A Review Study on MEMS (Micro Electro Mechanical Systems)

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Abstract*— MEMS has been identified as one of the most promising technologies for the 21st Century and has the potential to revolutionize both industrial and consumer products by combining silicon based microelectronics with micromachining technology. Its techniques and microsystem based devices have the potential to dramatically effect of all of our lives and the way we live. If semiconductor micro fabrication was seen to be the first micro manufacturing revolution, MEMS is the second revolution. This paper deals with the emerging field of micro-electromechanical systems, or MEMS and its applications and future scope. MEMS is a process technology used to create tiny integrated devices or systems that combine mechanical and electrical components. They are fabricated using integrated circuit (IC) batch processing techniques and can range in size from a few micrometers to millimetres. These devices (or systems) have the ability to sense, control and actuate on the micro scale, and generate effects on the macro scale.

Index Terms— **MEMS, Applications, NEMS.**

I. INTRODUCTION

Micro-Electro-Mechanical-Systems (MEMS) technologies can be used to produce structures, devices and systems on the scale of micrometers. Our goal is to closely look at MEMS and outline the main benefits and limitations of this cutting edge technology. In the process, we will investigate MEMS applications, fabrication processes, and the future of MEMS, namely Nano-Electro-Mechanical-Systems (NEMS).Although there are many technologies available to miniaturize devices, the acronym MEMS is used almost universally to refer to all devices that are produced by micro fabrication or micromachining except Integrated Circuit (IC) or other conventional semiconductor devices; micromachining is any process that deposits, etches or defines materials with minimum features measured in micrometers or less. The general field of miniaturization is known as other names as well, namely Micro Systems Technology (MST) which is popular in Europe, and Micro Machines which is popular in Asia.

In the most general form, MEMS consist of mechanical microstructures, microsensors, microactuators and microelectronics, all integrated on to the same silicon chip. Microsensors detect changes in the system’s environment by measuring mechanical, thermal, magnetic, chemical or electromagnetic information or phenomena. Microelectronics processes this information and signal the micro actuators to react and create some form of changes to the environment.

The interdisciplinary nature of MEMS utilizes design, engineering and manufacturing expertise from a wide and diverse range of technical areas including integrated circuit fabrication technology, mechanical engineering, materials science, electrical engineering, chemistry and chemical engineering, as well as fluid engineering, optics, instrumentation and packaging. The complexity of MEMS is also shown in the extensive range of markets and applications that incorporate MEMS devices. MEMS can be found in systems ranging across automotive, medical, electronic, communication and defence applications. Current MEMS devices include accelerometers for airbag sensors, inkjet printer heads, computer disk drive read/write heads, projection display chips, blood pressure sensors, optical switches, microvalves, biosensors and many other products that are all manufactured and shipped in high commercial volumes.

MEMS represent the combination of semiconductor processing and mechanical engineering, however at a very small scale. It is interesting to note that the first MEMS device was a gold resonating MOS gate structure in 1967. MEMS became firmly established in the mid-1980s; the technology has now matured to a level where many real-world applications can be implemented and utilized. As a general rule of thumb, MEMS typically have dimensions ranging from nanometers to centimeters; however, very little has been done with MEMS below one micrometer. On the contrary, recent developments in IC technologies can now mass produce chips with features as small as0.13 microns; the new Intel Pentium 4 processor running at 2.2 to 2.4 GHz is one such example. SEMATECH, a think-tank of semiconductor companies in the US, predicts that the minimum feature size will shrink to 0.07 microns (70 nanometers) by the year 2010.

MEMS are the integration of mechanical elements such as sensors and actuators with electronics on a common silicon substrate through utilization of microfabrication technology. ICs can be thought as the “brains” of the system while the MEMS augments this decision making capability with “eyes” and “arms” to allow the micro system to sense and control the environment. In the most basic form, the sensors gather information from the environment through measuring mechanical, thermal, biological, chemical, optical, and magnetic phenomena; the electronics process the information derived from the sensors and hence direct the actuators to respond by moving, positioning, regulating, pumping, and filtering, in order to control the environment for some desired outcome or purpose.

