Developments in Microelectromechanical Systems (MEMS): A Manufacturing Perspective

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This paper presents a discussion of some of the major issues that need to be considered for the successful commercialization of MEMS products. The diversity of MEMS devices and historical reasons have led to scattered developments in the MEMS manufacturing infrastructure. A good manufacturing strategy must include the complete device plan including package as part of the design and process development of the device. In spite of rapid advances in the field of MEMS there are daunting challenges that lie in the areas of MEMS packaging, and reliability testing. CAD tools for MEMS are starting to get more mature but are still limited in their overall performance. MEMS manufacturing is currently at a fragile state of evolution. In spite of all the wonderful possibilities, very few MEMS devices have been commercialized. In our opinion, the magnitude of the difficulty of fabricating MEMS devices at the manufacturing level is highly underestimated by both the current and emerging MEMS communities. A synopsis of MEMS manufacturing issues is presented here. [DOI: 10.1115/1.1617286]

1 Introduction

The advent of precision three-dimensional micromachining technologies in the last couple of decades has seen the birth of an exciting and potentially revolutionary field called Microelectromechanical Systems (MEMS). Predictions about the far-reaching implications and widespread prevalence of such miniaturized, smart, integrated systems and sub-systems have been made and yet as of today only modest market presence and commercial success has been attained [1,2]. Having arisen out of the silicon IC microfabrication technology in academic and research environment, the initial developments in MEMS were driven mainly by technical curiosity and demonstrability. Like in any emerging field, most of the developments have therefore been a haphazard array of: (i) new fabrication techniques, (ii) new materials, and (iii) new device structures for a host of sensor and actuator applications. However, it is becoming clear that if MEMS were to become commercially viable and successful the industrial and academic communities require tackling some of the daunting technical and commercialization issues impeding the market presence of such systems. In this paper, we will present MEMS overview in light of our efforts of commercializing vacuum pressure sensors for industrial and biomedical applications at Integrated Sensing Systems Incorporated (ISSYS).

The paper begins with a discussion on when and why micromachining techniques should be used. This section also lays out the some of the unique advantages that can be obtained by micromachining including performance and cost benefits. The next section presents a brief description of the popular micromachining processes. A discussion on currently available CAD tools for MEMS applications is discussed next. Section 5 is a discussion on packaging techniques for MEMS devices, section 6 a discussion on reliability testing and compensation issues. Current challenges and advances in this field are discussed these sections. The paper ends with a discussion of the challenges in the manufacturing of MEMS devices in light of the author's efforts in commercializing MEMS pressure sensors.

2 Is Micromachining the Right Solution?

The single most important question that requires to be answered at the onset of any MEMS project is ''Is micromachining the right solution?'' Although no easy checklist for answering this question exists, embarking on a MEMS project without a careful consideration to this question can easily result in a failed effort. Typically there are three cases where micromachined products make obvious sense: (i) MEMS enabled solutions that were hitherto considered impractical or impossible, (ii) leveraging the batch production capabilities of micromachining processes for manufacturing inexpensive micromachined components, and (iii) integrated microsystems capable of system level advantages. A micromachined component is defined as a part that has been realized using silicon microfabrication techniques, which has a high dimensional precision typically in the sub-micrometer scale. An example of a micromachined component is a silicon micronozzle used in ink jet printers. In this case the part (micronozzle) by its ability to drop picoliters of ink in a controlled manner enhances the overall performance of a macroscale printer [3,4]. On the contrary a MEMS product is a complete micro-electro-mechanical system, which can be used as a sensor or actuator by itself. Examples of MEMS products include the micromachined accelerometer from Analog Devices and pressure sensors. MEMS products not only contain a micromachined component but typically include electronic signal conditioning circuit, self-testing and calibration, and are packaged with all the required I/O ports and terminals. MEMS products represent completely autonomous miniaturized systems, which are capable of performing specified sensing and actuation functions in themselves or acts as subsystems in larger products. The eventual success in bringing a MEMS product to market requires the development and realization of inexpensive packaging, reliability testing, and certification of these products in addition to the successful implementation of the micromachined component.

The time to market and the economics of MEMS products are adversely affected by two important facts. First, the backend packaging and testing issues are of paramount importance. Second and more importantly, the fact the entire MEMS manufacturing cycle, from micromachined component fabrication to the assembly and packaging, is highly interactive has caused many serious problems. For example, a simple change in the fabrication process

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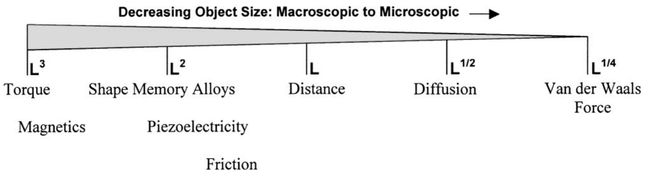

Fig. 1 Size (Linear dimension) dependence of common forces and phenomena

demands that the entire reliability and qualification tests are repeated. This is mainly because at MEMS scale where the thickness of materials is typically a few microns, changes in fabrication processes influence their material and mechanical properties quite significantly. For example the residual stress in degenerately boron-doped Si is typically tensile and 30–40 MPa [5]. A microelectromechanical structure made out of such a doped Si will therefore will have a performance that is slightly different than one made from undoped Si. While such a material modification may be necessary to improve the etch stop selectivity and dimensional tolerance during the release process in anisotropic etchant of Si such as ethylene diamine pyrocatechol (EDP), the change may result in a substantial redesign of the device structure. Additionally, packaging process variations may change the overall MEMS product performance and often necessitate a total redesign of the product.

