iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 4 **Issue:** IV **Month of publication:** April 2016

DOI:

Volume 4 Issue IV, April 2016
ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

MEMS Technology: Revolution of Electronics World

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Abstract: In last decades, micro-electromechanical systems is identified as one of the most promising technologies in the field of electronics and mechanical engineering which has the potential to revolutionize both industrial and consumer products by combining silicon-based microelectronics with micromachining technology. Its optimization techniques and micro system-based tiny devices have the potential to dramatically affect of all of our lives and the way we live. This paper will attempt to present a perspective on development & construction of MEMS devices and their operating principles.
Keywords: MEMS, LIGA, pressure sensor, surface micromachining, wafer bonding etc.

I. INTRODUCTION

Microelectromechanical systems (MEMS) refer to the collection of micro sensors and actuators that can sense its environment and have the ability to respond to the changes in that environment with the help of microcircuit control. For desired sensing and actuating functions, the system uses conventional microelectronics packaging, integrating antenna structures for command signals into microelectromechanical structures. For the proper functioning of the system it requires micro-power supply, micro-relay, and micro-signal processing units. The advantages of micro-components are to make the system faster, less bulky, reliable, cheaper, and capable of integrating more complex functions. In the beginning of 1990s, MEMS technology is emerged with the benefit of the development of integrated circuit (IC) fabrication processes, where sensors, actuators, and control functions are co fabricated on same silicon wafer. Since then, remarkable research progresses have been achieved in MEMS under the strong financial promotions from both government and industries. Considering the commercialization of less- integrated MEMS devices, like micro accelerometers, head of inkjet printer, micro mirrors for projection, etc., many researchers have been proposed the concepts and feasibility of more complex MEMS devices and demonstrated for the applications in many fields such as micro fluidics, aerospace, biomedical, chemical analysis, wireless communications, data storage, display, optics, etc [1,2]. Micromachining has become the fundamental technology for the fabrication of MEMS devices and miniaturized sensors and actuators. The most advanced of the micromachining technologies is silicon micromachining which allows the fabrication of MEMS in the submillimeter range. It refers to fashioning microscopic mechanical parts out of silicon substrate or on a silicon substrate, making the structures three dimensional and bringing new principles to the designer, silicon micromachining has been a key factor for the vast progress of MEMS in the last decade. This refers to the fashioning of microscopic mechanical parts outside of the silicon substrates and, more recently, other materials. It is used to fabricate such features as clamped beams, membranes, cantilevers, grooves, orifices, springs, gears, suspensions, etc. These can be assembled to create a variety of sensors. Recently, the Japanese exhibited a complete functioning micro machined automobile that operated for several minutes. The most commonly used method of micromachining is the bulk micromachinings, which is being replaced by surface micromachining that offers the variety of possibility of integrating the machined device with microelectronics that can be patterned and assembled on to the same silicon wafer[8]. Thus the ASICs can be incorporated for the implementation of power supply and signal processing circuitry. This proves the capability of fabricating several such complete packages using existing technology that makes this an attractive approach.

II. MEMS APPLICATIONS

A. Automotive airbag sensor

One of the first and wonderful commercial applications of MEMS is the automotive airbag sensors. They are in widespread use today in almost all vehicles in the form of a single chip consisting of a smart sensor, or accelerometer, which measures the rapid deceleration of a vehicle on hitting an object. The deceleration is sensed by means of change in voltage. An electronic control unit subsequently sends a signal to give the input signal and explosively fill the airbag. Initialilly the conventional mechanical ‘ball and

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ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

tube' type devices are used in air bag technology which were relatively complex, weighed and costly. They were usually mounted in the front of the dashboard of the vehicle with separate electronics system near the airbag. MEMS has enabled the same function to be performed by integrating an accelerometer and the electronics into a single silicon chip, resulting in a tiny device that can be placed within the steering wheel column and hence reduces the costs(Figures 1 and 2). The accelerometer is a capacitive or piezoresistive with a suspended pendulum proof mass/plate assembly. As acceleration acts on the proof mass, micromachined capacitive or piezoresistive plates sense a change in acceleration from deflection of the plates.