II. ESTABLISHED MEMS APPLICATIONS

Automotive airbag sensor

Automotive airbag sensors were one of the first commercial devices using MEMS. They are in widespread use today in the form of a single chip containing a smart sensor, or accelerometer, which measures the rapid deceleration of a vehicle on hitting an object. The deceleration is sensed by a change in voltage. An electronic control unit subsequently sends signal to trigger and explosively fill the airbag.

Initial air bag technology used conventional mechanical ‘ball and tube’ type devices which were relatively complex, weighed several pounds and cost several hundred dollars. They were usually mounted in the front of the vehicle with separate electronics near the airbag. MEMS has enabled the same function to be accomplished by integrating an accelerometer and the electronics into a single silicon chip, resulting in a tiny device that can be housed within the steering wheel column and costs only a few dollars (Figures 1 and 2).

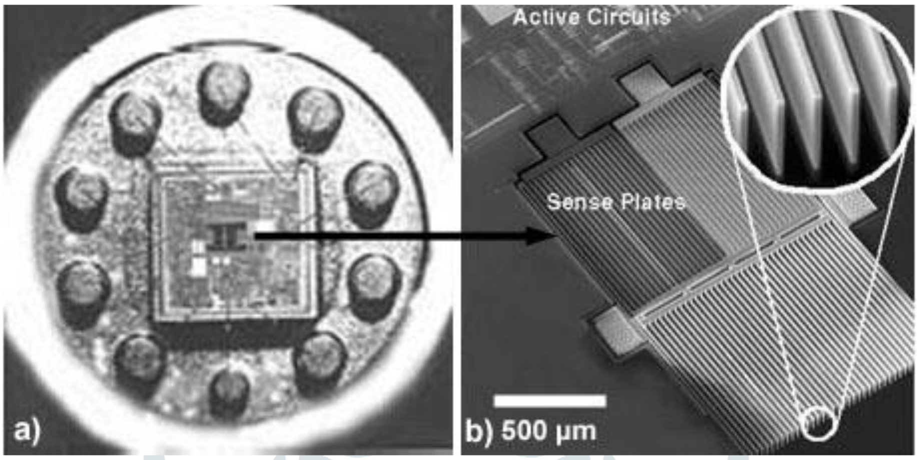

Figure 1: (a) The first commercial accelerometer from Analog Devices (1990); its size is less than 1 cm2 (left), and (b)capacitive sense plates, 60 microns deep (right) .

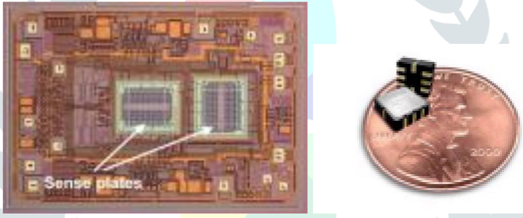

Figure 2: Modern day MEMS accelerometer (left), and the fully packaged device (right).

Medical pressure sensor

Another example of an extremely successful MEMS application is the miniature disposable pressure sensor used to monitor blood pressure in hospitals. These sensors connect to patient’s intravenous (IV) line and monitor the blood pressure through the IV solution. For a fraction of their cost ($10), they replace the early external blood pressure sensors that cost over $600 and had to be sterilized and recalibrated for reuse. These expensive devices measure blood pressure with a saline-filled tube and diaphragm arrangement that has to be connected to an artery with a needle.

