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MEMS Packaging: Material Requirements and Reliability

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Abstract—**Advancement of microelectromechanical systems strongly depends on reliability of MEMS packaging. MEMS packaging is related to the application as well as fabrication especially when moving parts are present - parts that interact with other components through optical thermal, electrical, mechanical and chemical interfaces. Standard packaging for each functional interface do not exist and integration of fabrication and packaging processes are usually application-dependent. In this paper, properties of three types of packages that are commonly used in MEMS technology will be presented: ceramic, metal and plastic packages along with die attach and substrate materials that must meet numerous electrical, thermal, physical and chemical requirements. For these reasons properties of these materials for MEMS will be discussed in detail along with related reliability issues.**

Key words – MEMS; packaging; die attach materials; substrate materials; reliability;

I. INTRODUCTION

Over the last few years, considerable effort has gone into the study of reliability of microelectromechanical systems (MEMS) [1]-[4]. However, MEMS packaging has been and continues to be a major reliability challenge. The packaging cost is about 50% to 90% of the total cost of the MEMS device. MEMS packaging strongly affects the device performance, especially in the case of devices with moving parts. The three main functions of the MEMS package are mechanical support, protection from the environment and electrical connection to other system components. The package should support and protect the device from thermal and mechanical shock, vibration, high acceleration, particles, and other physical damage during storage and operation of the part (Figure 1) and at the same time enable interaction with the environment in order to measure or affect the desired physical or chemical parameters. The MEMS packaging challenges are application dependent: some MEMS devices should be open to the environment (pressure sensors, microphones, chemical, fluidic sensors, etc.) while others need to be hermetically sealed (accelerometer, gyroscope, etc.). Some of the key application dependent MEMS packaging issues are presented in Table I.

Since MEMS package reliability depends on the package type and materials used, in the following section we will discuss properties of the three commonly used types of MEMS packages: ceramic, metal and plastic packages along with die attach and substrate materials. Properties of these materials will be discussed in detail, as well as related reliability issues, in order to make a contribution to better understanding of MEMS packaging challenges.

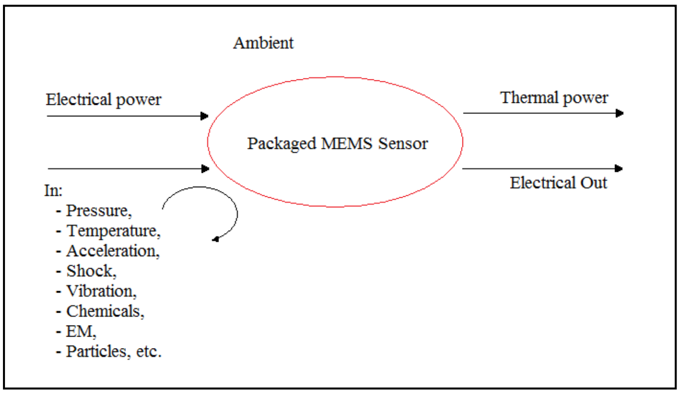

Figure 1. Schematic of the packaged MEMS sensor functional requirements

TABLE I. KEY MEMS PACKAGING ISSUES

MEMS Application	**Key Issues**
MEMS Accelerometer	– Free standing microstructures – Hermetic sealing – Temperature sensitive microelectronics
MEMS Gyroscope	– Free standing microstructures – Hermetic sealing – Vacuum encapsulation
Pressure Sensor	– Exposure to external pressure source – Housing for harsh environment – Interface coating
Optical MEMS	– Free standing microstructures – Hermetic sealing – Temperature sensitive microelectronics
Microfluidics	– Micro-to-Macro interconnector – Good sealing – Temperature sensitive materials
BioMEMS	– Micro-to-Macro interconnector – Good sealing – Temperature sensitive materials

II. RELIABILITY OF MEMS PACKAGING

Reliability is a key factor for successful commercialization of MEMS devices. Until recently the main areas of interest were MEMS fabrication techniques, designs, materials, devices and related infrastructure. However, with expansion of the MEMS market, MEMS packaging and reliability issues came into focus. When MEMS devices are in question it is usually very difficult to make partition between micromachining and packaging steps. Packaging requirements are very diverse and the lack of standardized packaging processes makes prediction of the effects of packaging on micromachined parts and performances of overall system very difficult. Packaging brings together various constituent parts with multitude of geometries using variety of materials and provides required input/output connections. On the other hand, minimal induced stress in micromachined parts from the packaging processes and package itself is required with minimal cost, improved manufacturability and reliability. These requirements are usually hard to meet because some packaging processes are intensive in generating particles, others involve high temperatures that affect thermo-mechanical behavior of micromachined structures or special tools to handle fragile micromechanical structures, etc. That can result in immediate inoperability of the device or can cause long-term drift and reliability problems.