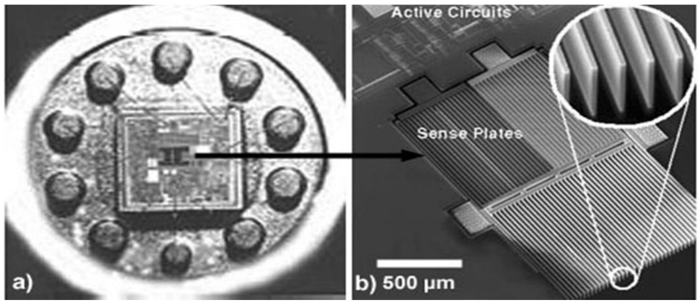
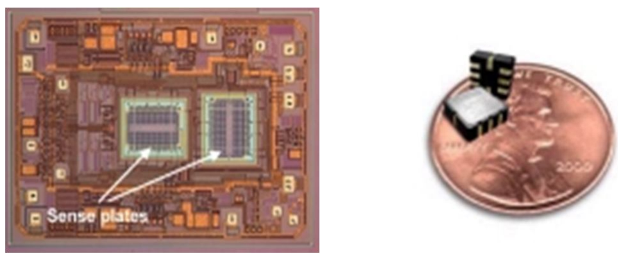


Figure (1) The first commercial accelerometer from Analog Devices (1990); its size is less than 1 cm 2 (left) [12], and (b) capacitive sense plates, 60 microns deep (right) [13].

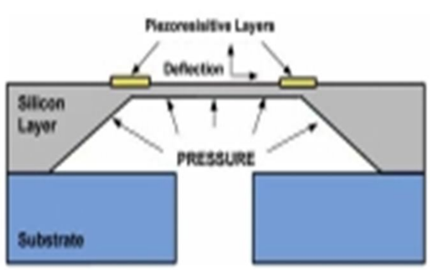


Figure(2). Modern day MEMS accelerometer (left), and the fully packaged device (right) [12].

The best example of this success is today's vehicles i.e. BMW 740i car has over 70 MEMS devices including anti-lock braking systems(ABS), active suspension, appliance and navigation control systems, vibration monitoring, fuel sensors, noise reduction, rollover detection, seatbelt restraint and tensioning etc. [1, 2]

B. Medical pressure sensor

Another good example of an extremely successful MEMS application is the miniature disposable pressure sensor for the monitoring of blood pressure. In this the sensors are connecting to a patient's intravenous (IV) line and monitor the blood pressure through the IV solution[9]. For a fraction of their cost ($10), they replace the early external blood pressure monitoring system that costs over $600 and had to be sterilized and recalibrated every time when 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.



A disposable sensor consists of silicon substrate which is etched to produce a membrane is used for this purpose and is bonded to a substrate. Near the edges a layer of piezoresistive material is applied on the membrane surface to convert the mechanical stresses into an electrical voltage. Now the deflection of the membrane corresponds to Pressure. The sensing element is mounted on a plastic or ceramic base with a plastic cap over it, designed to fit into a manufacturer's housing (Figure 3). A gel is used to separate the

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saline solution from the sensing element.

Figure (3) Disposable blood pressure sensor connected to an IV line ,(b) disposable blood pressure sensors (as shipped) , and (c) intracardial catheter-tip sensors for monitoring blood pressure during cardiac catheterisation, shown on the head of a pin.

C. Inkjet printer head

Another most successful MEMS applications is the Inkjet printer head.. It uses a series of nozzles to spray drops of ink directly on to a printing medium. The droplets of ink are formed either thermally or piezoelectrically, depending on the type of inkjet printer. The first inkjet printer was invented in 1979 by Hewlett-Packard, the thermal expansion of ink vapour is used in MEMS thermal inkjet printer head technology. An array of tiny resistors known as heaters are placed within the printer head. These resistors can be fired using microprocessor control with electronic pulses of a few milliseconds (usually less than 3 microseconds). The ink flows over each resistor, which then fired, heat up at 100 million o^C/ second, vaporizing the ink to form a bubble[4]. Some of the ink is pushed out from a nozzle within a nozzle plate, when the bubble expands, landing on the paper and solidifying almost instantaneously. A vacuum is created which pulls more ink into the print head from the reservoir in the cartridge when the bubble is collapsed(Figure 4). It is worth noting there are no moving parts in this system illustrating that not all MEMS devices are mechanical.

