# Fundamental Aspects of MEMS Packaging

## An Analysis of Material and Design Requirements

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## Abstract

An overview of the technological difficulties facing MEMS packaging engineering is addressed. Fundamental physical requirements of MEMS encapsulation and possible material solutions are examined. Concepts of packaging engineering are discussed along with their economic impacts. Two approaches to MEMS packaging will be addressed and compared based on manufacturability and economic feasibility.

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## 1.0 Introduction

Micro-electromechanical systems, or MEMS, are an emerging technology that may fundamentally affect every aspect of our lives. MEMS are centered on the high-level integration of dissimilar functions from seemingly unrelated branches of science [1]. They are devices and machines fabricated using techniques generally used in the microelectronics industry and used to unify "both energy and matter: motion, sound, atoms, molecules, light, radio and other electromagnetic radiation [1]." With the rapid improvement of processing techniques, the next decades will see the incorporation of new types of functionality onto the chip. MEMS have found commercial success in the medical industry, automotive industry, and the aeronautical industry [2] [3]. MEMS are being examined for use in detection of biological agents to counter the threat of bio-terrorism. Astrophysicists are using MEMS to examine the fundamental constants of the universe. MEMS are the eyes and ears for their cousin the IC, though are not limited to this role [1]. They can also act as hands, moving their own components as well as objects around them. As sizes continue to decrease in the semiconductor world, we can see in the near future the introduction of an independent "system on a chip (SoC)" [1]. However, one of the major issues hindering the progress of today's MEMS technology is the packaging that provides protection to MEMS devices.

Not unlike ICs, MEMS require encapsulation in a hard, corrosion resistant package "for reasons of protection, reliability and tuning of performance [5]." Engineering MEMS encapsulations is more difficult than those of ICs because most MEMS devices have

delicate moving parts and complex topographies [3]. Whereas the function of ICs is built into the nature of the IC material itself, MEMS operation depends on their mechanical surface characteristics. Therefore, MEMS packaging must not hinder or affected the behavior of the MEMS components. Because atmospheric contaminants, in the form of particulates or moisture, can damage the fragile parts of MEMS, hermetic encapsulation is essential [1]. In addition, severe radiation or mechanical loads can also cause damage to the fragile architecture [4]. The hermeticity of the package walls therefore determines the long term reliability of the device and thus, both materials selection and package design techniques are of paramount importance for device success [5].

Because of the stringent requirements placed on parameters of MEMS packaging, it should not be surprising that their cost can be relatively high. While die production costs have gone down, packaging costs have gone up. With more functions being integrated onto MEMS, the requirements on the package have increased. Many MEMS are required to interact with their environment in some manner. This raises an interesting problem: how can device reliability be maintained without sacrificing performance? Combine this with the fact that no uniform structure or methodology has been adopted for MEMS production, leading to the need of an inordinately large number of custom MEMS packages. It is commonly cited that packaging accounts for anywhere from 40% to 80% for the cost of a MEMS device, and these costs have prevented utilization of MEMS in a wider array of mundane applications [6] (Figure 1).