Inkjet printer head

One of the most successful MEMS applications is the inkjet printer head, superseding even automotive and medical pressure sensors. Inkjet printers use a series of nozzles to spray drops of ink directly on to a printing medium. Depending on the type of inkjet printer the droplets of ink are formed in different ways; thermally or piezoelectrically. Invented in 1979 by Hewlett-Packard, MEMS thermal inkjet printer head technology uses thermal expansion of ink vapour. Within the printer head there is an array of tiny resistors known as heaters. These resistors can be fired under microprocessor control with electronic pulses of a few milliseconds (usually less than 3 microseconds). Ink flows over each resistor, which when fired, heat up at 100 million ºC per second, vaporizing the ink to form a bubble. As the bubble expands, some of the ink is pushed out of a nozzle within a nozzle plate, landing on the paper and solidifying almost instantaneously.

Overhead projection display

One of the early MEMS devices used for a variety of display applications is the Digital Micromirror Device (DMD) from Texas Instruments. The device contains over a million tiny pixel-mirrors each measuring 16 µm by 16 µm and capable of rotating by ±10º, over 1000times a second (Figure 10). Light from a projection source impinges on the pupil of the lens (or mirror) and is reflected brightly onto a projection screen. DMD’s are used for displays for PC projectors, high definition televisions (HDTV’s) and for large venues such as digital cinemas where traditional liquid crystal technology cannot compete. MEMS has enabled the micromirrors to be only 1 µm apart, resulting in an image taking up a larger percentage (89percent) of space on the DMD chip's reflective surface, as compared to a typical LCD (12 to50 percent). This reduces the pixilation and produces an overall sharper and brighter image. Today over 30 manufacturers use the DMD (Kodak being the largest) and over 500,000systems have been shipped.

MEMS devices can be classified into two categories, mainly sensors and actuators. Sensors are non-intrusive while actuators modify the environment. Micro sensors are useful because of their small physical size which allows them to be less invasive. Micro actuators are useful because the amount of work they perform on the environment is also very small, and therefore it can be very precise. Some typical examples of MEMS technology are polysilicon resonator transducers, high aspect ratio electrostatic resonator, magnetic micro motors, precision engineered gears, etc. MEMS are already in wide use in the automotive industry, and are beginning to penetrate other industries as well, such as Nation Defense, etc. For example, MEMS are utilized for engine oil pressure, vacuum pressure, fuel injection pressure, transmission fluid pressure, ABS line pressure, tire pressure, stored airbag pressure, various temperature throughout an automobile, active suspension systems, etc. MEMS accelerometers can also be used to trigger airbags or lock seat belts in the event of an accident; it has been shown that the cost per sensor and the failure rate is dramatically reduced when it is built on the micro scale rather than on the macro scale. For example, the conventional approach uses several bulky accelerometers made of discrete components which are separate from the electronics near the airbag and costs over $50 for each set; MEMS has made it possible to integrate onto a single silicon chip the accelerometer and needed electronics that is only a small fraction of the size for under $5.

III. MEMS FABRICATION PROCESSES

MEMS fall into three general classifications; bulk micromachining, surface micromachining and high-aspect-ratio micromachining (HARM), which includes technology such as LIGA (a German acronym from Lithography, Galvanoformung, Abformung translated as lithography, electroforming and molding). Conventional macro scale manufacturing techniques e.g. injection moulding, turning, drilling etc, are good for producing three dimensional (3D) shapes and objects, but can be limited in terms of low complexity for small size applications. MEMS fabrication, by comparison, uses high volume IC style batch processing that involves the addition or subtraction of two-dimensional layers on a substrate (usually silicon) based on photolithography and chemical etching. As a result, the 3D aspect of MEMS devices is due to patterning and interaction of the 2D layers. Additional layers can be added using a variety of thin-film and bonding techniques as well as by etching through sacrificial ‘spacer layers’. Figure 3 shows the potential complexity of a MEMS system by the addition of independent structural layers.

