Material and Reliability Requirements for MEMS Packaging

Soheil Bigdeli
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Soheil Bigdeli
National Semiconductor
2900 Semiconductor Dr.
Santa Clara, CA 95052

ABSTRACT

Microelectromechanical Systems (MEMS) are the latest technology wave behind information revolution and microsystems. Miniaturization of mechanical systems promises new directions in science and technology. The major markets for MEMS are in optical communications, bio technology, car industry, and radio frequency (RF) applications. Also, many different MEMS sensors and actuators have been implemented. The rapid growth of MEMS requires a more thorough study of MEMS packaging. Although MEMS packaging uses many similar technologies to IC packaging, it is very difficult to follow standardized rules for MEMS packaging. One of the challenges that MEMS packaging faces is that the media, which MEMS devices operate in, varies drastically with applications. For example, the package that is designed for an electrostatic actuator (which is a moving device) follows different principles than a micro fluidic channel. Also, in many cases, the package should protect the structure from environment so that the device functions accurately. For example, all MEMS packages used for electrostatic actuators must provide protection against moisture. Moisture dampens the microscopic movement of the actuator.

Also, many MEMS devices are fabricated with integrated circuits on a single substrate. Due to the heat generated by IC, the properties of the materials which MEMS

are built upon them, change. Therefore, the material selection for MEMS package should be done carefully.

As with semiconductors dies, MEMS devices require to be attached to a package substrate. This requirement is very important in optical and sensor applications. Any die movement causes misalignment in optical packages. Also, sensing is usually done through use of electrostatic actuators which are very sensitive to movement. Any die movement causes faulty sensing. Therefore the die attach materials should be carefully chosen so that the CTE differences are minimized as much as possible. Also, as with semiconductors, the thermal expansion mismatch between MEMS and the substrate induces stress on the package which may cause reliability issues.

This paper covers die attach and substrate material selection for MEMS packaging. Also, reliability issues along with ways to improve MEMS packaging reliability will be presented.

1. Introduction

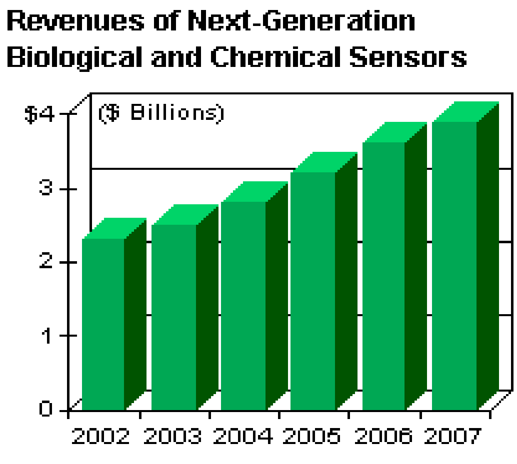
1.1 Introduction To MEMS Industry

The modern age of micromachining started in 1954. In 1967, Narvey and Nathanson at Westinghouse developed the first transistor with moving mechanical elements. Most of the efforts in 1980s and early 1990s went into development of different processes (micromachining) which the MEMS can be fabricated. Today, most of the efforts are going into designing structures using the available MEMS processes.

Most of the MEMS fabrication processes are based on the IC process standards. There are two common methods that are used to build MEMS. Bulk silicon etching (Bulk micromachining) is used to selectively remove silicon from the substrate. Surface micromachining is characterized by fabrication of micromechanical structures from deposited thin films. In this method, thin films of polycrystalline silicon are laid on top of silicon oxide (sacrificial layer) multiple times, and eventually the structure will be released by removing the silicon oxide.

There are many similarity and differences between semiconductors and MEMS. Many of the fabrications steps used in IC technology are used to fabricate MEMS. But the design of MEMS is based on mechanics not microelectronics. MEMS are different because they are mostly moving devices which are used to sense and actuate.

The current trends in MEMS industry show a major growth in next decade. The chart below shows the rapid growth in only sensor portion of the MEMS industry.



Source: In-Stat/MDR 3/03

1.2 Future Markets

Because of the variety of MEMS applications, there is a lot of room for future growth. MEMS military applications are currently in the research and development phase (flying insect is a great example. The insect which is barely 1cm long flies over an area and transmits data to its base). MEMS can have many more applications in automobile industry beyond just airbag system. Also, MEMS can be incorporated in wireless applications (for example variable capacitors and inductors which are the building blocks of RF systems can easily be implemented with MEMS technology). In addition, MEMS can be used as micro-mirrors or optical switches in many optoelectronics applications. Moreover, many of the MEMS sensors can be used to detected bio and chemical hazards.

