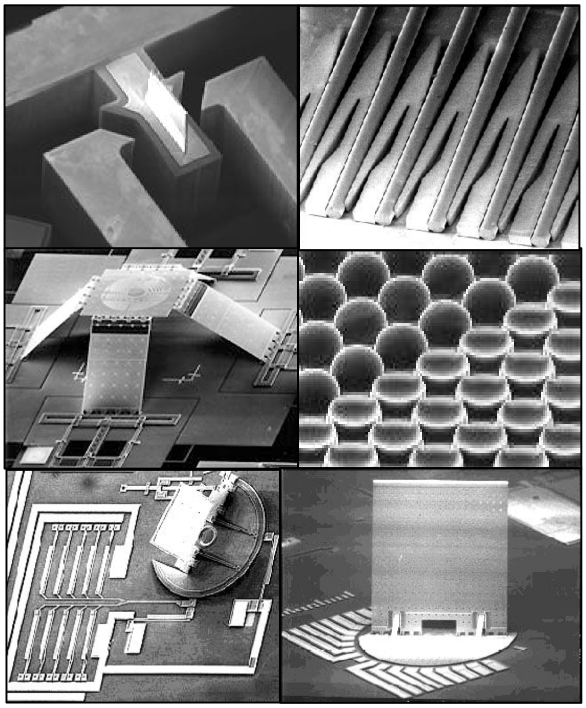


Figure 3 – MOEMS Structures

Micro Motors

So how do we build a motor to run a machine that can only been seen with a microscope? Easy! Just use the same processes that built the MEMS machine. We can construct electric motors by depositing magnetic coils, but there are easier ways of adding motion. One of the best engine concepts in the nanoworld uses electrostatic forces. Electrostatic engines are extremely efficient at this small scale because of the high surface area/mass ratio. These engines are also very easy to build since they are essentially just capacitor plates that can be made by vacuum depositing metal. All kinds of motion can be generated with electrostatic engines and it is one of the most popular methods.

The thermal engine is also an important driving force for MEMS. Simple heaters composed of metal are easy to construct. Electrical current is instantly converted to heat that can drive fluids, move elements or even produce steam to drive pistons and turbines. The famous ink jet and bubble jet printers rely on heaters to "fire" drops of ink (some are piezoelectric). But just about any macroworld concept can be implemented here. Even light can be used as "fuel". Lucent cleverly avoided requiring electrical power for an optical switch by adding an on-chip photoelectric generator. The device simply converts light (a wavelength specifically for power) to electricity that powers the electronics and motors. This allows the signal fiber to handle power and signal.

Telecom Photonics

The MOEMS devices for telecommunications have received considerable attention lately, but this large and dynamic area represents only a small region of the possibilities. However, telecom is certainly the most important business and technical driver for optical switches and micro-mirrors. The Internet has whole-heartedly embraced photonics for long-haul links and has created a demand for all kinds of amplifiers, controllers, analyzers and switches. Most of the Internet backbone, or long-haul segments, use optical fiber since this mode has much more bandwidth than anything that electronics can offer. But switching is still mostly electronic based.

Signals coming down the fiber are made up of light waves, or photons, that travel efficiently with almost no interaction since they have no mass or charge. Bandwidth has been boosted by orders of magnitude using multiple "colors". Eventually, more than 1000 wavelengths will travel over the same single fiber strand to boost bandwidth by an incredible 1000 times. However, each added wavelength brings more complexity to switching and routing of signals. The most common switching architecture involves converting optical signals to electrons where they can be switched by well-known electronic principles. Once switched, the electrons must be converted back to photons in order to ride optical fiber. This O-E-O (Opto-Electro-Opto) method becomes more and more problematic as wavelengths are added and data rates are boosted. So what is the answer?

Many believe that future switches and routers must be all-optical using an O-O (Opto-Opto) scheme. But how can we directly switch a beam of light? We could use micro-mirrors, shutters and a variety of other systems that can be built using MOEMS. Hence the intense interest in this field that has resulted in so many acquisitions by Internet hardware and network giants. We will explore several switching strategies and some other non-communications applications later. Let's first look at the package challenges for MEMS and MOEMS.