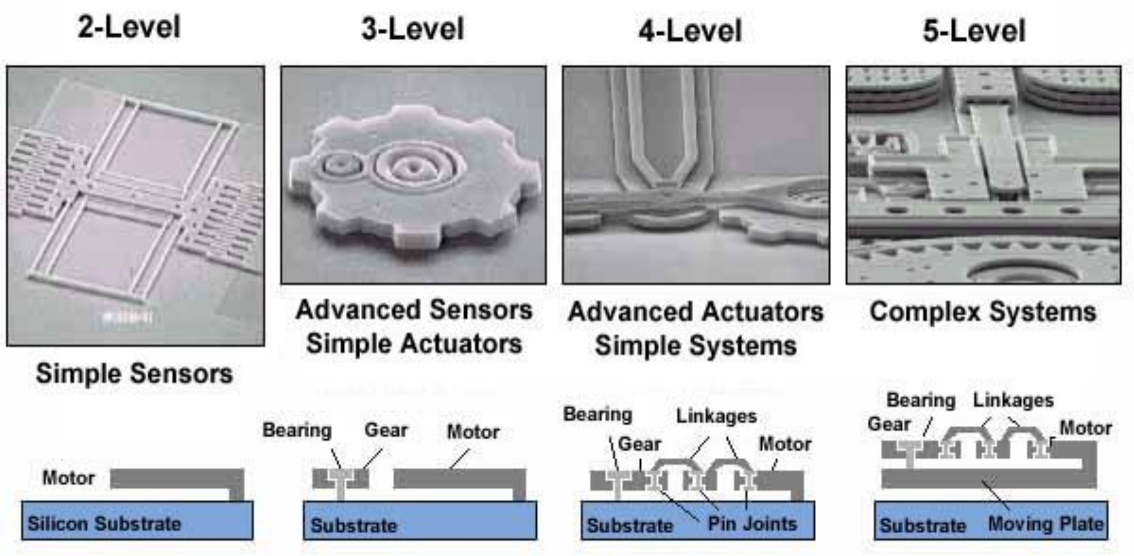

Figure 3: MEMS device complexity by structural layers

Typically, a MEMS device is first designed with a Computer Aided Design (CAD) tool. There are many tools currently available from companies such as MEMSCAP Inc. which allow the user to design a MEMS device, optimize it, simulate it, verify its functionality, and generate its layout. Existing CAD tools compute the equilibrium solutions in a lengthy iterative process. Ideally, the MEMS CAD tool would be capable of rapid solving, mechanical, thermal, electrostatic, magnetic, and fluidic, RF, and optical solutions in a coupled fashion. This layout is then sent to a foundry, where the chip is fabricated, a mask-less post-processing release step is performed where sacrificial layers are etched away, allowing the structural layers to move and rotate. Following the release, the devices are assembled and tested. Unfortunately, the cost of a micro fabrication facility capable of producing MEMS is prohibitively expensive for most companies and universities. In order to maximize the utility of the foundries, some micro fabrication facilities make their processes publicly available for modest fees. The most prominent MEMS foundries include MUMPS process by Cronos, the Summit process by Sandia National Laboratories, the iMEMS process by Analog Devices, and the IC foundry broker MOSIS.

Surface micromachining is an additive fabrication technique which involves the building of the device on top the surface of the supporting substrate. This technique is relatively independent of the substrate utilized, and therefore can be easily mixed with other fabrication techniques which modify the substrate first. An example is the fabrication of MEMS on a substrate with embedded control circuitry, in which MEMS technology is integrated with IC technology. Surface micromachining has been used to produce a wide variety of MEMS devices for many different applications; some of the commercially available MEMS devices were fabricated in large volumes of over 2 million parts per month. On the other hand, bulk micromachining is a subtractive fabrication technique which converts the substrate, typically single-crystal silicon, into the mechanical parts of the MEMS device. Packaging of the device tends to be more difficult, but structures with increased heights are easier to fabricate when compared to surface micromachining. This is because of the substrates can be thicker resulting in relatively thick unsupported devices. Exploiting the predictable anisotropic etching characteristic of single crystalsilicon, many high precision complex three-dimensional shapes, such as Vgrooves, channels, pyramidal pits, membranes, vias, and nozzles can be achieved.