2. MEMS Packaging

MEMS packaging has inherited some of the IC packaging techniques but, due to its broad range of applications, MEMS packaging is a lot more complex than IC packaging. The MEMS media of operations varies with application; therefore the package requirements vary with application. For example, the MEMS package provides full protection from environment in accelerometers so the package should be vacuum sealed. On the other hand, in sensors, the package allows access to the environment to measure a desired physical or chemical parameter. In addition, microscopic movement of MEMS mechanical structures has its own unique package requirements.

2.1 Types of MEMS Packaging

There are three types of packages which are used in MEMS technology. They are ceramic, metal, and plastic packages.

2.1.1 Ceramic Packaging

Ceramic packages are the commonly used for MEMS packaging. A ceramic package often consists of a base or a header onto which one or many dice are attached by adhesives or solder. Ceramic packages are generally electrically insulating. Ceramic packages are hermetic which makes them very attractive for MEMS sensor packages which the circuit should be protected from moisture intrusion. Also, the match between the linear coefficient of thermal expansion of ceramics and Si is fairly good (2.6 ppm/ºC vs. 5 to 7 ppm/°C for ceramics) [3] which reduces the amount of stress induced on the MEMS strucutre. Also, the ceramic packages have high mechanical strength (see table 3) which make them suitable for harsh environments where mechanical shock and vibration present. They are also resistant to chemicals, which makes them very attractive for wafer level packaging which the MEMS device can be released from the substrate after it is packaged [4]. As a result, excessive handling will be prevented. Ceramic packaging is significantly more expensive than plastic packaging ($0.063 for a 14-pin plastic package vs. $0.82 for a ceramic dual-in-line package) [5, 8].

2.1.2 Metal Packaging

Metal packages are attractive for MEMS, because they are robust and easy to assemble. They satisfy the pin-count requirements of most MEMS applications; they can be prototyped in small volumes with rather short turnaround periods. Also, they are hermetic when sealed [6]. They are more expensive than plastic packages [5].

2.1.3 Plastic Packaging

Plastic packages are attractive for MEMS packaging, because they cost less than ceramic and metal packages. Also, plastics packages weigh less than ceramic and metal packages. Unfortunately, plastic packages suffer from moisture absorption which causes reliability. For example, moisture absorption may causes MEMS sensors to sense incorrect data (moisture causes adhesion between the poly-silicon and silicon substrate which does not allow sensors to react quickly to sensed signal appropriately, see section 3.1.3). Also, delamination may occur if moisture stays in the package.

2.2 Material Requirements for MEMS Packaging

2.2.1 Die Attach Materials

As in IC packaging, almost all MEMS devices are diced from a wafer and mounted (inside a package) on a substrate which may be ceramic, metal, or plastic. The following eight factors will be considered in choosing die attach materials:

1. Tensile strength
2. Shear strength
3. Fatigue strength
4. Fracture toughness (for brittle attachment materials)
5. CTE
6. Thermal conductivity
7. Moisture absorption
8. Outgassing
9. Cost

Careful consideration must be given to die attaching process and the materials used. Die attach material should strongly bond the die to the substrate so that the die does not move at all. Die movement may cause various problems especially in optoelectronic MEMS devices which alignment is very important. For brittle attachment materials such as glass, fracture toughness is very important because it determines the material resistance to fracture. The CTE mismatch between the die attach, silicon, and substrate may result in undesirable stress which causes cracks in the bond. Also, much of the error in commercial piezo-resistive-based sensors is caused by induced CTE mismatch stress, since the sensor element is basically a MEMS strain gage [2]. In addition, when the attachment material must conduct heat from the die to the substrate, thermal conductivity is a critical factor. Moreover, moisture absorption degrades the bonding properties of the die attach. Die attach materials commonly used for MEMS and IC packaging are described in [1].