2.1 Enabling Capabilities of MEMS Devices. The easiest justification of micromachined devices is where they offer solutions that cannot be attained by existing macromachined products and such devices are characterized by their uniqueness [6,7]. The ability to fabricate three-dimensional structures with sub-micron dimensional accuracies and spacings can provide unique solutions [8,9]. Figure 1 show the typical scaling of fundamental forces as a function of linear dimensions. For example a device that relies for its operation on increasing the surface area to volume ratio will greatly benefit from such miniaturization. These situations occur in thermal microstructures, microfluidic material transport, electrostatic devices, etc.

As a specific example let us consider the motivation for the development of capacitive pressure sensors for vacuum applications at ISSYS. Currently available macromachined capacitance diaphragm gages for the measurement of vacuum on semiconductor manufacturing equipment are capable of covering 1000 Torr to 1 mTorr. However, extending their range beyond this pressure is not possible by this approach. For a circular diaphragm of radius a, thickness d, made from a material of Young's modulus E and Poisson's ration σ, the maximum deflection ($y_{\max}$) in the middle of a simply supported diaphragm on the edge when a pressure P is applied is given by [10]

$$y_{\max}=-\frac{3}{16}\frac{Pa^4}{Ed^3}(1-\sigma)(5+\sigma) \qquad (1)$$

For a steel diaphragm 2″ in diameter and 0.002″ thick, the center deflection is 1.5 μm for an applied pressure of 1 mTorr. For a circular diaphragm air-gap capacitor of diameter of 2″, which has a plate separation of 500 μm, the change in electrode spacing due to the application of the 1mTorr results in less than 0.3% change in capacitance at a equilibrium capacitance value of 35 pF. Thus detection of 1 μTorr using such a sensor requires accurate measurement of less than 0.1fF of signal values. Using a high accuracy mill in the manufacturing of the macro-capacitance diaphragm gages, the highest possible accuracy for the capacitance spacing will be ~15 μm which would still only achieve ~1.5% capacitance change for 1 mTorr pressure change. It is therefore evident that using macromachining techniques it not possible to push this technology much further. However, if a micromachined diaphragm was realized using MEMS techniques, it is possible to make diaphragms of the thickness of a few micrometers, diameter of a few millimeters, which can be accurately spaced from the static electrode by a few micrometers. Using the values of the dimensions of the pressure sensors fabricated at ISSYS Inc. and the material properties of bulk silicon for the diaphragm in Eq. (1), we expect a sensitivity of about 0.1% capacitance change for an applied pressure of 1 μTorr at an equilibrium capacitance of ~70 pF [11]. This represents a dramatic increase in the sensitivity of the device and therefore a uniqueness not attained by macroscopically machined devices. An optical picture of a micromachined high vacuum pressure sensor is shown in Fig. 2. In addition, the successful realization of these devices open up new applications such as high-sensitivity altimeters (with potential of 1″ of altitude resolution) and accurate monitoring of arterial blood pressure.

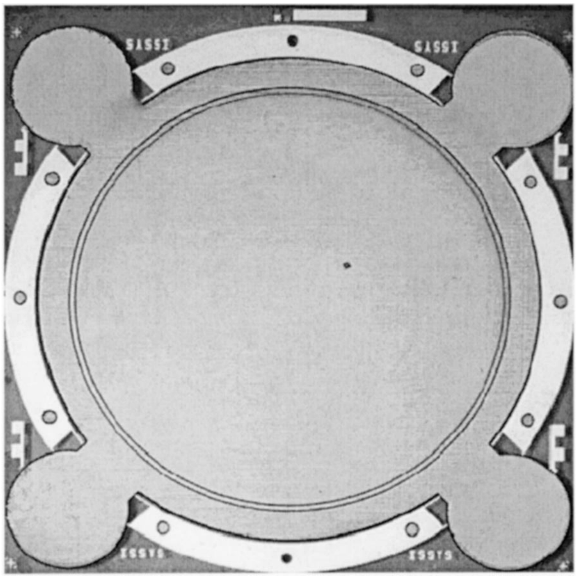

Fig. 2 The top view of the ultra-sensitive, vacuum absolute pressure sensor

2.2 Economics of Batch Fabrication. A second major motivation for miniaturizing devices is the capability of using the economic considerations, which have made IC devices commercially viable. Assuming that the MEMS device offers no specific performance advantage in comparison to an existing product in the market, then the economics of batch fabrication can be a major impetus for the fabrication of such a device. In this case, a careful consideration of the market study coupled with wafer level economics needs to be carried out. A typical deep reactive ion etcher can etch silicon at the rate of ~3 μm/min although etch rates as high as 6 μm/min have been recently reported [12]. At an etch rate of 3 μm/min, a through wafer high-aspect ratio etch of the silicon wafer using a DRIE etcher can take 3–4 hours for a 550μm thick wafer at a cost of ~\$500–1000 per wafer. Such steps can easily determine the final die cost and become the rate limiting step for high-throughput. Figure 3 shows the cost of producing a MEMS chip as a function of the number of wafers (NW) and the number of chips per wafer (NCW). The graph is obtained by assuming a non-recurring development cost (DC) of \$1 Million, wafer production cost (WPC) of \$1000 per wafer and using the formula,

$$\text{MEMS Chip Production Cost}=\frac{\text{DC}}{\text{NW*NCW}}+\frac{\text{WPC}}{\text{NCW}} \qquad (2)$$

Considering that a 4″ wafer contains ~300 chips of size of 5 mm×5 mm, production levels of around 10000 wafers are required to result in MEMS chip production cost of under \$10. This