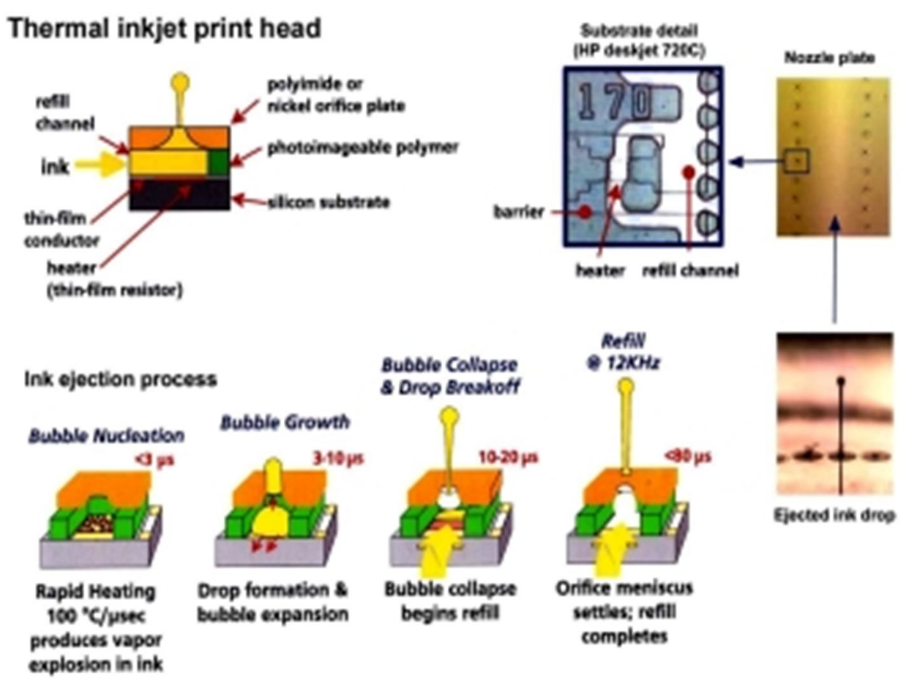

Figure 4: Injet printer head

D. Overhead projection display

One of the latest MEMS devices used for a variety of display applications is the Digital Micromirror Device (DMD) from Texas

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Instruments. This devices contains over a million of tiny pixel-mirrors each of sizes 16 μm by 16 μm which able to rotates by ±10o, over 1000 times per second (Figure 5). The light from a projection source impinges on the pupil of the lens (or mirror) and is reflected brightly onto a projection screen. These are used for displays of PC projectors, high definition televisions (HDTV's) and in digital cinemas where traditional liquid crystal technology cannot compete[6]. MEMS has enabled the micromirrors to be only 1 μm apart, resulting in an image taking up a larger percentage (89 percent) of space on the DMD chip's reflective surface, as compared to a typical LCD (12 to 50 percent). This will help to reduce the pixelation and produces an overall sharper and brighter image. Today over 30 manufacturers use the DMD (Kodak being the largest) and over 500,000 systems have been shipped.

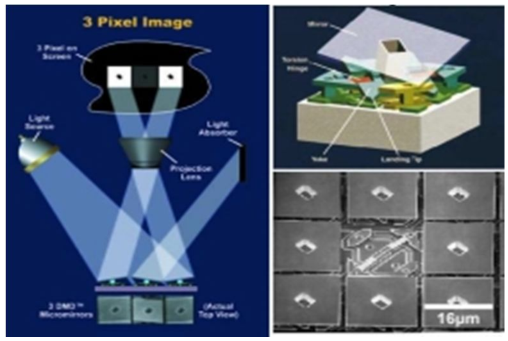

Figure 5. The MEMS Digital Micromirror Device (DMD) [7].