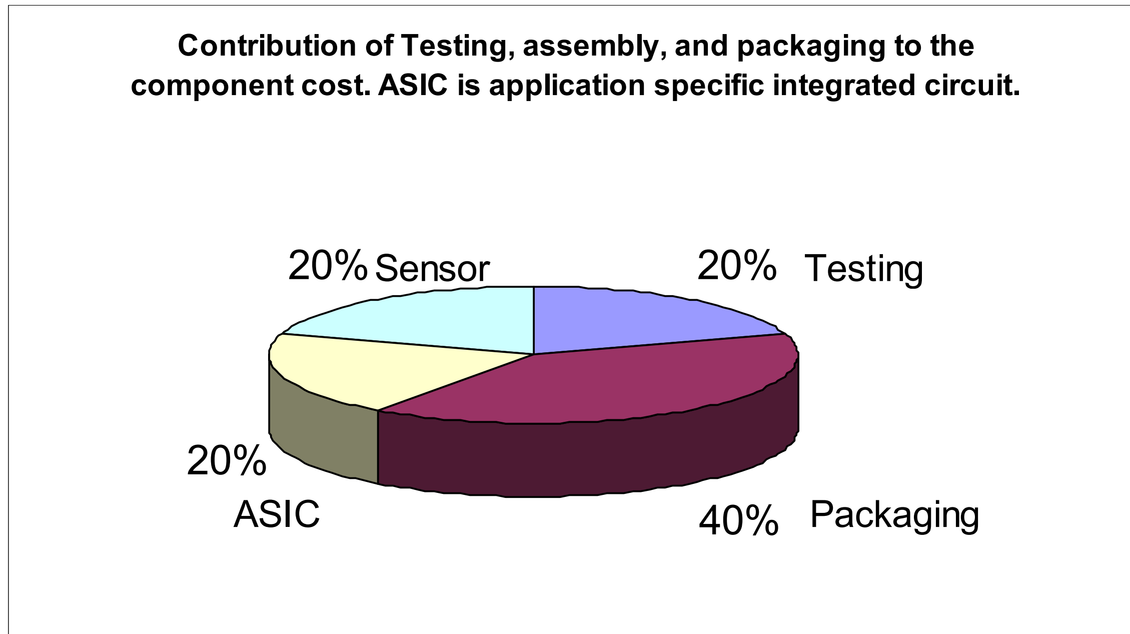


Fig.1 Economic breakdown of MEMS production [6]

Despite the substantial obstacles, several methods of packaging MEMS are being implemented. The numbers of applications that must be addressed when engineering MEMS packaging exceed the scope of this paper. Instead it will focus on two specific packaging approaches: wafer level and chip level packaging. The selection of suitable materials, design of package architecture, and economic considerations will be discussed.

MEMS are a burgeoning technology with applications in virtually every technical field imaginable. Methods for manufacturing MEMS are readily available from the already well established infrastructure of the IC manufacturing industry [4]. The unique nature of MEMS operations gives rise to their packaging complexity. It is this complexity combined with the cost of manufacturing the packages that has inhibited the infusion into the world of general applications.

## 2.0 Principle Mechanism

MEMS packages are in themselves complex systems. Aside from protecting the MEMS from the environment, they often have to maintain a very specific set of conditions for optimal operation of the MEMS. Rather than just the outer shell itself, MEMS packages are a combination of materials, each with a specific purpose and specific property requirements. The requirements and difficulties posed by designing MEMS packaging will be discussed individually, starting at the encapsulation itself, and proceeding through the finished product.

MEMS packages are typically built from a ceramic, metal, or molded plastic material, but are typically made from ceramics or metals. This is because of the high level of protection metals and ceramics offer. Aside from just environmental protection, MEMS packages must provide mechanical stability, electrical signal integrity, and thermal management. Differences in the coefficient of thermal expansion (CTE) between the MEMS, package, and printed wiring board should be minimized, as temperature gradients can change the stress distribution in the device's active region compromising the MEMS performance and reliability [7]. The chemistry and physics of the interacting surfaces of the package must also be taken into consideration, since surface and near surface properties of composite materials rarely mimic their bulk properties. Interfaces must be able to conduct stress, heat, and current efficiently to prevent delamination, which would then introduce particulates into the MEMS operating cavity, or 'head space' [8]. In addition to thermal conductivity, dielectric constant and dielectric loss will be

pertinent as device frequency and power demands increase [4]. Materials must then be selected with similar thermal and electrical properties to each other to ensure interfacial compatibility and proper functionality of the MEMS. Therefore, the material selected must be able to provide protection and isolation for the MEMS device, connect the device to the outside world, and maintain thermal stability with the device to ensure proper operation. However, aside from protecting the device from the external environment, the package must also maintain stringent environmental conditions within the head space to ensure the device reliability and functionality.

Controlling the head space chemistry poses a daunting problem in itself. Many MEMS devices require a vacuum or inert gas environment for operation. This requires that package also be hermetically sealed. Materials selection will then be based on permeation, out-gassing, and hermeticity in addition to physical rigidity and thermal and electrical compatibility. However, the applications of some MEMS devices may require interaction with the environment on a limited basis. Therefore, materials may be required to be partially permeable to specific chemicals or to be transparent to a specific spectrum of light [2] [3]. The total requirements for packaging materials, as described, can be extensive.

Until now we have just discussed the principles requirements of the box itself. The internal environment requires as much attention. As stated above, some MEMS require interaction with the environment. Also stated above was that out gassing is a factor in material selection. With both cases, the internal environment of the MEMS device can be

compromised. To counter these effects, compounds, called getters, can be introduced which absorb or neutralize unwanted contaminants. Getters are commercially available in many forms and are capable of absorbing solids, liquids, and vapors. They are typically a polymer suspension of a material that attracts and binds onto the foreign body but does not produce any contamination of their own. This allows them to be applied as a paste or film. They can be simple, like a permanently sticky polymer to pick up stray particles developed from MEMS component friction, or complicated, like a polymer bound palladium suspension used to absorb hydrogen[1][4].