There are three types of MEMS packages: ceramic, plastic and metal. Ceramic packages are commonly used for MEMS packaging. They usually consist of a base or a header onto which one or more dice are attached using adhesives or solder. They are generally electrically insulting and hermetic. They protect device from the moisture intrusion and because of high mechanical strength they are suitable for use in harsh environments where shock and vibration are present. The match between coefficients of thermal expansion (CTE) of ceramics and Si is fairly good which reduces amount of stress on the MEMS structure. They are resistant to chemicals and that makes them suitable for wafer level packaging. However they are more expensive than metal and plastic packages. Metal packages are robust and easy to assemble and when sealed they can be hermetic (Figure 2). Plastic packages are light and cost less than ceramic and metal packages. However, they suffer from moisture absorption that causes significant reliability issues, as well as from vibration-induced fatigue [5]. Mechanical vibration of certain MEMS devices during operation can cause cyclic stresses that may lead to vibration-induced fatigue of plastic package causing the degradation of the material. Packaging of released MEMS structures requires special care because they are susceptible to mechanical shock, contamination, excessive handling and moisture induced stiction. The best way to protect released MEMS structures is wafer level vacuum packaging. Before packaging, entire wafer is passivated to protect MEMS structures from contamination. Then, each die is surrounded by a metal seal ring with the corresponding seal ring on a silicon lid wafer. MEMS and lid are then placed in a vacuum chamber and baked. Finally, structures are released and wafers are sealed using solder seal, thermocompression bond seal, or anodic seal. Wafer-scale packaging offers many advantages including lower cost, requires less space and weighs much less than a conventional package.

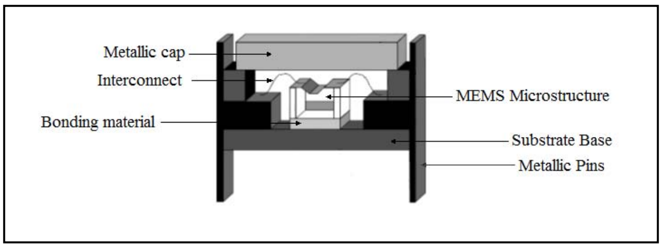

Figure 2. Schematic of the metal MEMS package

A vast majority of MEMS devices are diced from a wafer and mounted inside a package on a substrate. Attaching process must be carefully selected as well as die attach material. Die attach material selection depends on several factors: tensile strength, shear strength, fatigue strength, fracture toughness, CTE, thermal conductivity, moisture absorption, outgassing and cost. Selected material should firmly bond the die to the substrate disabling any movement. This is especially significant for various optical MEMS applications where alignment is of the great importance. Material resistance to fracture – fracture toughness is important for brittle materials such as glass. A common cause of failure is excessive thermal stress caused by the CTE mismatch between die attach, silicon and substrate. Excessive thermal stress may initiate local fractures in the bond. CTE mismatch stress may also lead to unwanted change of geometry of key components such as MEMS strain gauge in piezoresistive-based pressure sensors. In cases where the attachment material must conduct heat from the die to the substrate thermal conductivity must be taken into consideration. Moisture absorption significantly degrades bonding properties of the die attach. Many organic die attach materials absorb moisture that degrades the adhesion between the die and the substrate. Moisture absorption usually affects hermetically sealed MEMS packages. Another factor that may contribute to the structure failure is outgassing (Figure 3). Improperly chosen material may release gasses that can change the surrounding environment of the package and hence cause the failure of the device. The water and organic vapors generated in outgassing lead to stiction and corrosion of the device. Stiction prevents operation of the moving parts, while corrosion affects electrical conduction paths causing electrical failures. Possible solutions to outgassing challenges include very low outgassing die attach materials with sufficiently high elastic modulus and removal of outgassing vapors during die attach curing [6]. The problem of outgassing when the packaged die is in question is application of getters - materials which, when properly activated, can remove traces of gas in a vacuum package by reacting with gas molecules. Gettering a MEMS package has severe constraints that must be met: the getter must have a large active surface area, it must not damage the device during the activation process and it must be activated at relatively low temperature (300 - 500°C). The getter must also exhibit high sorption performances at room temperature, be free of particles and possess good mechanical strength. There are two types of getters: evaporable and non-evaporable. To maintain the desired ambient in MEMS packages non-evaporable getters and moisture getters are typically used. For hermetically sealed MEMS packages evaporable getters are non-applicable as large internal surfaces areas are required on which to deposit them.