III. MEMS FABRICATION METHODS

The general classification of MEMS fall into three class; bulk micromachining, surface micromachining and high-aspect-ratio micromachining, which includes technology such as LIGA (a German acronym from Lithographie, Galvanoformung, Abformung adapted as lithography, electroforming and moulding).

A. Bulk Micromachining of Silicon

Bulk micromachining is the most widely used silicon micromachining technologies in MEMS. It emerged in the early 1960s and used in the fabrication of different microstructures. Almost all commercial devices are manufactured using this technology. i.e. almost all of pressure sensors, silicon valves and 90 percent of silicon accelerometers. This type of micromachining is used to realize micromechanical structures in the bulk of a single-crystal silicon wafer by selectively 'etching' the wafer, hence the term bulk micromachining. This microstructures may cover the thickness range from submicron to full wafer thickness (200–500 μ m), and the lateral size range from submicron to the lateral dimensions of a full wafer[7]. This technique allows removing significant amounts of silicon from a substrate to form membranes on one side of a wafer, a variety of trenches, holes, or other structures. Bulk micromachining technique can broadly classified according to the phase of etchants as wet etching and dry etching of silicon. Liquid etchants, almost exclusively replying on flowing chemicals, are referred to as wet etching. Vapor and plasma are referred to as dry etching.

B. Surface Micromachining of Silicon

Surface micromachining does not shape the bulk silicon but instead builds structures on the surface of the silicon by depositing thin films of 'sacrificial layers' and 'structural layers' and by eventually removing the sacrificial layers to release the mechanical structures. The dimensions can be several orders of magnitude smaller than bulk-micromachined structures. The majour advantage of surface-micromachined structures is their easy integration with IC components, because the wafer is also the working area for IC elements. It should be noted that as miniaturization is hugely increased by surface micromachining, the small mass structure involved may be insufficient for a number of mechanical sensing and actuation applications.

C. Wafer Bonding for MEMS

The limitations of Silicon micromachining has in formation of complex 3D microstructures in a monolithic format. Thus in order to overcome this, the multichip structures are then proposed for advanced MEMS, in which wafer-to-wafer bonding is critical in the formation [5]. It is classified into three major class: anodic bonding, intermediate-layer bonding-assisted bonding, and direct bonding.

1) *Anodic Bonding:* It is also called field-assisted thermal bonding, electrostatic bonding, etc. Anodic bonding is usually established between a sodium glass and silicon for MEMS. For this, a cathode and an anode are attached to the glass and silicon wafer, respectively, and voltages applied ranged from 200 to 1KV. At the same time, the anode is put on a heater providing the bonding temperature around 180 3⁄4 500 Ž C (Figure 1.4). During the bonding, oxygen ions from the glass migrate into the silicon resulting in the formation of silicon dioxide layer between silicon wafer and glass wafer and form a strong and tight chemical bond. The advantage of anodic bonding is the low temperature used can ensure the metalization layer (aluminum) to withstand this temperature without degradation.
2) *Direct Bonding:* It is also called silicon fusion bonding, which is used for silicon–silicon bonding. Direct bonding is based on a chemical reaction between OH-groups present at the surface of native silicon or grown oxides covering the wafers [7]. The direct bonding usually follows three steps: surface preparation, contacting, and thermal annealing.