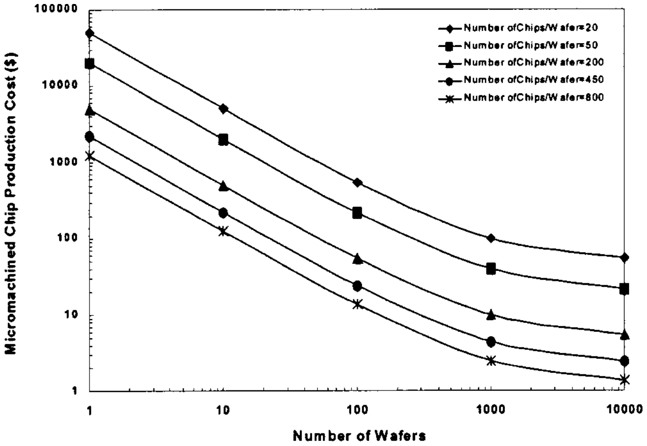

Fig. 3 Cost of production of MEMS chip as a function of the number of wafer and the number of chips per wafer. Further, the following assumptions have been made: Non-recurring Development Cost of $1 Million, and Production Cost/Wafer of $1000.

analysis also assumes that the market size is at least of the size of 3 million units to justify the production of 10000 wafers. These calculations can be easily extended for 5″ and 6″ wafers too which are used in some MEMS foundries. Note the above analysis has omitted any costs for packaging, assembly, and testing which for MEMS devices are estimated in the range of 75–80% of the final product cost. It is important to note that with the exception of very few micromachined devices, the costs of packaging, assembly and testing are rather high and are likely to result in a MEMS product cost of few tens to $100. The high-volume MEMS market has been mainly driven by the automotive industry with airbag accelerometers and manifold pressure sensors. However, in the authors opinion major market players have found it hard to make money from these sensors due to the extremely small profit margins and high-initial development costs. The other end of the spectrum of low-volume high profit margin markets promise MEMS devices a greater probability of commercial success.

MEMS fabrication requires dedicated processes and equipment, which are not necessarily found in a standard CMOS fabrication line. In addition, several of these processes have to be optimized for the electromechanical properties of the thin films and materials rather than their electrical characteristics. For example, the control of stress in deposited thin films of polysilicon and silicon nitride layers plays a major role in the success of a surface micromachined device. Similarly, when silicon dioxide is used as a sacrificial material it should ideally be easy to etch it away (i.e. low quality film) whereas when it is used as a structural material its mechanical and structural properties have to be very carefully controlled for reliable and repeatable device performance. Thus most MEMS foundries are able to offer only a limited spectrum of allowable fabrication processes and materials. Even in these cases the cost of producing MEMS wafers is very high typically $1000/wafer depending upon the process complexity and the required quantity. This coupled with enormous cost of setting up a cleanroom based fabrication facility have deterred many small businesses to succeed in their efforts of commercializing MEMS devices. The cost of setting up a cleanroom can range upwards from $300/sq. ft. for just the cleanroom space and utilities and an additional capital investment of at least a few million dollars to equip it with basic production equipment.

2.3 Integrated Microsystems. One of the main goals of miniaturization through microengineering is to be able to integrate microelectronic circuitry along with micromachined three-dimensional structures, and be able to produce completely integrated microelectromechanical Systems [13,14]. Integrated microsystems offer several advantages as compared to standalone sensors, actuators, or circuits. System level advantages include improved reliability and performance, low capital and ownership costs, and ease of use. In addition, the use of batch fabrication techniques is expected to result in the manufacturing of a large number of such systems at low cost and high reproducibility. Although integrated microsystems are very desirable, considerable technical research and development effort is required prior to the successful realization of such systems. Since the range of applications of microsystems is virtually limitless, the associated problems and solutions in each case are almost always unique and depend upon the specific application and the choice of the transduction technique. Microsystems can be implemented by using either monolithic integration techniques or by using hybrid integration techniques.

In hybrid microsystems, the sensor/actuator structures are located on a separate chip(s) from the electronic circuit chip. The obvious advantage of using hybrid techniques is that the micromachined chip and the integrated circuit chip are fabricated separately, which gives large latitude in the choice of the fabrication processes and materials for each of the chip constituting the microsystem. The main disadvantages are that it generally degrades performance and often adds complexity to the packaging (connectivity) of the overall system. In some cases such as in large imaging or display arrays this technique is completely impractical to implement.

Monolithic integration of microelectromechanical structures with microelectronic circuits can potentially create the most compact and versatile microsystems. In some cases such as imaging arrays it is the only way to implement the required objectives. In addition to the various limitations imposed by the inclusion of a micromechanical structure, monolithic integration of the micromechanical device with microcircuit often adds greater complexity to the design and fabrication process. Since most integrated circuits are fabricated from silicon, this constrains the materials and processes for the micromechanical structure to be compatible with silicon and its processing techniques. Fortunately, silicon turns out to have excellent mechanical properties with Young's modulus and hardness similar to stainless steels at 1/3 its density. In addition, single crystal silicon exhibits three times the yield strength of steel and has no creep or plastic deformation phase. Silicon is also a good thermal conductor. Examples of commercialized integrated MEMS include the digital micromirror array from Texas Instruments, the surface micromachined accelerometers from Analog Devices, and the room temperature bolometer infrared array from Honeywell.

The partitioning of microsystems and the concomitant choice of the techniques and materials used needs to be carefully considered. There are no universal solutions since these must be carefully chosen to fit the desired system requirements. While the specification of the individual parts may be relatively straightforward, once they are brought together into a single package, these specifications tend to affect each other [15]. In effect, the exact package and packaging techniques used influence the performance of the overall system. It is this closed loop iteration between the choice of the various materials, partitions, processes and packaging that makes the development of integrated microsystems such a difficult and challenging task. Slowly, there is starting to emerge some standardization in the design rules for the fabrication processes specifically aimed at microelectromechanical systems.