In addition to internal contamination, attractive forces between MEMS components can pose another significant problem. This problem is commonly called stiction and may be caused by capillary forces, electrostatic attraction, and direct chemical bonding. Stiction can require a high initial force to overcome and can possibly disable the MEMS device permanently. The complex chemistry of silicon and its oxides, the dominant material selected for MEMS architecture, make surface coatings a possible solution. These coatings would need to have a low surface energy to prevent stiction between other components as well hydrophobic to minimize effects from moisture. The coating would need to be very thin in order prevent the coating itself from hindering operation [1].

Despite the differences in materials requirements for MEMS encapsulation, they must all still be able to be produced using the standard processing techniques found in the IC industry for electrical contacts [4]. Cost reduction is also a universal factor for determining MEMS packaging parameters. However, to reduce manufacturing costs,

ease production difficulties, and improve reliability, universal processing techniques need to be developed that can manage the broad range of requirements.

## 3.0 Application

MEMS production is carried out similar to IC production. However, as stated before, there exist a significant number of unique requirements for packaging MEMS. The number of options available for packaging are too numerous to be discussed in detail here. Instead, this paper will focus on two general types of packaging techniques: component level, or die level, and wafer level packaging.

Component level packaging is the packaging of the MEMS device in a ceramic or metal box after the die has been separated from the wafer. The device is attached with a solder perform. The package is then sealed with a lid, usually silicon on germanium, and vacuum baked to outgas the package and lid. After out gassing, the lid is attached with a solder seal or some other method.

Component level packaging has the advantage of having a readily available finished product immediately following the attachment of the lid. This allows for a much quicker pass to the testing and demonstration phase of manufacturing, making it ideal for prototype chip packaging. Component level packaging also offers flexibility of design making it easier to accommodate custom or specialty chips. However, the cost of manufacturing is excessively high, as each chip must be individually packaged. The possibility of contamination from wafer particles or moisture during the dicing phase of

the process is also very high. There is also a high probability that the internal mechanism of the chip will be damaged the increased amount of time it is being handled by a technician [6]. Thus, the yield numbers regarding this option are comparatively low while the cost per die is high, making this process economically unfeasible for high volume production.

The material selection for the component level packaging can vary depending on application (Table 1). Ceramics, metal cans, and plastics are all used. For ceramic packages, the material is typically an oxide, such as $Al_2O_3$, selected for its hardness and wear resistance. The material for the lid can also vary, though it is dependent on the box material selection as well as the application (Table 1). Si and Ge are typical material selections for oxide boxes because of their similar CTEs, though glasses can be used as well for optical applications [6] [9]. In this case, the lid can be attached using a micro heater raise the temperature around the seal of the glass softening point (or higher) with the intention of creating a silicon-to-glass eutectic bond.

**Lid Techniques for Various Packages**

| Package Type | Interconnect Method | Lid Type |
|---|---|---|
| Metal | Brazing, welding, soldering, adhesive | Metal Lid |
| Ceramic | Brazing, welding, soldering | Ceramic Lid, Glass Lid |
| Premolded Plastic | Gel coating, ultrasonic welding, adhesive, mechanical | None, or Premolded Lid |

**Material Selection**

| | Hermeticity | Manufacturability | Cost |
|---|---|---|---|
| Metal | ++ | o | x |
| Ceramic | + | + | x |
| Premolded Plastic | +/o | ++ | + |

Key:++=ideal; +=suitable; o=suitable under certain conditions; x=not suitable

Table 1 [6]

Wafer level packaging offers a solution for high volume devices. In this process, the packaging of the device is carried out prior to dicing. Around each device on the silicon wafer is a metal seal ring. On the silicon cap wafer is an identical ring. The two wafers are vacuum baked to outgas the material and then sealed using either solder or other method. The wafers are then diced. This method drastically reduces the cost and time required per die while also reduces the possibility of contamination due to handling. The cap wafer is processed with either wet etching or plasma etching to manufacture the appropriate head space for the device. This method also decreases the number of materials that are needed to interact with one another, since the lid and container are the same material (Figure 2) [4] [5].