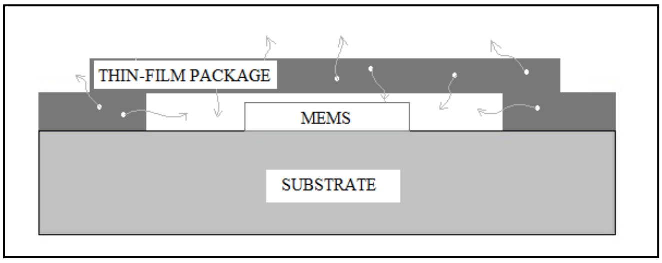

Figure 3. Outgassing of the MEMS package - schematic presentation

Organic die attach materials that minimize stress induced to the die, such as epoxies, silicones and polyimides are widely used when passivated MEMS structures are in question because outgassing of organic die attach materials may affect the properties of unpassivated MEMS structures. When ceramic packaging is in question, organic die attach materials are not used. After the die attach process, higher temperatures used to produce frit seal may result in degradation of adhesive properties. For improved thermal and electrical conductivity, epoxies and polyimides can be filled with precious metals such as silver.

Gold-based eutectics can also be used as die attach materials because of their excellent fatigue resistance. Inorganic eutectic die attaches provide the lowest level of contaminant gases. However, the lack of plastic flow results in CTE mismatch between the die and the substrate.

One of the greatest reliability issues, when die attach process is in question, is CTE mismatch. CTE mismatch between the silicon, die attach material and substrate induces stress on MEMS structure that may lead to cracking. Die cracking occurs when hard adhesives are being used and CTE mismatch stress is transferred to the die causing cracking. In case of soft adhesives, the adhesive material acts as a strain buffer at the die-substrate interface causing cracking of die attach. Peripheral voids may also cause die cracking. They induce non-uniform stress on the die thus increasing chance of die cracking and die attach bond fatigue. Solution to these problems is careful application-specific die attach materials selection and detailed deposition parameters consideration.

Proper selection of the substrate material for MEMS package can significantly affect reliability of the device [7]. They must meet a number of requirements (electrical, thermal, physical, chemical, etc.) and, for that reason, several factors should be considered: substrate dielectric constant, loss tangent, CTE, elastic modulus, thermal conductivity, resistance to chemicals, porosity, purity and cost. Dielectric constant is one of the most important factors in substrate selection. High dielectric constant causes cross talk between wires. High loss tangent also affects reliability of MEMS package. Many MEMS devices are sensitive to the frequency of the applied signals and lossy substrate may lead to significant reduction of MEMS device performances. In order to reduce thermo-mechanical stresses in the package CTE of the substrate, the die and the die attach material must match. High thermal conductivity of the substrate is usually required since heat generated by active devices that may be present in the package must be transferred. Low porosity and high purity are required to prevent moisture penetration through the substrate. There are two types of substrates that are being used for MEMS realization: single layer and multilayer substrates. Ceramic substrates are most commonly used single layer substrates in MEMS packaging. Their properties make them very suitable for the most of the MEMS applications, especially MEMS accelerometers, optical MEMS, micro-fluidic MEMS, etc. Low dielectric constants prevent cross talking, high modulus of elasticity make them suitable for harsh working conditions where shock and vibrations are present and they are resistant to chemicals. This allows that device can be mounted on the substrate and then released thus avoiding excessive handling. Hermetic packages can be implemented with ceramic substrates. There are several ceramic materials that are being used as single layer substrates for MEMS packages but there are three commonly used ceramics: aluminum nitride (AlN), alumina (96% Al_2O_3 and 99% Al_2O_3) and beryllia (BeO) as single layer substrates (Table II). They have similar modulus of elasticity, dielectric constant, dielectric strength and loss tangent. However, although alumina has very low dielectric constant it is the CTE mismatch between alumina and silicon that limits the usage of alumina in MEMS packaging. CTE mismatch may induce stress on the die causing cracking or bending. Beryllia has higher thermal conductivity than alumina but is toxic and more expensive. Aluminum nitride has better properties than alumina and beryllia when MEMS packaging is in question. It has lower CTE, high thermal conductivity, high strength and low hardness. These properties make it suitable for a wide variety of MEMS applications, especially microfluidic MEMS devices.