3 Fabrication Techniques

Microfabrication processes capable of creating three-dimensional structures in silicon were the driving force for the emergence of early MEMS devices. The evolution of these microfabrication processes has led to the classification of major micromachining techniques namely, bulk micromachining, surface micromachining, dissolved wafer process, LIGA, and electro-discharge machining (EDM) [16,17,18,19]. A typical MEMS device can be realized by using any of these processes in their most prevalent form or several variants of these processes can be used. The choice of the fabrication process is very important in that it defines the overall performance and cost of the micromachined part.

3.1 Bulk Micromachining. Bulk micromachining is based on a combination of isotropic and anisotropic etchings of single-crystalline silicon to form micro mechanical structures from the bulk of the silicon wafer [20]. Strongly alkaline liquids such as potassium hydroxide (KOH), tetra-methyl-ammonium-hydroxide (TMAH), ethylene-diamine-pyrocatechol (EDP) etc. preferentially etch the 100 planes of single crystal silicon in comparison to the 111 planes. The difference in these etch rates can be used to create large three-dimensional structures in silicon substrates using standard photolithography techniques in conjunction with good masking layers such as silicon dioxide and silicon nitride layers. However, the etch rate of silicon in these chemicals is of the order of ~ 1 μm/min and therefore takes in excess of 8 hours to etch through a 550 μm thick wafer. Wet etching can be used either from the front side of the wafer, backside of the wafer or from both sides to realize an array of micromechanical structures. In addition, these chemicals are not compatible with CMOS fabrication processes due to the presence of heavy metal and alkali ions. Thus any device process has to be carefully designed to prevent the possibility of contamination. For example, wet anisotropic Si etching can be used after completing CMOS processing for releasing the micromechanical structures so that contamination issues can be avoided [21]. Bulk micromachining based on wet anisotropic etching also prevents efficient use of the silicon real estate since large etch-windows need to be defined on one surface of the silicon wafer to realize relatively small micromechanical structure on the other surface of the silicon wafer. This leads to low device densities and high device cost. The main attraction of anisotropic wet etching arises from the inexpensive capital investment in realizing this process step. For example, KOH etch module including precision temperature control, in-situ filtering and stirring etc. costs under $25,000. In contrast high-aspect ratio, anisotropic etching of silicon using deep reactive ion etchers is not crystal orientation dependent and is capable of etching rates as high as 6 μm/min with load locked cassette to cassette wafer-handling systems. However, such systems cost in excess of a million dollars.

3.2 Surface Micromachining. Surface micromachining, on the other hand, is based on sequential deposition and etching of thin films on the surface of a carrier substrate [22]. One of the big advantages of surface micromachining is that a very slightly modified CMOS process can be used for the realization of the MEMS device. Typical structural materials are chosen from CMOS materials such as polysilicon and silicon nitride while the sacrificial layer is silicon dioxide. The micromechanical structure is released from the substrate by etching away the sacrificial oxide in HF. Initial efforts in surface micromachining were largely affected by the stresses in the structural layers and the release processes. Micromechanical structures upon release in the wet etchant suffered from stiction problems. These problems have been largely solved and complex CMOS based micromachining processes using up to 3-layers of polysilicon have been used to fabricate very complex micromechanical structures such as microgears, micromotors, micromirrors etc [23]. Due to the thickness of the structural layer being limited to a few microns, the one disadvantage of surface micromachining is that micromechanical structures with large mass or dimensions are difficult to fabricate. Such structures are required for the proof mass of accelerometers or in nozzles for inkjet printer heads etc.

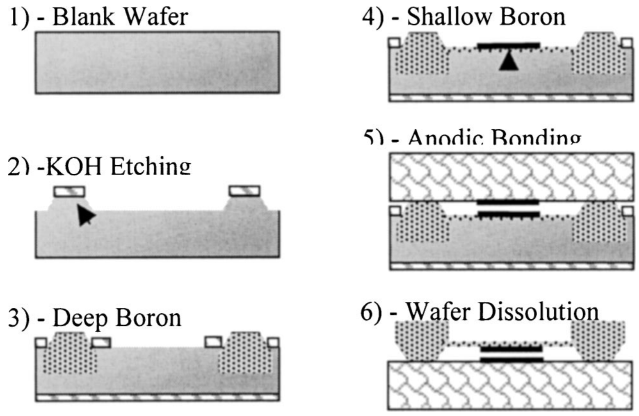

Fig. 4 Schematic diagram of Dissolved Wafer Process

3.3 Dissolved Wafer Process. An innovative process that combines the advantages of both surface and bulk micromachining techniques was developed at the University of Michigan and is called dissolved wafer process [24]. In this process the micromechanical structure is defined in a silicon wafer by boron doping the areas, which will constitute the mechanical structure. In order to create topographical features the silicon is first anisotropically etched and then followed by the doping step. Once the silicon process is complete, the wafer is bonded onto a borosilicate glass (e.g. PYREX™ 7740) wafer. Thereafter, the silicon wafer is dissolved away in EDP etchant leaving behind the boron-doped micromechanical structures on the glass substrate. Boron-doped micromechanical structures fabricated using this technique can range from 2–15 μm in thickness. The main advantage of this process is that the micromechanical structures can be fabricated at high densities and can have higher aspect ratios as compared to surface micromachined parts. In some applications the high dielectric constant of the glass substrate offers additional advantages. Figure 4 shows the schematic diagram of dissolved wafer process.