IV. MEMS TRANSDUCERS

Microsensors and microactuators are at the very core of a MEMS device or system. A micro sensor detects changes in the system’s environment; an ‘intelligent’ part processes the information detected by the sensor and makes a decision in the form of a signal; and a micro actuator acts on this signal to create some form of changes in the environment. Microelectronic components make up most of the intelligent part of the device and, as an established technology, will not be discussed here.

Sensors and actuators are broadly termed transducers and are essentially devices that convert one form of energy into another. Many of the MEMS sensors and actuators described in this section have been developed within the microelectronics industry and do not all involve any special micromachining techniques; they are based on conventional integrated circuits that, through inherent mechanisms, sense light, temperature etc. However, many of these can be enhanced by the use of MEMS.

Basic MEMS mechanisms and structures consist of both in-plane and out-of-plane mechanisms as well as structural members to couple energy between the actuator and sensors as well as with the physical interface of a mechanical system. Mechanisms such as joints, linkages, gears and hinges are very typical.

This section concentrates on the phenomena that can be sensed or acted upon with MEMS devices with a brief description of the basic sensing and actuation mechanisms. It is important to note that although these devices are mechanical and have been categorized in terms of their sensing domain (e.g. thermal, chemical, radiation), there are many overlaps, and forms of mechanical transducer can be commonly found as intermediate mechanisms in other devices. Some types of transducers-

- Mechanical Transducers
- Radiation Transducers
- Thermal Transducers
- Magnetic Transducers
- Chemical and Biological Transducers

V. THE FUTURE OF MEMS

Major challenges facing the MEMS industries-

Access to Foundries

MEMS companies today have very limited access to MEMS fabrication facilities, or foundries, for prototype and device manufacture. In addition, the majority of the organizations expected to benefit from this technology currently do not have the required capabilities and competencies to support MEMS fabrication. For example, telecommunication companies do not currently maintain micromachining facilities for the fabrication of optical switches. Affordable and receptive access to MEMS fabrication facilities is crucial for the commercialization of MEMS.

Design, Simulation and Modelling

Due to the highly integrated and interdisciplinary nature of MEMS, it is difficult to separate device design from the complexities of fabrication. Consequently, a high level of manufacturing and fabrication knowledge is necessary to design a MEMS device. Furthermore, considerable time and expense is spent during this development and subsequent prototype stage. In order to increase innovation and creativity, and reduce unnecessary ‘time-to-market’ costs, an interface should be created to separate design and fabrication. As successful device development also necessitates modelling and simulation, it is important that MEMS designers have access to adequate analytical tools. Currently, MEMS devices use older design tools and are fabricated on a ‘trial and error’ basis. Therefore, more powerful and advanced simulation and modelling tools are necessary for accurate prediction of MEMS device behaviour.

Packaging and Testing

The packaging and testing of devices is probably the greatest challenge facing the MEMS industry. As previously described, MEMS packaging presents unique problems compared to traditional IC packaging in that a MEMS package typically must provide protection from an operating environment as well as enable access to it. Currently, there are no generic MEMS packaging solution, with each device requiring a specialized format. Consequently, packaging is the most expensive fabrication step and often makes up 90% (or more) of the final cost of a MEMS device.

Standardization

Due to the relatively low number of commercial MEMS devices and the pace at which the current technology is developing, standardization has been very difficult. To date, high quality control and basic forms of standardization are generally only found at multi-million dollar (or billion dollars) investment facilities. However, in 2000, progress in industry communication and knowledge sharing was made through the formation of a MEMS trade organization. Based in Pittsburgh, USA, the MEMS industry group (MEMS-IG) with founding members including Xerox, Corning, Honeywell, Intel and JDS Uniphase, grew out of study teams sponsored by DARPA that identified a need for technology road mapping and source for objective statistics about the MEMS industry. In addition, a MEMS industry roadmap, sponsored by the Semiconductor Equipment and Materials International organization (SEMI), has also been identified to share pre-competitive information on the processes, technology, application and markets for MEMS. This web-based organization can be found at http://www.roadmap.nl.