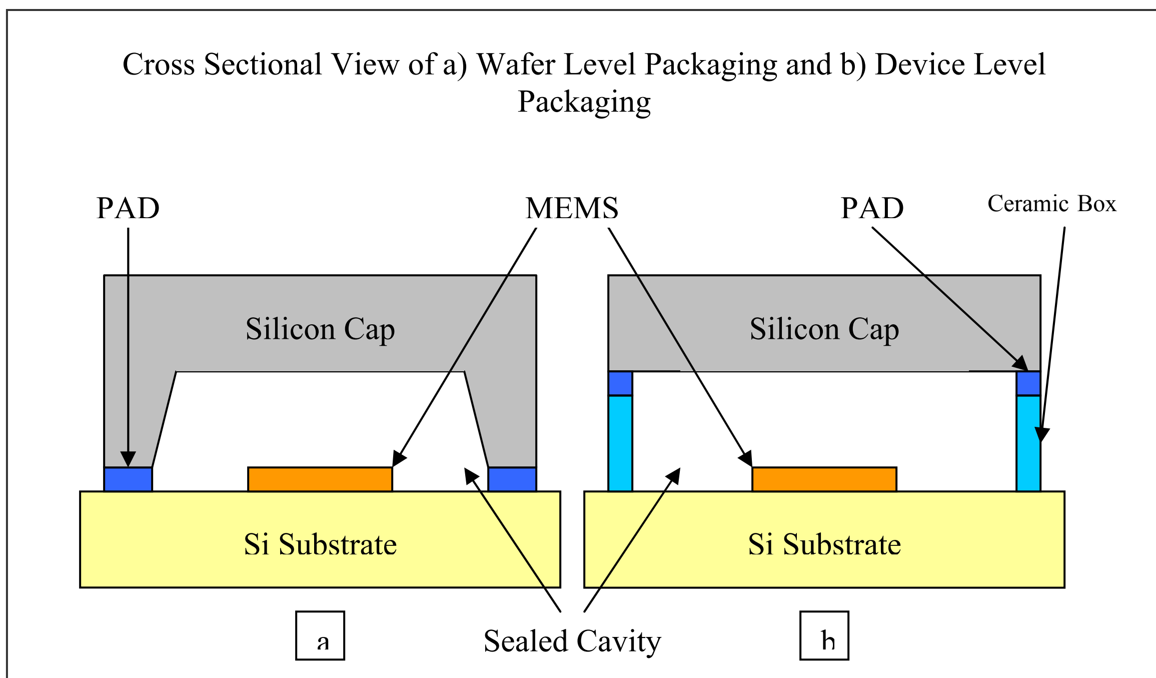


Fig. 2

The material for the cap wafer is typically Si because the substrate for most MEMS is Si, eliminating the problem of thermal characteristic mismatch. The wafers can be bonded together by a number of methods for different applications (Table 2).

**Bonding Technologies to Connect Leds and Component Wafers**

| Method | Process Temp | Hermeticity | Comments |
|---|---|---|---|
| Anodic bonding | ~400°C | Hermetic | High voltage required |
| Silicon direct bonding | 450-1000°C | Hermetic | |
| Soldering | ~200-300°C | Hermetic | Added metallization required |
| Laser spot welding | N/A | Hermetic | Not commercialized |
| Adhesive bonding | ~RT-260°C | Near-hermetic | Added deposition of adhesive requ |

RT=Room Temperature

Table 2[6]

Though economically superior for high volume applications, wafer level packaging typically does not accommodate optical MEMS. This is because the packaging materials are nearly always opaque, requiring fiber optic integration into the component. Though this does present a significant draw back, the positives outweigh the negatives. The cap wafer, being a separate component in itself, is processed independently from the MEMS device. This allows integration of getters into the cap, further reducing processing on the device [1] [7]. Wafer level packaging holds considerable promise to decrease manufacturing costs while increasing yields.

## 4.0 Conclusion

MEMS emerged as a revolutionary technology. They combined multiple aspects of unrelated sciences into a single device. The potential number of applications for MEMS seems limitless, bounded only by the constraints of our manufacturing ability. However, before they can reach widespread use, their manufacturing costs must come down. Ironically, the cost of manufacturing these complex devices is modest when compared

with the cost of protecting them. Packaging sciences must be drastically improved to make large scale integration of MEMS feasible. Methods are currently being developed to minimize the cost and yield loss of manufacturing MEMS, but they are not universally applicable to all MEMS devices. Improvements in secondary packaging technologies like getters and anti-stiction coatings could decrease the cost of package manufacturing by helping to reduce the requirements placed on the external encapsulation. Most importantly, a standardized method of MEMS packaging must be developed in order to drive down the cost associated with product specific packaging engineering.

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