3.4 LIGA Process. LIGA process has relied upon the use of x-ray lithography to define high aspect ratio structures in photoresist, which are then used as templates for plating and molding processes [25]. Electroplated nickel is typically used for creating molds from the high-aspect ratio photoresist patterns on the silicon wafer and subsequently used to fabricate precision parts. Current developments in LIGA process are geared towards making it more manufactureable and to enable precision microstructures as thick as several mm. More recently thick optical negative photoresists such as SU-8 have become available which can also be used for realizing high-aspect ratio structures. Current developments in the fabrication techniques based upon plating and molding techniques include wet developing process, thermal stress control, materials issues, plating high-strength alloys, etc. The potential benefit is the low-cost manufacturing of microstructures with virtually unlimited choices of structural materials, excellent heat transfer characteristics in the final devices, molds for polymer medical devices, etc.

4 CAD for MEMS

The early success stories of MEMS products such as pressure sensors, accelerometers, micromirror displays etc. required development efforts of several engineers and scientists working over a period of at least 10 years after the demonstration of the R&D prototypes in Universities and Research Laboratories. During this mostly development phase, efforts were typically directed towards producing a reliable, reproducible and high-yield microelectromechanical chip. This period also saw some of the pioneering developments in MEMS related fabrication processes, materials development and characterization for mechanical properties, and foundries that could handle MEMS oriented processes. However, the biggest constraint for rapid prototyping has been the lack of a unified simulation platform, which is capable of accurately predicting the performance of the final device including packaging effects. The lack of such simulation software has led to tedious and time-consuming iterations in device designs, materials, and fabrication processes in turn causing long times to market. However, recent years have seen the development of several CAD simulation softwares capable of simulating the electromechanical performance of MEMS devices.

The scope of such integrated simulation software is very broad and diverse [26]. It must include many engineering disciplines: electrical, thermal, mechanical, optical, electromagnetic, fluidic, chemical and biochemical. Recently, commercial MEMS simulation software such as COVENTORWARE®, INTELLICAD®, MEMSCAP®, etc. have become available [27,28,29]. These softwares are capable of analyzing MEMS devices from mask layout level, including some basic processes as a way to building the microstructure and finally the simulation of their electromechanical behavior using finite element techniques. Process simulation typically involves the conversion of a two-dimensional layout geometry using user defined process information inputted in the form of intended process and material information into a three-dimensional geometry. The shape of the resulting three-dimensional micromechanical structure is derived from this information and serves as the starting point for the finite element simulation of the device. These simulations tend to become very complex once several layers of different materials and geometries are included as part of the simulated structure. In addition, it is very important to realize the limitations of such softwares as the dimensions of the devices become very small. The capabilities of these simulation softwares are still evolving in a rapidly changing environment of evolving MEMS fabrication processes and materials.

Probably the most difficult aspect of simulating MEMS devices is to include packaging effects and effects of the physical interface between the microelectromechanical structure and the environment. Since package is usually an integral part of the device, package and device have to be designed and simulated at the same time. In order to accurately predict the overall performance of such a device, physical and semi-empirical models are incorporated into the software based on widely used processes. However, there is no widespread consensus in MEMS industry on either the fabrication processes or the packaging techniques. The application specific nature of these devices makes it very hard to standardize the materials and processes which in turn has complicated the development of comprehensive CAD programs very challenging.

5 Packaging and Assembly of Microelectromechanical Systems

No MEMS product is complete unless it is fully packaged. At present, packaging is one of the major technical barriers that has caused long development times and high-costs of MEMS products [30,31,32]. Since MEMS device structures are typically very small, stresses and thermal effects, induced in the substrates during the packaging and interconnection steps, can adversely affect their mechanical performance. Thus package strongly affects a MEMS device performance and reliability. It is estimated that MEMS packaging costs are in the range of 50%–75% of the component's total cost. At present MEMS industry leverages largely from the robust and viable infrastructure of the electronics manufacturing industry but direct application of electronics packaging techniques to most MEMS parts is not feasible. Since MEMS devices are used in a variety of applications requiring a very diverse interfacing and performance capabilities, no generic solutions can be proposed. However, in the recent years broad based solutions applicable to specific areas of applications are starting to emerge. These include optical device packaging, wafer level vacuum or hermetically sealed packaging techniques, microfluidic device packaging etc.

Separation of dies and packaging processes begin upon the completion of the fabrication of the devices. Typically backend processes refer to fabrication steps such as dicing, wafer bonding, anisotropic wet etching, coating of functional layers etc. which follow frontend processes such as lithography, high temperature multilayer deposition and etching steps akin to CMOS fabrication processes. MEMS packaging and assembly include all backend, packaging, and handling and assembly processes required to produce a fully functional unit. However in MEMS devices, fabrication and packaging processes are not as clearly partitioned as in the IC industry. There are two major reasons for this: (i) requirement of new MEMS-specific backend processes such as wafer bonding, bulk or through-wafer etching, supercritical release processes, etc., and (ii) it is often necessary to go back and forth between backend and packaging steps to achieve a high yield, low-cost process flow. For example, in an ideal scenario, one would complete the entire micromachining process prior to packaging. However, the presence of freestanding structures on wafers makes a routine packaging step such as wafer dicing nearly impossible and so constrains a process flow to dicing of wafers prior to the final release process (a backend process). This kind of switching the order of backend and packaging process steps is not often as simple as it seems since it has implications on the over all manufactureability of a device. Continuing with the previous example, the final release process may need to be accompanied by a photolithography step where certain areas of the wafer are protected from the release etchant. An R&D prototype in a University or Research Laboratory can be easily demonstrated by performing die-level lithography but such a process would be of no practical value from a manufacturing standpoint. It is these kinds of manufacturing related backend and packaging process issues that have caused lengthy delays and prevented the rapid commercialization of MEMS devices from fabrication standpoint.

