International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347-6435(Online) Volume 3, Issue 1, July 2014)

Five Decades of Innovations in MEMS Technology

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Abstract- **Micro Electro Mechanical Systems (MEMS) encompass the process-based technologies used to fabricate tiny integrated devices and systems that integrate functionalities from different physical domains into one device. The products range in size from a few microns to millimeters and have the ability to sense, control and actuate on the micro scale and generate effects on the macro scale. MEMS have been found in systems ranging from consumer electronics, automotive, medical, communication to defense applications. Here, a brief review is presented on the established technologies in MEMS and the upcoming new innovations in the field. Also, the materials used in MEMS are getting more and more adventurous and an overview of the current research ongoing in this area is presented. Issues regarding commercialization and technology are minimally discussed. Concluding remarks are based on the future of the MEMS technology.**

Keywords- MEMS.

I. Introduction

MEMS encompass the process-based technologies used to fabricate tiny integrated devices and systems that integrate functionalities from different physical domains into one device. Such devices are fabricated using a wide range of technologies having in common the ability to create structures with micro-scale and even nano-scale accuracies. The products range in size from a few microns to millimeters. These devices have the ability to sense, control and actuate on the micro scale and generate effects on the macro scale.

The interdisciplinary nature of MEMS relies on 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 seen in the extensive range of markets and applications that incorporate such devices. MEMS can be found in systems ranging from consumer electronics, automotive, medical, communication to defense applications.

Current examples of MEMS devices include accelerometers for airbag sensors, microphones, projection display chips, blood and tire pressure sensors, optical switches, and analytical components such as lab-on-chip, biosensors and many other products.

Here, a review of the established technologies is discussed followed by the recent innovations in the MEMS industry.

II. A Brief Background And Applications

A. 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 transmitted by a change in voltage. An electronic control unit subsequently sends a signal to trigger and explosively fill the protective airbag.

Initially, 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 less than a dollar. The accelerometer is essentially a capacitive or piezoresistive device consisting of a suspended pendulum proof mass/plate assembly. As acceleration acts on the proof mass, micro- machined capacitive or piezoresistive plates sense a change in acceleration from deflection of the plates.

The airbag sensor has been pivotal to the success of MEMS and micromachining technology. With over a hundred million devices in production and sold in the last 15 years. It is worth noting that such devices are operating within such a challenging environment as is found within a vehicle, proving the reliability of the technology.

An example of this success is witnessed in some of today's vehicles which have over 75 MEMS devices including anti-lock braking systems, active suspension, appliance and navigation control systems, vibration monitoring, fuel sensors, noise reduction, rollover detection, seatbelt restraint and tensioning. As a result, the automotive industry has become one of the main drivers for the development of MEMS often leading the way for other equally or even more demanding environments.

B. Medical pressure sensor

As in the case of the MEMS airbag sensor, the disposable blood pressure sensor has been one of the strongest MEMS success stories to date. These sensors connect to a patient's intravenous (IV) line and monitor the blood pressure through the IV solution. For a fraction of their cost ($2), these devices replaced the early external blood pressure sensors that cost over $600 and had to be sterilized and recalibrated for reuse. Such expensive devices measure blood pressure using a saline-filled tube and diaphragm arrangement that had to be connected to an artery with a needle.

The disposable sensor consists of a silicon substrate which is etched to produce a membrane and is bonded to a substrate. A piezoresistive layer is applied onto the membrane surface near the edges to convert the mechanical stress into an electrical voltage. Pressure corresponds to the deflection of the membrane. The sensing element is mounted onto a plastic or ceramic base with a plastic cap placed over it, designed to fit into a manufacturer's housing. A gel is used to separate the saline solution from the sensing element.

C. Inkjet printer head

Probably the most successful MEMS product up till now 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. Thermal inkjet print-heads are the most generally used type for home and small office printing equipment. The piezoelectric principle is often used for industrial scale printing.

Invented in 1979 by Hewlett-Packard, MEMS thermal inkjet printer head technology relies on the thermal expansion of the ink vapour. Within the printer head there is an array of tiny resistors acting as heaters. These resistors can be fired under microprocessor control with electronic pulses which are usually less than 3 microseconds.

Ink flows over each resistor, which when fired, heats up, 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. When the bubble collapses, a vacuum is created which pulls more ink into the print head from the reservoir in the cartridge. It is worth noting there are no moving parts in this system (apart from the ink itself).