One way to minimize the stress induced to the die is to use organic rather than inorganic materials for the die attach [2]. Also, Organic adhesives are widely used due to their low cost and ease of rework. However, MEMS structures may be unpassivated (a layer of SiO_2 is used to protect the device) therefore their properties may be affected by small amount of contamination such as those from outgassing of organic die attach materials. Also, organic die attach materials are typically not used for ceramic packages because, the higher temperature needed to produce a frit seal after the die attach process, may degrade the properties of the adhesive. Common organic die attach materials are epoxies, silicones and polyimides (see table 1).

Epoxies and polyimides are sometimes filled with precious metals such as silver (70 to 80%) which enhances electrical and thermal conductivity [1, p28]. Example of a new epoxy used frequently in MEMS packaging is Ablefilm 5025 which is a silver-filled epoxy adhesive film designed to provide good thermal and electrical (see table 2) conductivity when MEMS and ICs are integrated on a single die (for example in an accelerometer, the integrated circuit and MEMS device are fabricated on one die, see figure 2).

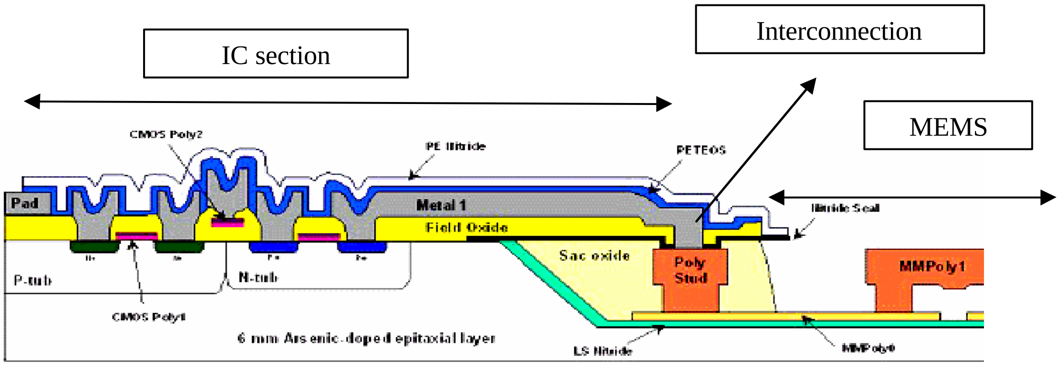


Figure 2: MEMS and IC on one substrate

Gold-based eutectics such as Au-Si, Au-Sn, and Au-Ge are also used as die attach materials. These materials have high flow-stresses (onset of plastic flow) and as a result, they show excellent fatigue resistance. In addition, the inorganic eutectic die attaches such as Au-Si provide lowest level of contaminant gases [2]. Their disadvantage is due to the lack of plastic flow, which results in mismatch in CTE between the die and substrate [1, p28]. They are also more expensive than organic die attach materials.

2.2.2 Substrates Materials

The following factors must be considered to choose a substrate for a MEMS package:

1) Dielectric constant
2) Loss tangent
3) CTE
4) Elastic modulus
5) Thermal conductivity
6) Resistance to chemical (for example HF which is commonly used to remove sacrificial layers)
7) Porosity and purity
8) Cost

Substrate materials are required to meet numerous electrical, thermal, physical, and chemical requirements (properties of some of the common substrates are shown in table 3-5). Dielectric constant (which is directly proportional to capacitance) is one of the most important factors in designing MEMS packages. High dielectric constant causes cross talk between wires (for example in an accelerometer which the wires connect an electrostatic sensor to an analog circuit. Both sensor and the analog circuit are fabricated a single die). Low loss tangent is another property of substrates which needs to be considered. High loss tangent causes the signals to lose their amplitude and frequency as they propagate through the wires. If the substrate is lossy, the performance of MEMS devices are reduced significantly since many of the MEMS devices are sensitive to the frequency of the applied signals (for example, RF MEMS such as variable capacitors may require to run at GHz range frequencies [7]. The quality of resonance (or quality factor, Q) which measures the performance of the MEMS devices is very sensitive to the frequency of the applied signal. High substrate loss tangent degrades the signal frequency, thus, the Q of the MEMS device is reduce).

An appropriate CTE is also required for substrates. The CTE of the substrate must match the CTE of the die and die attach materials in order to minimize the thermal-mechanical stresses in the package. The thermal-mechanical stress not only causes cracks also, much of the error in commercial piezo-resistive-based sensors is caused by induced CTE mismatch stress, since the sensor element is basically a MEMS strain gage [2]. Thermal conductivity of substrates is another important factor. Many MEMS control circuits are fabricated on a single die along with MEMS device. The control circuits usually consist of active devices (resistors) which generate heat. The substrate must have a high thermal conductivity so the heat can be transferred out of the package. Also, low porosity and high purity is also required for substrates to prevent moisture penetration through the substrate.