Besides fabrication related issues, packaging encompasses several other aspects that have also affected the overall manufacturability of MEMS devices. These include; (i) functional interfacing of the device and their standardization, (ii) reliability and drift issues, (iii) hermetic sealing techniques, (iv) assembly and handling techniques, and (v) modeling issues.

5.1 Functional Interfacing. This is probably the hardest part of packaging a MEMS device. For example, a package needs to be designed in such a way that it allows the desired input signal without any attenuation or degradation while preventing all other negative influences on the device. The problem tends to be somewhat easier for devices such as accelerometers or infrared detectors where the device can be enclosed in a hermetically sealed microelectronic TO-8 style package. This is because, the acceleration or IR input can be easily coupled to the enclosed micromechanical structure though the package. However, packaging for microfluidic sensors such as pressure sensors, chemical sensors, flow sensors etc. can be very complicated [33,34]. Here the microelectromechanical structure needs to directly interface to the environment, which can have detrimental effects on the long-term performance of the device. Isolation of the electrical interconnection leads from environment and protection of the MEMS structure using passivation layers in these cases further increase the complexity of the MEMS device. Although it is impossible to come-up with a standardized MEMS package for all applications, it is feasible to address packaging issues for a broad category of MEMS sensors and actuators. Such standardization will help in the in the development and availability of core packaging capabilities for rapid prototyping and eventually production.

5.2 Hermetic Sealing Techniques. Many MEMS devices such as accelerometers, RF filters, digital micromirror displays etc. require the moving parts to be enclosed in hermetically sealed cavities. The cavity pressure in this case determines the frequency response of the micromechanical structure due to viscous damping effects [35]. Another device that requires a sealed vacuum cavity is an absolute pressure sensor, where the reference cavity needs to be enclosed in ultrahigh vacuum if it is to be used for high vacuum measurements. These high vacuum cavities can be fabricated by using wafer level bonding techniques. However, even if

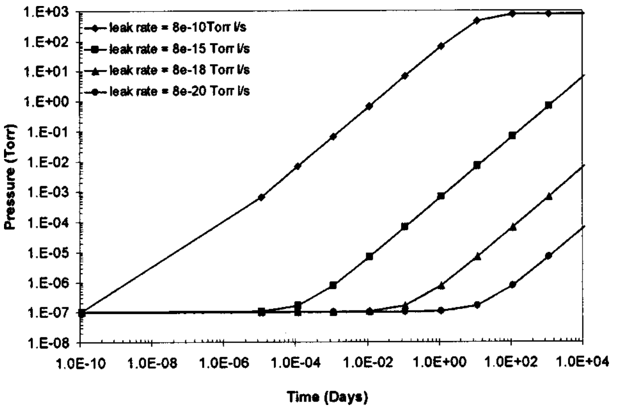

Fig. 5 Calculated increase in cavity pressure as a function of time for a 4 mm×100 μm high hermetically sealed cavity

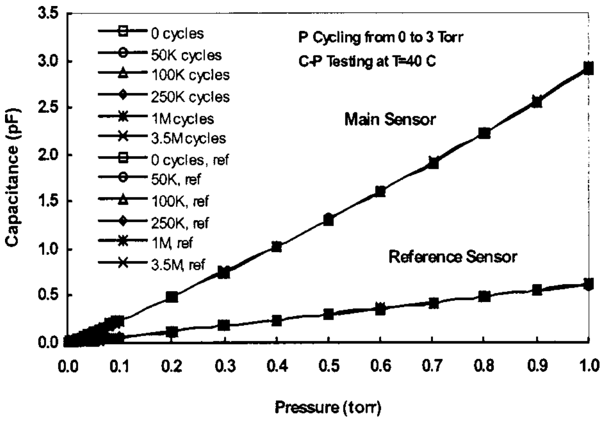

Fig. 6 Performance of the main and reference capacitors measured after 3.5 million cycles shows no detectable variations in the deflection sensitivity of the diaphragm

the bonding process is performed in high vacuum environment, it is found that the pressure in the enclosed cavities is high. This is thought to be due to outgassing effects and the generation of gaseous by-products during the bonding reaction. An even more important problem concerns the maintenance of the high vacuum over the lifetime of the sensors [36]. As can be seen from Fig. 5 to maintain a reference vacuum of 10^{-7} Torr in a micromachined cavity 4 mm in diameter and 100 μm in height, for a period of 1 year or greater, we require the accumulated leak rates (including any outgassing rates) through the bonded joints to be smaller than 8×10^{-20} Torr l/s. This is an extremely small leak rate and impossible to measure using conventional leak-rate detection methods. This situation gets even worse when the bonding is done using polymeric or sealing glasses where the best-obtained leak rates tend to be high compared to anodic bonding. New solutions using active gettering materials inside these enclosed cavities have been proposed. Another major problem associated with enclosed cavities is the ability to transfer electrical leads through them.

5.3 CAD for Packaging. In an ideal case, the package will be included as part of the overall device. This is very important since the both the package materials as well as the package processes will significantly influence the final performance of the device. In order to be able to simulate such a complete structure, prior knowledge of the packaging processes and the semi-empirical models for such materials/processes need to be developed. Recent years have seen the development of some basic CAD capabilities in this direction. Without standardization of packaging materials or their processes this area is still a long way from accurately predicting the overall performance of packaged MEMS devices.

The authors strongly feel that an overall top-down approach where all the processes, materials, handling and assembly, and connectivity have been carefully taken into account greatly increases the chances of commercializing a MEMS product. Packaging a MEMS device, as an afterthought is a recipe for guaranteed failure or very long times to market. CAD is also required for the simulation of the overall reliability of the device and possible compensation algorithms for temperature or ageing related drifts.