A piezoelectric element can also be used to force the ink through the nozzles. In this case, a piezoelectric crystal located at the back of the ink reservoir of each nozzle receives a very small electric charge causing it to vibrate. When it vibrates inwards it forces a tiny amount of ink out of the nozzle. As the element vibrates back out, it pulls some more ink into the reservoir to replace the ink that was sprayed out. Epson patented this technology but it is also used by other companies.

MEMS have enabled more and more heating elements and piezoelectric crystals to be incorporated into a printer head. Early printers had 12 nozzles with resolutions of up to 92 dpi. Today they can have up to 600 nozzles which can all fire a droplet simultaneously enabling 1200 dpi at high speed.

D. Overhead projection display

Texas Instruments (TI) was the pioneers in developing DLP (Digital Light Processor) MEMS products. The DLP's micromirrors are mounted on small hinges that enable them to be tilted either toward the light source or away from it creating a light or dark pixel on the projection surface. The 1024×768 array of aluminium micro-mirrors are fabricated over 5-transistor SRAM driver cells. The individual mirrors are 12.7 μm widths on a 13.7 μm pitch. The device is packaged in a solidly built hermetic glass/metal/ceramic assembly, complete with a substantial heat slug and internal getter strips. The MEMS devices are constructed from five layers of metal, three for the CMOS circuitry, and two for the MEMS structure.

E. Gyroscopes

Gyroscopes are used to sense rotation with respect to a reference system. Most of the systems on the market use vibrating elements. When the system is rotated, the vibrating element experiences the Coriolis acceleration effect, which causes a secondary vibration orthogonal to the original vibrating direction. The sensors can be made either by bulk or surface micromachining. Their smaller size and lower fabrication cost make them very attractive for other market segments, notably consumer electronics.

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Gyros are an integral part of all aeronautical control systems for the attitude and rotational rates for navigation. They also have military uses: missiles guidance, navigation and smart munitions. MEMS gyros are witnessing especially high growth opportunities in high-volume applications such as automotive (e.g., vehicle stability control, rollover detection) and consumer (e.g., computer input devices, camcorder stabilization) applications

F. Microphones

The first MEMS based microphones were developed in the eighties, but commercial success was difficult to achieve due to it being a replacement product. The new devices had to compete with very well entrenched traditional products such as the Electret condenser microphone which is inexpensive ($0.50 or less) and shows a good performance in terms of frequency response and sensitivity. However, as MEMS microphones have the advantage of better temperature resistance, they are therefore better suited for a highly automated assembly line; in contrast to the Electret condenser microphone, which have to be soldered by hand. Other advantages include the option of integration with electronics and the ability to fabricate arrays into one chip. The main application areas for such devices include digital cameras, mobile phones, electronic note books/pads, hands free sets of mobile phones in cars. Clearly hearing aids is also an important application area.

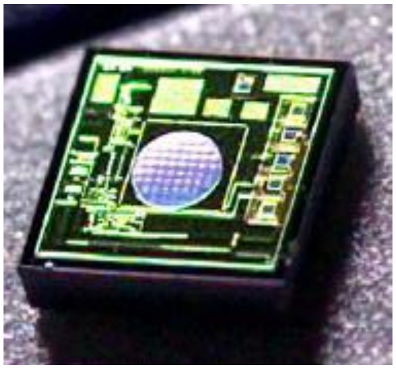

Fig1. Schematic cross section of a MEMS microphone

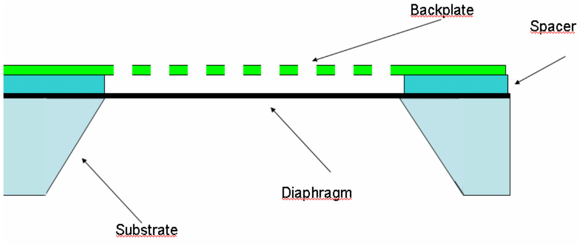

Fig 2. MEMS microphone (As seen in Akustica)

The MEMS microphones are fabricated on the surface of a silicon wafer, as seen in Fig 1. A membrane layer is deposit on a silicon wafer on which a spacer layer is deposited and used to separate this diaphragm from the back plate. By a combination of bulk and surface micromachining the membrane is released, so it can vibrate freely with incoming sound. The changing capacitance of the charged capacitor formed by the back plate and diaphragm transforms the sound signal into an electrical signal Fig 2.

III. Recent Innovations In The MEMS Market

The experience gained from these early MEMS applications has resulted in an enabling technology for new biomedical applications (e.g. Lab on Chip) and optical or wireless communications, also referred to as respectively Micro Opto Electro Mechanical Systems (MOEMS), and Radio Frequency MEMS (RF MEMS).