Several other European initiatives supported by governments and the European commission have been coordinated: Euro practice (Microsystems Service for Europe), NEXUS (Network of Excellence in Multifunctional Microsystems), aimed at enhancing European industrial competitiveness in the global marketplace, and Net pack, whose role is to drive the development and use of advanced packaging and integration technologies. The networking of these smaller companies and organizations on both a European and a global scale is extremely important and necessary to lay the foundation for a formal standardization system.

Education and Training

The complexity and interdisciplinary nature of MEMS require educated and well-trained scientists and engineers from a diversity of fields and backgrounds. The current numbers of qualified MEMS-specific personnel is relatively small and certainly lower than present industry demand. Education at graduate level is usually necessary and although the number of universities offering MEMS-based degrees is increasing, gaining knowledge is an expensive and time-consuming process. Therefore, in order to match the projected need for these MEMS scientists and engineers, an efficient and lower cost education methodology is necessary. One approach, for example, is industry-led (or driven) academic research centre offering technology-specific programmers with commercial integration, training and technology transfer.

Future of MEMS: NEMS

NEMS stands for Nano-Electro-Mechanical-Systems is the technology that is similar to MEMS, however it involves fabrication on the nanometer scale rather than the micrometer scale. According to Michael Roukes in, NEMS can be built with masses approaching a few attograms (10-18 grams) and with a cross-section of about 10nanometers.

Processes such as electron-beam lithography and nanomachining now enable semiconductor nanostructures to be fabricated below 10 nm. Although the technology exists to create NEMS, there are three principal challenges that must be addressed before the full potential of NEMS can be realized. First of all, communicating signals from the nanoscale to the macroscopic world can pose a great challenge. Understanding and controlling mesoscopic mechanisms is still at the very early stages. Thermal conductance in this regime is quantized, which implies that quantum mechanics places an upper limit on the rate at which energy can be dissipated in small devices by vibrations. Lastly, we do not have the methods for reproducible and routing mass nanofabrication; device reproducibility is currently very hard and almost unachievable. It is clear that if NEMS are ever to become a reality, cleaner environments and higher precision of nanofabrication techniques are needed.

VI. CONCLUSIONS

The market for MEMS devices is still being developed but does not have the explosive growth of, for example, the IC industry in the 1970s. Comparison will always be made between the two, but this is not realistic as there is no ‘dominant technology’ in MEMS analogous to metal oxide semiconductor circuitry, which accelerated the exponential growth of the digital electronics industry. Most of the research today is focused on surface micromachining, but in industry the majority of shipped devices are still manufactured using much older bulk methods. Although some surface micro machined devices are being produced in volume, it will take a few more years for this approach to make a large impact; devices using both surface and bulk continue to be marketed.

The potential exists for MEMS to establish a second technological revolution of miniaturization that may create an industry that exceeds the IC industry in both size and impact on society. Micromachining and MEMS technologies are powerful tools for enabling the miniaturization of sensors, actuators and systems. In particular, batch fabrication techniques promise to reduce the cost of MEMS, particularly those produced in high volumes. Reductions in cost and increases in performance of microsensors, microactuators and microsystems will enable an unprecedented level of quantification and control of our physical world.

Although the development of commercially successful micro sensors is generally far ahead of the development of microactuators and microsystems, there is an increasing demand for sophisticated and robust microactuators and microsystems. The miniaturization of a complete microsystem represents one of the greatest challenges to the field of MEMS. Reducing the cost and size of high-performance sensors and actuator scan improve the cost performance of macroscopic systems, but the miniaturization of entire high-performance systems can result in radically new possibilities and benefits to society.

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