6 Reliability and Compensation

There are two major issues related to MEMS reliability. One is the reliability assurance by testing existing structures and the other is by qualifying processes/materials development. For the reliability test, MEMS technologies are new, and thereby introduce many new failure mechanisms that are poorly understood. Accelerated testing tends to be very diverse depending upon the specific application of the device. Often several parameters need to be tested such as resistance to shock, material-ageing effects, stiction related effects in contacting moving surfaces, frictional and wear effects, and effects arising from finite leak-rates. Ideally any long term or short term drifts can be modeled as functions of time, temperature or other external parameters and these behaviors need to be reproducible and repeatable. Under such circumstances, these undesirable but unavoidable effects can be compensated and is one of the major goals of reliability testing.

6.1 Stiction. Almost all MEMS devices experience problems relating to stiction. Stiction is the strong and undesirable attraction between parts in contact and can arise in either during (i) the fabrication of the devices (wet-release processes) and (ii) during operation in devices where the freestanding structure requires making repeated contacts to another surface. These effects are a natural consequence of a very high surface area/mass ratio and the small restoring forces generated in these structures. There are several ways to avoid fabrication based stiction effects, which include the use of low surface tension liquids, and supercritical drying processes. Operation related stiction situations occur for example in the operation of MEMS based micromechanical switches, in micromirror displays etc. New fluorinated materials are now available which might act as good anti-stiction coating and are stable up to temperatures of about 300–500C. Additionally, in the operation of RF MEMS switches considerable damages occur on the switch contacts under repeated use due to phenomena of cold welding, arcing and material wear.

6.2 Accelerated Testing. In order to understand the long-term drift and reliability of the MEMS devices, we require developing accelerated testing techniques to hasten the effects of the failure mechanisms. Once again the diversity of MEMS devices and their applications makes standardization of reliability testing a challenging task. In general, accelerated testing needs to be designed for the testing of the failure mechanisms (i) of the moving micromechanical structures, (ii) arising from the interaction of the micromachined structures to the measurand ambient which can include humidity, temperature, corrosives etc., and (iii) arising from limit testing such as overstressing to determine the failure zones [37]. Often, though the failure mechanisms and their accelerators are not known apriori and so the challenge often is figuring out relevant failure mechanisms for a given life cycle environment and to design an accelerated test that is actually able to accelerate only the relevant mechanisms. For example, ISSYS has performed cycling tests on the pressure sensors to determine the long-term effects of cycling the pressure sensor diaphragm through three times overpressure cycles and measured the sensitivity of the sensors. Figure 6 shows the result of such reliability testing after different number of cycles. It is evident from these results that the single crystal diaphragm is very robust and its mechanical prop-

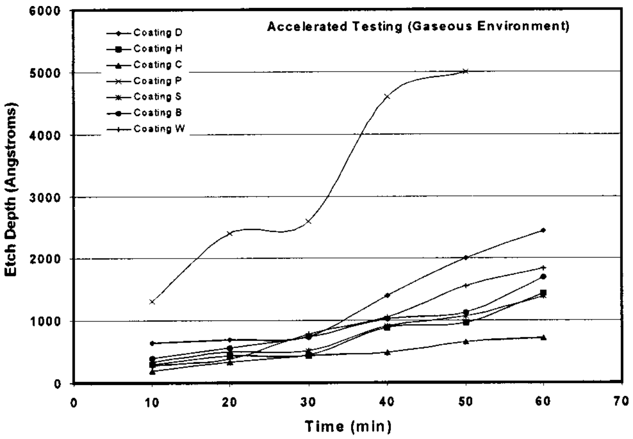

Fig. 7 Evaluation of protective coatings by measuring the etch (corrosion) depths in an accelerated gaseous environment

erties do not seem to change appreciably over millions of cycles. Figure 7 shows the results of accelerated testing of protective coatings being developed for use with these pressure sensors in an accelerated corrosive gaseous environment.

6.3 Qualification. The eventual goal of reliability testing and an important step in the manufacturing of any MEMS device is its qualification. Qualification is the ability to verify (guarantee) whether or not the anticipated reliability is achieved under actual life cycle loads for a specified length of time. The purpose of qualification is to ''verify'' the ability of the design, manufacture, and assembly to meet the reliability goals. For MEMS products, where the paradigm of batch fabrication techniques is to be exploited for the realization of low cost, high performance products, qualification tasks constitute a large part of MEMS product cost and designing high-throughput, rapid testing techniques applicable for a large number of MEMS products remains a challenge. Meanwhile, the final cost of the MEMS device seems to be ultimately determined by the costs of packaging, reliability testing and qualification of the units.

7 Manufacturing MEMS

Figure 8 shows the market projection for year 2003 for MEMS devices by areas of technology. It is anticipated that microfluidics and biological MEMS devices will become very prolific within the next few years. There are rapid developments in the area of RF and Optical MEMS too. The more traditional fields of pressure sensing and inertial MEMS are anticipated to shrink relatively, as their market presence is more mature. A number of new MEMS start-up companies addressing all these areas of applications have sprung-up in the last couple of years. From a manufacturing standpoint it is very important to realize that fabrication is at the core of any MEMS product. Although, there are many other aspects of a MEMS product that would affect the product, such as readout electronics and package, it is the reliability of the micromachined part that determines the overall functionality of the product. Moreover, the best MEMS–based products can achieve is the performance of the micromachined components. MEMS manufacturing technology refers to standardized fabrication processes and design rules which can allow for the design and realization of a variety of micromachined components with high reliability, repeatability, and reproducibility. Currently MEMS manufacturing technology is the most underdeveloped segment of the entire MEMS field [38,39,40,41]. MEMS manufacturing problems demand a great deal of work, time, and money. Therefore, in spite of all the developments in MEMS fabrication technology, from a manufacturing standpoint, there is a great need to refocus on the basics of MEMS fabrication rather than exploring new fabrication technologies and materials. There is no doubt that the emphasis on new fabrication technologies and materials is both exciting and attractive, with a great potential for new devices. However, MEMS manufacturing is currently at a fragile state of evolution that has often jeopardized the successful commercialization of MEMS products. MEMS industry is currently at a much more vulnerable position than it appears, regardless of how wonderful its future may look like. In our opinion, the magnitude of the difficulty of fabricating MEMS devices at the manufacturing level is highly underestimated by both the current and emerging MEMS communities. An important consideration is that although the success of the basic MEMS fabrication processes has been limited, they nevertheless offer a great potential for the mass manufacturing of a variety of products. In other words, the current fabrication technologies and materials are advanced enough to satisfy the needs of the market; they are, however, long way from being mature from a manufacturing standpoint. There is a great need to go back to the basics of MEMS manufacturing fabrication. We will next discuss MEMS from a manufacturing standpoint.