D. LIGA Process

MEMS require complex microstructures that are thick and three-dimensional [2]. In order to achieve high aspect ratio (height-to-width), many microfabrication technologies have been developed and 3D devices. LIGA process is one of those microfabrications. LIGA is a German acronym for Lithographie, Galvanoformung, Abformung (lithography, galvanoforming, molding). It was developed in the early 1980s by the research Center Karlsruhe in Germany using X-ray lithography for mask exposure, galvanoforming to form the metallic parts, and molding to produce microparts with plastic, metal, ceramics, or their combinations [5]. With the LIGA process, microstructure's height can be up to hundreds of microns to millimetre scale, while the lateral resolution is kept at submicron scale because of the advanced X-ray lithography. Various materials can be integrated into LIGA process to allow electric, magnetic, piezoelectric, optic, and insulating properties of sensors and actuators with a high-aspect ratio, which are not possible to make with the silicon-based processes. Besides, by combining the sacrificial layer technique and LIGA process, advanced MEMS with moveable microstructures can be built (Figure 6). However, the high production cost of LIGA process because of the fact that it is not easy to access X-ray source limits the application of LIGA. Another disadvantage of LIGA process relies on the fact that structures fabricated using LIGA are not truly three dimensional, because the third dimension is always in a straight feature. As we know that complex thick 3D structures are necessary for some advanced MEMS, it means that other 3D-microfabrication processes need to be developed for MEMS.

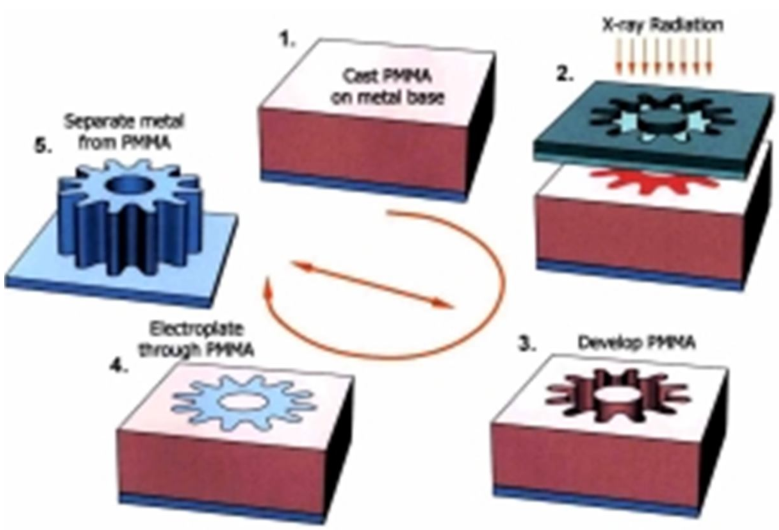

Figure 6. The LIGA process

E. Assembly and System Integration

The MEMS fabrication process essentially uses the same process as the microelectronics industry as shown in Figure 7.

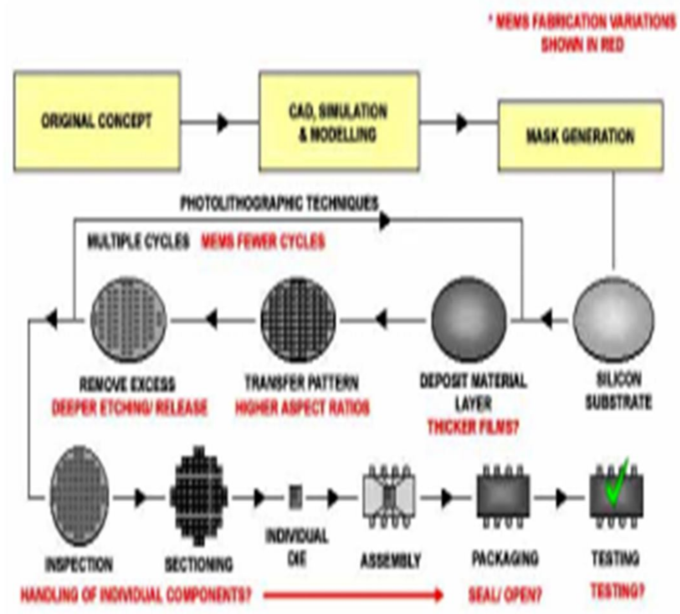

Figure 7. Similarities between IC and MEMS microfabrication processes

Despite the fact that MEMS uses some of the same tools as those used with ICs, the greatest challenge facing the MEMS industry is system integration between the miniature mechanical systems and the electronic interface. For the cost-effective production of MEMS devices it is necessary to combine complex mechanical structures together with microelectronics to form integrated mechanical and electrical systems on a single chip that can be batch fabricated with high yield and no additional or subsequent assembly (Figure 8).