A. Lab-On-Chip

Biochips are biological microchips that host reactions between DNA, proteins, chemical and biological reagents on glass, silicon or plastic plates in order to extract information. The main advantages of Lab on Chip components include ease-of-use, speed of analysis, low sample and reagent consumption and high reproducibility due to standardization and automation. As is clear from the term Lab on Chip, the goal is to place the entire process of a laboratory onto a single chip. Microfluidic systems therefore typically contain silicon micromachined pumps, flow sensors, microchannels, microreactors and chemical sensors.

They enable fast and easy manipulation and analysis of small volumes of liquids. The ability to receive test results in a few hours or even minutes, rather than a week or so, will make a vast difference in diagnosis and treatment, but also in the patient's well being. There are three main application areas for Lab on Chip: medical diagnostics, clinical diagnostics and life science research.

B. MOEMS (Micro Electro Optical Mechanical Systems)

Optical communications has emerged as a practical means to address the network scaling issues created by the tremendous growth in data traffic caused, in part, due to the rapid rise of the use of internet. The most significant MOEMS based products include, variable optical attenuators, optical switching units and tuneable filters. Their small size, low cost, low power consumption, mechanical durability, high accuracy, high switching density as well as the low cost batch processing of these MEMS-based devices make them a perfect solution to the problems of the control and switching of optical signals in telephone networks.

C. RF MEMS

Initially most of the RF MEMS research went in to relays and switches. Low power loss and the ability of integration with each other or with other electronic components on one chip made them likely candidates for early commercialization. It was however an oscillator achieving the status of the first RF MEMS mass product. This micromachined product vibrates at a specific frequency due to external excitation. The benefits over the traditional quartz oscillators are: cost, size, power consumption and ability to provide multiple frequencies. The main application areas are in electronics which include digital camera, camcorders, USB sticks, MP3 players etc. Other RF MEMS products also promise to offer substantial improvements over semiconductor solutions in the areas of signal loss, isolation, signal purity, and design simplicity.

RF MEMS constitute one of the fastest growing areas in commercial MEMS technology. RF MEMS are designed specifically for use within the electronics in mobile phones and other wireless communication applications such as radar, global positioning satellite systems (GPS) and steerable antennae. The main advantages gained from such devices include higher isolation and therefore less power loss and an ability to be integrated with other electronics. MEMS has enabled the performance, reliability and function of these devices to be enhanced while driving down their size and cost at the same time.

The comb drive resonator, one of the basic structures used in RF MEMS is shown below Fig 3.

D. IR sensors

Infrared sensors are devices which can be used to measure the temperature of an object by detecting electromagnetic radiation.

Thermopile: based on a junction of two metals having a large thermo electric power and opposite polarities. They are generally used for low price applications in white goods like ovens, medical: thermometers, automotive: cabin control etc., and in air conditioners and ventilation units.

Microbolometer: based on temperature dependent resistive layer, they are more sensitive compared to thermopiles, but also more expensive. In the form of arrays they can be used in medical diagnostics and security monitoring.

Pyroelectric detectors: based on polarized material, changing its polarization according to the temperature, they are relative low cost devices and used often as motion sensors.

What they have in common technology wise is the need for thermal isolation of the sensor area from the surrounding. Therefore the sensors are normally positioned on top a membrane, which can be constructed by bulk- or surface micromachining.

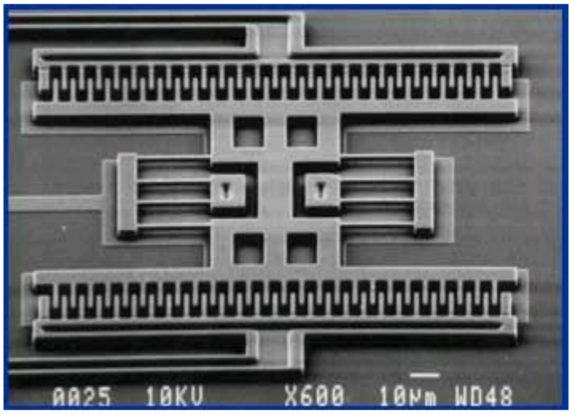

Fig 3. Combdrive resonator (As seen in Discera)

E. MEMS artificial retina

The MEMS artificial retina consists of an electrode microarray that is placed on the retina inside the eye. This microarray interfaces with external components like a camera and a microprocessor, which are contained in the patient's glasses, and the brain via the optic nerve.

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The camera image is converted into a series of electrical pulses that are sent to the brain from the microarray via the optic nerve. The brain translates these pulses into flashes of light for a low resolution image. This technology offers a promising future for the blind and those affected by total/partial loss of sight due to the degeneration of retinal cells.