MEMS and MOEMS Packaging

Packaging has never been easy for electronic devices, but practical systems, materials and processes have evolved during the more than 40 years that this field has existed. Even today, we are seeing a continuing packaging revolution that attempts to tame and protect the powerful beasts born of the semiconductor industry. The packaging industry has made products that are chip-size, learned to accommodate nearly 10,000 connections and recently commercialized economical 3D stacked and other multichip packages. But the challenge of dealing with chips that move, sniff, hear and see is considerably more difficult. Many feel that packaging MOEMS in an economical form factor, is the greatest challenge ever encountered by the packaging industry[2].

The first restriction is that there can't be a restriction. Device elements must be free to move and operate. Some contaminants must be excluded or at least controlled. Micro-particles can jam mechanical components and they must be controlled with package getters. Water vapor will harm optics and also intensify or even catalyze the *show-stopping* phenomenon of "stiction". Stiction, simply put, is parts getting permanently stuck when they touch. This can happen because surfaces are smooth, area is relatively high and mass is comparatively low. It's less common in the macro world because the area/mass ratio isn't that high. However, you may have experienced a form of stiction when trying to separate microscope slides. The package atmosphere can play a role in stiction and other phenomenon. Moisture reduction may be important but data suggests that a specific range is best. Getters can reduce moisture and are commonly used in MOEMS packages along with particle getters.

A MOEMS package must have a window or light port and this adds just one more level of difficulty. Most MOEMS packages are expensive hermetic types with bonded windows. Work is underway to reduce packaging cost that is typically many times higher than the MEMS and MOEMS devices. In the future we can expect to see lower cost, mass-produced wafer-level packaging. Transparent disks will be bonded to wafers and then sawn to produce hermetic chips that we can call Cap-on-Chip.

Nearly all of the large field of photonics can probably benefit by adopting the hard-won principles from electronic packaging and assembly[3], but there appears to be great reluctance to even discuss issues. The offer, "We're from electronics and here to help", is not being met with open arms by the photonics industry. Perhaps the nay saying gurus are right, photonics is different than electronics and we can't use the same tricks of integration, packaging and assembly. Some have even stated that photonics will not be integrated because light pipes don't scale downward. This may be true, but only when conventional thinking is applied. This was the argument when the transistor replaced the hermetically encapsulated vacuum tube. But please note that something monumental happened when a "circuit guy" entered the electronic device industry. The integrated circuit (IC) was born and the father was former circuit engineer Jack Kilby who recently won a Nobel Prize.

Figure 4 shows the traditional MOEMS hermetic package design similar to the one used by TI.

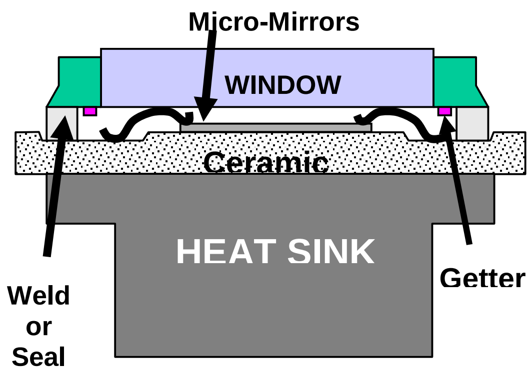


Figure 4 – MOEMS Package

The packaging industry is attempting to bring modern chip-scale concepts to the optical area however. We can expect to see many new concepts emerge here. Figure 5 shows one new product from ShellCase specifically targeting optical devices. The product is produced at wafer-level and may satisfy some, but certainly not all of MOEMS needs.

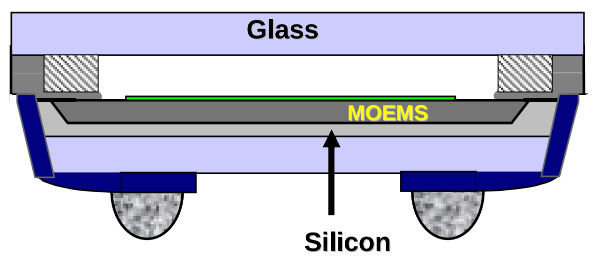


Figure 5 – Wafer-Level Optical Package (ShellCase)

What's This Stuff Good For Anyway?

Do we really need these devices with their tongue-twisting acronyms? What good is MEMS and its cousin MOEMS? Let's look closer.