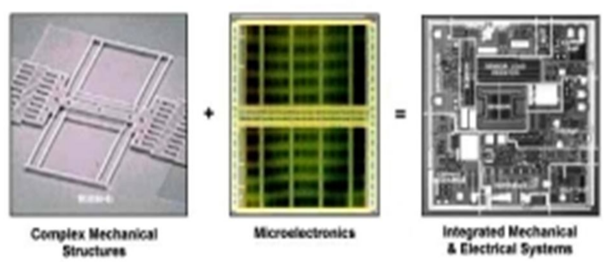

Figure 8. Integration of mechanical structures and microelectronics

Over the years different approaches have been developed for the integration of the electronic interface. These include hybrid integration using conventional wire bonding and flip-chips and monolithic integration. Monolithic integration offers superior system integration performance to hybrid systems but at an overall higher price in terms of involved technology and processing. Monolithic integration can be carried out in three ways:

1) *IC before MEMS:* Monolithic integration by IC first has proved to be successful and relatively cheap; an example is the technology in Texas Instrument's DMD (Figure 5). The process relies heavily on bulk micromachining and the addition of new layers through electroplating. It is a relatively simple integrated system but suffers from residual stresses within the device materials. To date, refractory metals need to be used within the IC components in order to withstand the high temperature annealing cycles required to relieve the stress in structural polysilicon.
2) *Mixed MEMS-IC fabrication:* A typical example of MEMS and microelectronics being fabricated side by side is the airbag accelerometer (Figures 4 and 5). Monolithic processing of this device as well as the reduced number of parts enable a very compact device with high reliability at a very low cost. The trade-off lies within its complexity as this process leads to a very rigid and constrained process flow which is expensive, thus requiring very high volumes.

3) *MEMS fabricated prior to IC:* The most promising monolithic integration technique includes fabricating the MEMS device prior to the microelectronics. Using technology known as iMEMS (Integrated Micro- electromechanical Systems) patented by Sandia National Laboratories, USA, MEMS components are fabricated in trenches on a silicon substrate and then the standard electronics are processed onto the same substrate.
4) *Packaging:* The proper operation of MEMS devices depends critically upon the 'clean' environment provided by the package and is considered an enabler for the commercialisation of MEMS. Packaging of microsensors presents special problems as part of the sensor requires environmental access while the rest may require protection from environmental conditions and handling.

Although there is no generic package for a MEMS device, the package should:

a) provide protection and be robust enough to withstand its operating environment
b) Allow for environmental access and connections to physical domain (optical fibres, fluid feed lines etc.)
c) minimize electrical interference effects from inside and outside the device
d) dissipate generated heat and withstand high operating temperatures (where necessary)
e) minimize stress from external loading
f) Handle power from electrical connection leads without signal disruption.

IV. THE FUTURE OF MEMS

A. *Industry Challenges*

Some of the major challenges facing the MEMS industry include:

1) *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 commercialisation of MEMS.
2) 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.
3) 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 is 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.
4) 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 dollar) investment facilities. However, in 2000, progress in industry communication and knowledge sharing was made through the formation of a MEMS trade organization.
5) 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 centres offering technology-specific programmes with commercial integration, training and technology transfer.

B. The Way Ahead

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 micromachined 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.

V. CONCLUSION

MEMS technology offers wide range applications in almost all fields such as biomedical, aerodynamics, thermodynamics and telecommunication and mechanical engineering. Both application specific devices as well as associated micropackaging system that will allow for the integration of devices or circuits, made with non compatible technologies, with a SOC environment can be fabricated using MEMS. MEMS technology allows permanent, semi permanent and temporary connectivity. The integration of MEMS to present technology will give way to cutting edge technology that will give outstanding functionality and far reaching efficiency regarding space, accuracy precision, cost, and will wide range applications. Describing typical application of MEMS in a hearing instrument application the flexibility and design challenges and various innovative features of MEMS technology is made to understand. In the hearing aid instrument microphone arrays are used to produce directional sensitivity and improve speech intelligibility. The various components and necessary signal conditioning algorithms are implemented in a custom micropackaging that can be implanted inside the ear canal is described.