F. Sensium digital bandage

Toumaz Technology is taking things a step further with its Sensium digital bandage[Figure 4], which can interface with and switch between three different sensors (e.g., a tri-axis accelerometer, blood glucose sensor, pH sensor, pressure sensor, and/or electrocardiogram), although it can only measure one parameter at a time. Even more intriguing is the use of a printed zinc battery, which has a 5-7 day lifespan.

G. Micromachined Probes

Scanning Probe Microscopes (SPM) are used to measure properties of surfaces. They include Atomic Force Microscopes (AFM) and Scanning Tunnel Microscopes (STM). Initially they were used just to measure surface topology, but nowadays a plethora of properties can be measured, including electromagnetic and electrochemical attractions. All SPM's techniques use a sharp needle which is mounted on a cantilever. This cantilever deforms according to the forces on it from the surface to be measured. The deformation of the cantilever is detected by piezoresistors on top of it or by optical means. Probes are often constructed by etching silicon using the same bulk micromachining etching technology as for instance pressure sensors and microsieves. As this is a well know batch process, those probes can be fabricated cost effectively. They can be coated to make them application specific, like for instance coating the tip specifically with a magnetic layer.

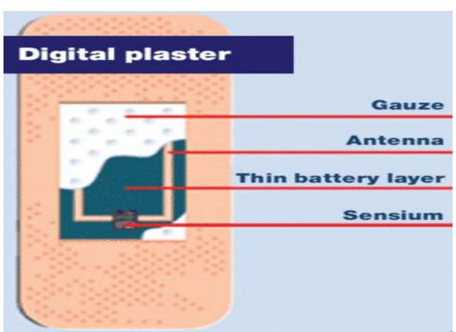

Fig 4. Digital Bandage (As seen in Toumaz Technology)

IV. MEMS Materials – A New Look

In this section we look at how the innovative use of materials is opening the door to applying existing MEMS device technology in new ways. Few companies have successfully commercialized MEMS switches. There are a number of reasons why, but perhaps the issue lies in the choice of material used. Maybe silicon isn't the answer—so, how about plastic switches instead?

Researchers at Tokyo have revealed the development of thin, flexible sheets of plastic that can transmit electrical energy to nearby objects, without the need for direct electrical contact. Even more interesting is the fact that one layer of this plastic material is an array of plastic MEMS switches; the other layers consist of inkjet-printed organic insulating and semiconducting materials, as well as metal nanoparticles (which act as transistors). This certainly offers some very potential possibilities, most notably for wirelessly powering consumer electronics, smart appliances, sensors, and other similar devices within the home (Fig.5).

Another remarkable research in this field has been the tiny micromachined magnets created by the researchers at NIST. These tiny micromachined magnets have a physical shape that provides for a precisely tunable RF signal, and thus creates images simply by moving water through and around the structures. Even more interesting is the fact that the signals can be converted into color. Each micro-magnet consists of two round, vertically stacked discs a few microns in diameter and separated by an air gap. The magnetic field for each micro-magnet can be customized by changing the material, adjusting the gap between the discs, or changing the discs' thickness or diameter.

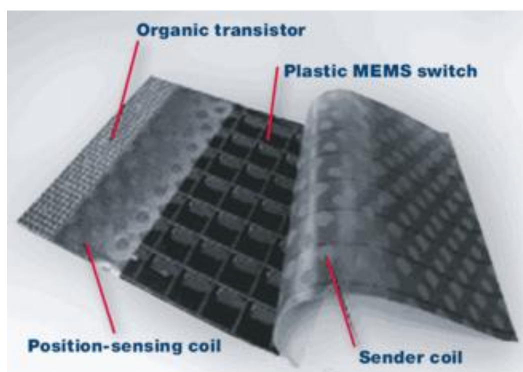

Fig 5. Various materials seen in a MEMS system. (As seen in U. of Tokyo)

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V. COMMERCIALISATION AND INDUSTRIALISATION

For many MEMS products, the ability to integrate with other electronic components is a major advantage. Such a capability will lead to increased performance due to savings in power consumption and increased performance, both associated with shorter lengths of interconnections. This will also lead to a decrease in assembly cost.

Over the years MEMS products have been transformed from relatively simple components for special applications to complex CMOS integrated devices for demanding, high volume, applications. Associated with the choice of a technology platform for a specific product, is a basic question, namely: Whether to adopt a hybrid design concept (CMOS and MST structure on separate dies), or rely on monolithic integration (CMOS and MST structures on one die)

Pros of the monolithic approach include:

- Fewer assembly steps.
- More compact designs.
- Lower parasitic loads of interconnects, often leading to optimal (sub-)systems characteristics.
- Mechanically more robust.
- Easier to protect against electromagnetic interference.
- Exploiting existing high volume capital infrastructure rather than building a specialized line.