You may have been in a crash where the instantly deployed airbag saved your life or at least know of such an instance. Life was saved by a MEMS accelerometer. A carefully crafted motion sensor detected the abrupt change in motion and sent the electrical signal that fired the airbag. This is no trivial task since the device must last longer than the vehicle and remain exactly at the right sensitivity level. On-chip electronics analyzes and conditions the signals. Figure 6 shows the spring-loaded capacitor design used by Analog Devices in the millions of MEMS devices that they produce. Motion change moves the beam plate and thus changes capacitance that is constantly measured. Figure 7 shows the actual chip from Analog Devices. The chip must be packaged in a way that does not interfere with movement or substantially change the detection characteristics. And assembly to a board must also be done so as not to reduce sensitivity.

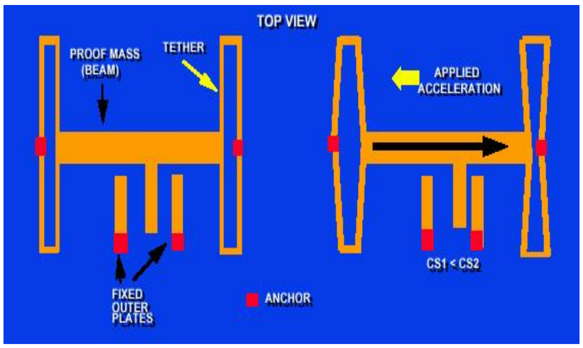


Figure 6 – Accelerometer Design (Analog Devices)

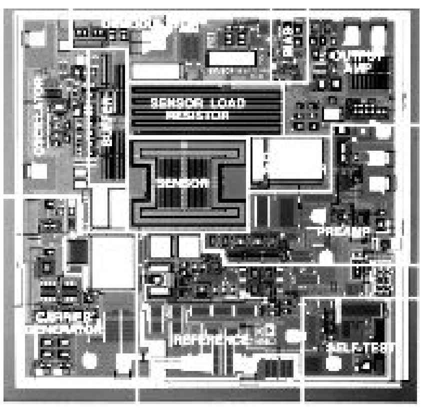


Figure 7 – Accelerometer (Analog Devices)

MEMS motion devices are growing more complex and two-axis products are now used for all kinds of products including video games. The dual-axis product is able to measure small forces in the human movement range and these integrated MEMS (or iMEMS; term used by Analog Devices) products are now available for less than $3 in SMT packages. While game input products such as motion gloves, are a major target, the devices will eventually move to the general human/machine interface to change the way we use computers, PDAs and cell phones. Figure 8 shows the dual-axis motion detector concept. The center mass with its four capacitor plates is suspended with silicon spring tethers in each corner. Movement in X and Y changes the distance between capacitor plates accordingly.

Other important MEMS devices include pressure sensors, camera stabilizers, chemical detectors, tiny motors and dozens of other devices. The list will continue to grow as this market, already at about $14 billion dollars, continues to expand and new start-ups add their innovation. Table 1 lists some of the many applications.

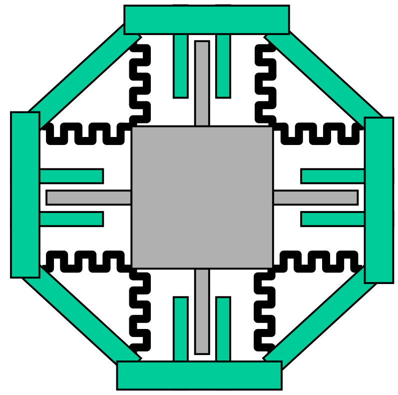


Figure 8 – Dual-Axis Accelerometer

TABLE 1

MEMS / MOEMS Device	Input
Accelerometer	Motion
2D and 3D Motion Detection	Motion
Ink Jet*	Electrical
Digital Mirror Array	Electrical & light
Micro-Spectrophotometer	“Light”
DNA Analyzer	Biological samples
Disk Drive Heads	Magnetic
Optical Switches	Electrical and light
Capacitors, Tunable	Electrical/RF
RF Tuners	Electrical/RF
Gyroscopes	Electrical/motion
Diagnostics (in vitro)	Electrical, samples
Infrared Imagers	IR, Electrical
Micro-Relay	Electrical
Pressure Sensors	Force

* Some ink jets use thermal heaters with no moving parts and may not fit a precise MEMS definition. Others use piezoelectric actuators that move

MOEMS - Just Add Light

Let’s look more closely at MOEMS using one of the best examples around, the Texas Instruments DMD™ (Digital Mirror Device). The system has been in commercial use in compact digital projectors for some time. More recently, the technology has been employed in digital cinema projectors first tested in San Jose, CA. The mirror module contains over 1.5-million microscopic mirrors and each can be individually addressed giving a near-instantaneous motion response. Figure 9 shows a close-up of the DMD array while Figure 10 shows the mechanical design features[4, 5]. This device uses 2D mirrors that point out (on) or away (off). The product must be housed in a dry, particle-free atmosphere with a window to allow the entry and exit of light. TI uses a hermetic package with a transparent window. While the package functions as required, the cost is high and a simpler idea is being sought. The package design is similar to the type previously shown in Figure 4 but is said to be moving to lower coast quasi-hermetic styles[6].