TABLE II. PROPERTIES OF COMMONLY USED SINGLE LAYER SUBSTRATES FOR MEMS PACKAGING [8]

Single Layer Substrates	**Si**	**BeO**	**AlN**	**Al_2O_3 (96%)**	**Al_2O_3 (99%)**
Tensile Strength (MPa)	-	230	-	127.4	206.9
Elastic Modulus (GPa)	310-343	345	190	310.3	345
Flexural Strength (MPa)	360	250	580	317	345
Dielectric Strength (kV/mm)	0.55	0.78	-	0.33	0.33
Dielectric Const. @ 1MHz	8.5-10	6.7-8.9	11.9	4.5-10	4.5-10
Thermal Conductivity (W/m°C)	82-320	150-300	125-148	15-33	15-33
CTE (ppm/°C)	4.3-4.7	6.3-7.5	2.33	4.3-7.4	4.3-7.4

Low temperature cofired ceramic (LTCC) is often used as multilayer substrate material for MEMS packaging. LTCC properties are given in Table III. It is possible to make cavities in the substrate in which the silicon-based MEMS can be bonded and hermetically sealed. The match between CTE of the ceramics and Si is fairly good which is very important for sensitive MEMS devices in wider temperature range applications. LTCC based MEMS are usually used for RF MEMS realization.

TABLE III. PROPERTIES OF SINTERED LTCC [9]

Multilayer Substrate - LTCC	
LTCC	6-9
CTE (ppm/°C)	5-7
Density (g/cm^2)	2,5-3,2
Flexural Strength (MPa)	170-320
Elastic Modulus (GPa)	90-110
Thermal Conductivity (W/m°C)	2-4,5
Dielectric Constant	7,5-8
Loss tangent (x10-3)	1,5-2

It is obvious that multiple variables affect behavior and functionality of MEMS package. Very high levels of reliability required in most MEMS applications, can be achieved by good understanding of MEMS internal packaging variables (i.e., technologies related) and external packaging variables (i.e., environment). For better insight in MEMS packaging reliability issues, the most common packaging related failure mechanisms can be classified in six categories as presented in Table IV.

TABLE IV. MEMS PACKAGING RELATED FAILURE MECHANISMS

Failure mode	**Causes**
Mechanical failure	- Vibration induced high cycle fatigue failure of plastic packages - Thermal stresses by packaging materials CTE mismatch
Electro-mechanical breakdown	- Failure of electrical conduction paths caused by excessive deformation
Materials deterioration	- Aging and degassing of plastic and polymers - Corrosion and erosion of materials
Excessive intrinsic stresses	- Residual stresses from microfabrication
Improper packaging steps	- Improper bonding and sealing, poor die protection and isolation
Environmental effects	- Temperature, humidity, dusty and toxic atmosphere

III. CONCLUSION

MEMS packaging is much different from conventional integrated circuit (IC) packaging. Many MEMS devices must interact with the environment in order to perform their intended function. Package must be able to provide this interaction and at the same time protect the device. Also, package must not interfere with MEMS device operation and the fabrication processes must be compatible with each other. The goal is to provide reliable, economical and application specific packages by choosing adequate packaging types and compatible materials combinations. In this paper some of the MEMS challenges have been discussed. It is shown that device performances are strongly affected by packaging and that it is of the great importance that design and realization of the MEMS package must include all levels of reliability issues from the onset of the packaging project.

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