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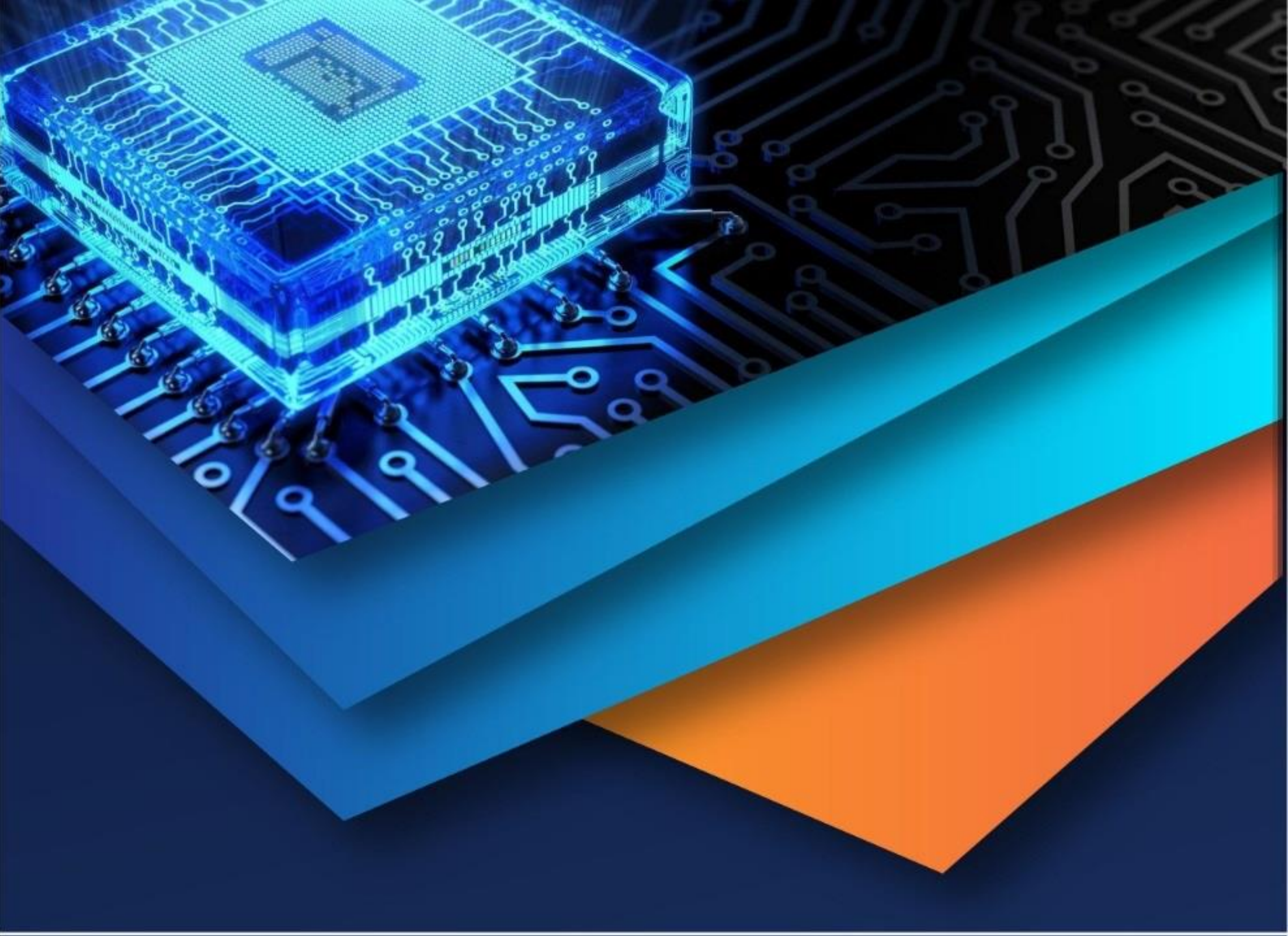

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