Commonly Used Substrates

Single Layer Substrates:

Ceramic substrates are the most commonly used substrates in the MEMS packaging. They have been developed for MEMS accelerometers, optical switches, and micro-fluidic channels. They have low dielectric constants (see table 5), which prevent cross talking (great for sensor applications where the sensed data will be transmitted to the circuitry for signal processing. Low substrate dielectric constant prevents the data to be crossed talked to other wires which means reliable sensing). Also, some ceramics (for example AlN) exibit high thermal conductivity. Moreover, ceramic packages have high modulus of elasticity (290 GPa for 92% $Al_2O_{3,}$ 310-343GPa for AlN) therefore they are very strong and suitable for harsh environments where mechanical shock and vibration are present (see table 3 for mechanical properties of ceramics). In addition, ceramics are resistant to chemicals (almost all ceramics are resistant to HF which is normally used to remove the sacrificial layer of the MEMS structures (releasing). As a result, the MEMS device can be mounted on the substrate and then be released. This process avoids mounting the released device to the substrate which improves the reliability by reducing excessive handling). Hermetic packages can be implemented with ceramic substrates which make them very suitable for almost all MEMS applications especially optical MEMS.

Alumina (Al_2O_3) is the most commonly used ceramic substrate for integrated circuits. The dielectric of alumina is 4.5-10 (which is very low, refer to table 5). But, the CTE of alumina is 4.3-7.4 ppm/?C which is almost three times the CTE of silicon. The CTE mismatch between alumina and silicon induces thermal-mechanical stress on the die which makes alumina not a good choice for MEMS packaging. Beryllia (BeO) is another potential ceramic substrate for MEMS packaging. The thermal conductivity of BeO is almost eight times that of alumina (see table 4). However, BeO is a toxic material and more expensive than alumina to produce. Also, it has no significant advantage over alumina with regard to CTE, dielectric constant, and loss tangent(see tables 4 and 5).

Aluminum nitride (AlN) is by far the best choice among ceramic substrates for MEMS packaging. It has a lower CTE than Al_2O_3 and BeO (closer to Si than alumina and beryllia) which reduces thermal-mechanical stress on silicon. It also has a very high thermal conductivity (see table 4). It has a similar modulus of elasticity (see table 3), dielectric constant, dielectric strength, and loss tangent as of alumina and beryllia. In addition, AlN is relatively cheaper than beryllia. Moreover, flexural strength of AlN is higher than alumina (see table 3) and Vickers hardness of AlN is half of alumina [8, p328]. High strength and low hardness allows AlN to be machined into different shapes (great for making microfluidic channels). Other substrates such as steatite, forsterite, quartz, and sapphire exist but by looking at tables 3-5, they all show disadvantages over the three substrates mentioned above.

Multilayer Substrates:

Low temperature cofired ceramic (LTCC) can be used as a multilayer substrate material for MEMS packaging [3]. It has a CTE of 5-7ppm/°C (similar to alumina) and a dielectric constant of 6-9 (at 1MHz, 25°C). The thermal conductivity of LTCC is about 2-3 W/mK which is somewhat lower than AlN and alumina. Hermetic packages can be built using LTCC. Since cavities can be implemented using LTCC [3], LTCC can be the substrate of choice for RF MEMS. Many RF MEMS devices have movements in Z direction. For example, a variable capacitor (the main component of RF devices) has been implemented which uses Z direction for variation in capacitance [9]. In order to package such devices, cavities can be implemented in LTCC to allow the Z direction movement.