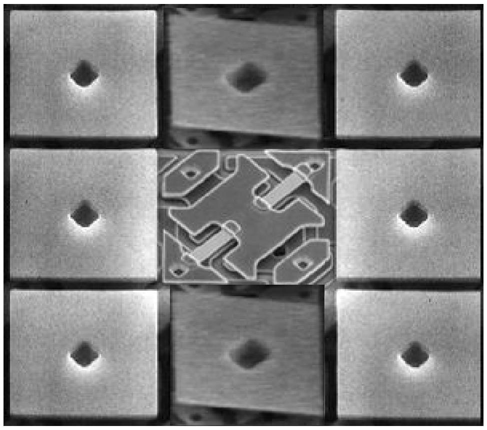


Figure 9 – DMD Close Up (ref. 4, 5)
(Center reflector removed for visualization)

Note that this intricate structure was produced by photolithography and etching and that the mirror arrays are produced on wafers that contain about 1/4 billion mirrors. Future miniaturization and wafer scaling will likely break the billion mirrors per wafer mark.

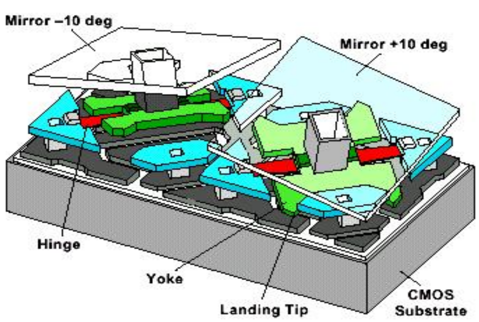


Figure 10 – DMD Mechanism (ref. 4,5)

Internet Hardware

The demand for more bandwidth on the Internet has created many new hardware opportunities in the optoelectronics area. Products include laser diode sources, amplifiers, signal analyzers, switches, wave conditioners, multiplexers, demultiplexers and many others. Some needs can be met by MOEMS. The most exciting area where MOEMS will play a key role is the switch/router realm. Most companies are pursuing the micro-mirror concept. The TI DMD single-axis structure is being adopted for switching applications. A single-axis mirror produces an on-off switching principle but others are pursuing a 2-axis 3D mirror principle that will aim the lightwave to any point in an area array. Lucent's LamdaRouter™ employs a 2-axis mirror structure shown in Figure 11.

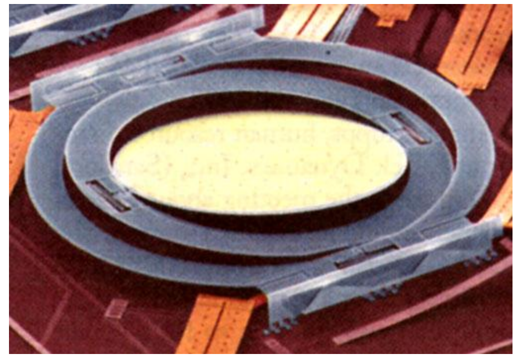


Figure 11 – LamdaRouter MOEMS (Lucent)

There are other concepts for switching light and one of the most unusual comes from Agilent. Borrowing from Hewlet-Packard's long experience with bubble jet/ink jet devices, they have come up with a fluid switch. The cross-switch uses tiny electrical heaters to instantly move an optical fluid into a light path to cause switching. Agilent claims that the technology provides a simpler, lower cost optical switch. The switch is in field testing. Figures 12A and B show the switch and patent drawing, respectively.