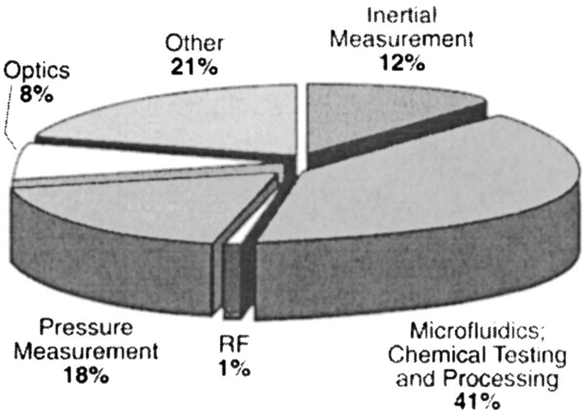

Fig. 8 Projected sales of MEMS devices by technology area. (Courtesy: System Planning Corporation Report 1999).

7.1 Limited Number of MEMS Manufacturers and Products. There are very few companies with real MEMS fabrication facilities at the manufacturing level. As of today, only a handful of MEMS products have been manufactured, primarily, in the areas such as automotive industry, ink jet nozzles, and disposables pressure sensors for blood bag applications. Most of other MEMS products are currently on the bubble of ''to be or not to be.'' Many MEMS companies that have been acquired in the recent months at high price tags by the optical communication companies have neither real products nor ''real'' manufacturing capabilities. According to the CEO's of these communication companies, the MEMS-based companies were acquired based on their perceived potentials (intangibles), and not based on their current states (tangibles). Therefore, one cannot look at these acquisitions as a sign of MEMS manufacturing success. Similarly, there is no manufacturing success story in the creation of many recent MEMS startups; most of the startup companies have money but no real fabrication processes, manufacturing facilities or production expertise. It is worthwhile asking why there are only few MEMS manufacturers, and why the basic MEMS fabrication processes discussed earlier still find very limited manufacturing prevalence.

7.2 MEMS and Microelectronics Processes Are Not the Same. Although MEMS fabrication technologies have evolved from microelectronics fabrication technology, they are not the same [42]. Indeed, MEMS and microelectronics fabrication processes are far from being the same. This fact is evident by the long development times and high costs incurred in the MEMS technology development phase by large companies such as Delphi-Delco, Motorola, Ford Microelectronics, and Analog Devices before the introduction of their MEMS products. The benefits that MEMS leverages from the microelectronics industry usually stop at the facility and equipment level, and in most cases, cannot be expanded to the fabrication manufacturing. Microelectronics fabrication is 2D while MEMS is a 3D process. The mechanical properties that are not important to microelectronics are vital to MEMS fabrication. A CMOS fabrication process is independent of the circuit under manufacturing (product); while a MEMS process must be custom designed for a specific product. At this time, establishing an ASIC paradigm equivalent for MEMS looks increasingly impractical.

7.3 Difficulty of MEMS Fabrication at Manufacturing Level. MEMS fabrication at the manufacturing level is a very difficult task and to a large extent much more difficult than that of microelectronics. For successful commercialization of MEMS products one should consider a few vital factors, including manufacturing yield, process repeatability, product reliability, product cost, and ownership cost of the manufacturing line. Microelectronics fabrication (manufacturing) is recognized as a stand-alone field and as such there is a great deal of effort in understanding its issues and overcoming its problems. As of today, MEMS fabrication (manufacturing) does not exist as a standalone field; rather, it is perceived as a branch of microelectronics fabrication technology. Therefore, there is a lack of organized, and more importantly focused, effort towards its development. Although individual companies have paid attention to these manufacturing related issues, often out of necessity and the expense of a few years, there is a lack of appreciation of these needs at a broader national level. At best there exists a fragmented and incomplete infrastructure for MEMS manufacturing and at worst none at all. All the efforts have so far been at individual company level resulting in reinventing the wheel over and over again.

8 Conclusions

In conclusion, a discussion of some of the major issues that need to be considered for the successful commercialization of MEMS products was provided. The diversity of MEMS devices makes the development of coherent standards nearly impossible. A good manufacturing strategy must include the complete device plan including package as part of the design and process development of the device. In spite of rapid advances in the field of MEMS there are daunting challenges that lie in the areas of MEMS packaging, and reliability testing. CAD tools for MEMS are starting get more mature but are still limited in their overall performance. MEMS manufacturing is currently at a fragile state of evolution that has often jeopardized the successful commercialization of MEMS products. This industry is currently at a much more vulnerable position than it appears, regardless of how wonderful its future may look like. In our opinion, the magnitude of the difficulty of fabricating MEMS devices at the manufacturing level is highly underestimated by both the current and emerging MEMS communities.

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