Cons of the monolithic approach include:

- The development of the processing technology is time consuming and costly.
- For volume production the wafer processing is relatively costly.
- Only a few fabs offer this approach as an open access foundry service, compared with the realm of specialized open foundries for the hybrid approach, i.e. less choice, and less opportunity for second sourcing.
- Constraints on either the MEMS processing and/or the circuitry processing, often leading to less-than-optimal (sub-) component characteristics.
- Requires, in general, a larger design and simulation effort compared with the hybrid approach.

VI. TECHNOLOGICAL ISSUES

In order to successfully manufacture MEMS devices, basic physics and operating principles need to be fully understood and appreciated at both a macro and a micro level.

In essence, scaling is often not straightforward. Sometimes little advantages in terms of performance, size/weight, reliability and cost can be gained with a MEMS device. Increased surface area(S)-to-volume (V) ratios at micro scales has both considerable advantages and disadvantages.

Some of these micro-level issues include the following:

- Friction is greater than inertia. Capillary, electrostatic and atomic forces as well as friction can be significant.
- Heat dissipation improves with smaller dimensions, contrary to heat storage; consequently thermal transport properties could be a problem or, conversely, a great benefit.
- Fluidic or mass transport properties are extremely important. Tiny flow channels are prone to blockages but can conversely regulate fluid movement.
- Material properties (Young's modulus, Poisson's ratio, grain structure) and mechanical behavior (residual stress, wear and fatigue etc.) may be size dependent.
- Integration with on-chip circuitry is complex and device/domain specific.
- Miniature device packaging and testing is not straightforward. Certain MEMS sensors require environmental access as well as protection from other external influences. Likewise, many devices are fragile or sensitive to external influences.
- Testing is not rapid and is expensive in comparison with conventional IC devices.
- Cost for the successful commercialization of a MEMS device, needs to leverage the IC batch fabrication resource and be mass-produced. Hence mass-market drivers must be identified to generate the high volume production.

Miniaturization and cost are strongly related, especially for products made with wafer scale technologies. Basically, the smaller the device real estate area, the more devices one can place on a wafer, the lower the processing cost per die (assuming the processing cost per wafer remains the same). This principle led to a continuous drive towards the miniaturization of the MEMS products, as is for instance seen at accelerometers.

It must be stated that reduction in size is achieved by both a reduction of the package thickness and savings on surface area on the wafer.

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As an accelerometer consists of more than just a MEMS structure, the question arises on how this relates to the sharing between the MEMS and the CMOS of the available/usable real estate on the wafer. In practice, it turns out that the MEMS structure has shrunk over the years, although it hasn't shrunk as much as the surrounding electronics.

VII. CONCLUSION

The future of MEMS is integrally linked to market trends in general and driven by the increasing demand to monitor and control our environment and the equipment and instruments we use in our daily lives. This demand does, undoubtedly, lead to the need for more sensors in cars, more sensors in industrial equipment and installation and, more sensors for our ambient intelligence. In order to avoid the need for a multitude of wires, such sensors must be self sustaining and able to communicate wirelessly. As a result, not only more sensors are needed, but also small energy generating modules and wireless transmission components. Clearly, the increased numbers of devices will drive size reduction which in turn will enable higher levels of integration.

Studies also show that there is an increasing trend to spend on health care, due to the growing numbers of elderly people in developed countries and a growing medical and pharmaceutical infrastructure in developing countries. There is also a trend to transfer diagnostics from the central analytical laboratory to a surgeries or clinics that are smaller and closer to the patients. This fuels a growing demand for small and affordable devices for diagnostics, especially for point of care diagnostics.

In addition, national security is of increased importance related to the growing fear from terrorist attacks and outbreaks of infectious human or animal diseases. This drives a need for small multi parameter instruments to test air, water blood etc. for microbiological threats.

Simultaneously, there are some general technical trends which will influence the MEMS industry. In the first place the, long awaited, ending of the Moore's law will lead to an increasing attention in the IC industry for other ways to improve the performance of ICs. There is also a tendency to explore more flexible and more affordable production technologies. This will be driven by the production research into typical low cost, large surface area devices like solar cell, displays, wearable electronics and disposable diagnostics devices. Last but not least, a plethora of products will come from the large amount of nanotechnology research investments; in many cases MEMS will act as an interface between the nano and human size world.

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