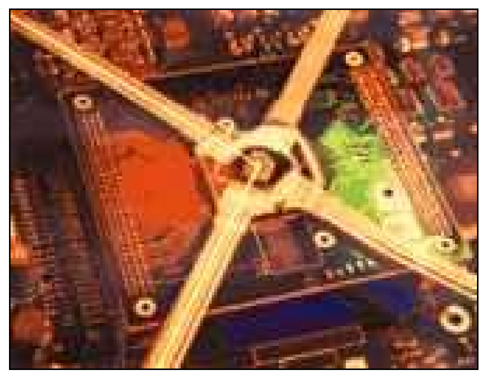


Figure 12A **– Agilent Bubble Switch**

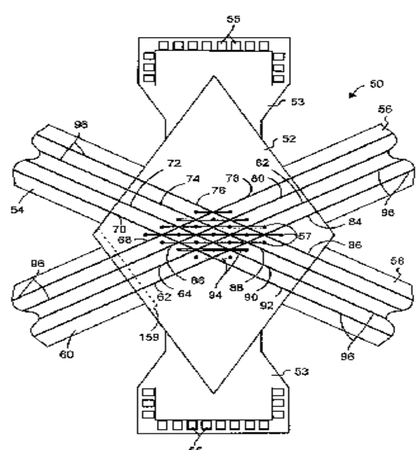


Figure 12B – Agilent Bubble Switch

Beyond Telecom

The telecom arena is certainly a 3-ring circus with plenty of action as stated right from the beginning. Although communications is important, even vital, there's a lot more to nano-life than moving and switching voice and data. We'll now complete the MEMS/MOEMS picture by looking at some of these emerging applications.

Recent technological breakthroughs have made DNA chips possible. Genetic chips are the result of achievements in molecular biology, MEMS and nano technology. Many of us believe that biotech and the medical area will be the most important field for new developments in the MEMS field. A few dozen companies are already developing and even producing biological detectors and analyzers. Some detect pathogens while others can even determine if DNA is abnormal. IBM recently announced a DNA detector based on MEMS. Very thin, cantilevered beams made of silicon are the detectors. These are coated with receptive agents that will attract and bond various biological materials of interest including slices of DNA. When the biological material bonds to the treated surface, the stressed beam bends and the curvature is detected as an electrical signal response. Figure 13 shows the IBM MEMS detector.

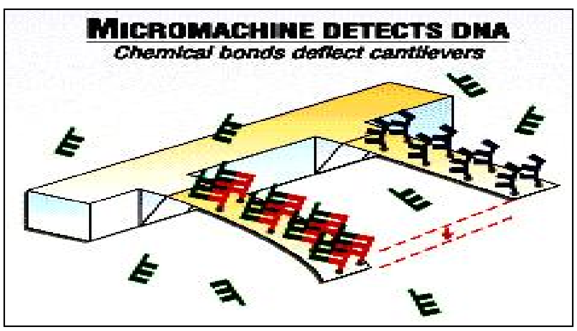


Figure 13- MEMS DNA Detector (IBM)

Other methods use light. DNA detectors can use light-directed chemical synthesis process, which combine solid-phase chemical synthesis with photolithographic fabrication techniques employed in the semiconductor industry. Exposure sites are fabricated into the chip and coated with specific chemicals. The high-density detector sights occupy predefined positions in the array. Multiple probe arrays are synthesized simultaneously on a large wafer. This parallel process enhances reproducibility and helps achieve economies of scale. The wafers are then diced, and individual probe arrays are packaged in injection-molded plastic cartridges that protect them from the environment and serve as chambers for hybridization.

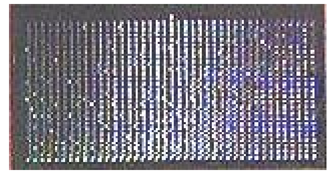


Figure 14 – DNA Chip (PE Applied Biosystems)

Conclusions & Predictions

MEMS has been with us for decades but in a simple form used for singular tasks like impact detection and pressure measurement. Today, much more complex nano-machines are being built that mimic all of our senses. More recently, light has been added to produce MOEMS, the ultimate nano-system. The ability to measure and control light opens up a new vista of exciting possibilities. MOEMS now produces clear images on screens for presentations. The technology is just starting to move into the mass entertainment field. In a not to distant future, the big screen movies will be projected using MOEMS. And the "movies" will arrive at the theater via the Internet using MOEMS routers.

The nano-technologies have already been applied to the biosciences to built DNA detectors. But MEMS and MOEMS in the biomedical areas are embryonic. We are just beginning on a journey that will eventually unravel the secrets of life and perhaps make disease a thing of the past. MEMS/MOEMS will be the hallmark technology of the 21st century.

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