Table 1: Mechanical properties of die attach materials (source: Electronic packaging materials, Page 27)

Material	Tensile Strength (MPa)	Shear strength (Mpa)	Modulus of Elasticity (GPa)
Silicone	10.3	-	2.21
Urethane	5.5-55	15.5	-
Acrylic	12.4-13.8	-	0.69-10.3
Epoxy silicone	-	11.7	-
Epoxy novolak	55-82.7	26.2	2.76-3.45
Epoxy, electrically conductive	3.4-34	-	-
Polyimide	-	16.5	3.0
Epoxy polyimide	-	41	-
Modified polyimide	-	-	0.275
Epoxy polyurethane	-	-	-
Epoxy bisphenol	43-85	-	2.7-3.3

Table 2: Properties of Ablefilm 5025E (source: Electronic Packaging Materials, 29)

Property	Unit
Shear Strength (Al to Al at 25°C)	17237 KPa
Shear Strength (Au to Au at 25°C)	20684.4 KPa
Glass Transition Temp.	90°C
CTE below Tg	65ppm/°C
CTE above Tg	1.5ppm/°C
Thermal Conductivity	3.462W/m°C

Table 3: Mechanical Properties of some of the common substrates (source: Electronic Packaging Materials

Materials	Tensile Strength (MPa)	Elastic Modulus (GPa)	Fexural Strength (MPa)
BeO	230	345	250
AlN	-	310-343	360
Si	-	190	580
Alumina (96%)	127.4	310.3	317
Alumina (99%)	206.9	345	345
Steatite	55.2-69	90-103	110
Fosterite	55.2-69	90-103	124
Quartz	48.3	71.7	-

Table 4: Thermal Properties of some of the common substrates (source: Electronic Packaging Materials)

Materials	Thermal Conductivity (W/m°C)	CTE (ppm/ºC)
BeO	150-300	6.3-7.5
AIN	82-320	4.3-4.7
Si	125-148	2.33
Alumina (96%)	15-33	4.3-7.4
Alumina (99%)	15-33	4.3-7.4
Steatite	2.1-2.5	8.6-10.5
Fosterite	2.1-4.2	11
Quartz	43	1.0-5.5

Table 5: Electrical Properties of some of the common substrates (source: Electronic Packaging Materials)

Materials	Dielectric Constant @ 1MHz	Dielectric Strength (kV/mm)
BeO	6.7-8.9	0.78
AIN	8.5-10	0.55
Si	11.9	-
Alumina (96%)	4.5-10	0.33
Alumina (99%)	4.5-10	0.33
Steatite	5.5-7.5	7.9-15.7
Fosterite	6.2	7.9-11.8
Quartz	4.6	-

3. MEMS Package Reliability

3.1 Die Attach Reliability Issues

3.1.1 CTE Mismatch

Die attach materials provide mechanical connection between the substrate and the MEMS structure. CTE mismatch between the substrate, die attach material, and silicon induces stress on the MEMS structure. The induced stress may cause cracks on the silicon MEMS structure. One study shows that the crack not only propagates through the silicon substrate, but it also propagates through the polysilicon, which is the building block of all MEMS structures [10]. Also, the induced stress due to CTE mismatch may cause misalignment in opto-MEMS devices.

Die cracks can either happen at the center of the die (due to bending stress) or at the corners of the die (stress singularity and sharp edges tend to increase the chance for corner cracks) [11]. Die cracking is usually seen when hard adhesives such as Au-based eutectics or solders glass are used as die attach materials. In this case, CTE mismatch stress is transferred to the die which causes cracks. However, the die attach itself may also crack if soft adhesives such as Pb-based solders or organic die attach materials are used [20]. The reason for this type of cracking is that the die attach material acts like a strain buffer at the die substrate interface. One study shows by increasing the adhesive thickness or by using lower modulus adhesive, thermal stress due to CTE mismatch is reduced significantly [12]. Die attach material recommendation for lower CTE mismatch is also included in [12]. Also, peripheral voids increase the chance of die cracking and die attach bond fatigue due to CTE mismatch between silicon MEMS and substrate. The peripheral voids induce non-uniform stress on the die. This induced stress increases the chance of die cracking. Tummala suggests a peripheral full fillet around the die-substrate periphery to prevent peripheral voids [11].

3.1.2 Outgassing

Many MEMS deices operate in vacuum environment. Therefore, it is important to ensure no substantial amount of unstable material escapes from the adhesive and damage the vacuum. Outgassing is of major concern especially if organic die attach materials are used for adhesion. Vacuum packaging is a potential solution for outgassing. The vacuum package protects the MEMS structures from damage and contamination. It also provides vacuum for many high quality factor MEMS resonator (for example, the typical mass for a typical high frequency resonator is about 10^{-13} kg. Even a small amount of gas (which act as a loading) significantly changes the resonance frequency of the resonator [13]).

3.1.3 Moisture Absorption

Many organic die attach materials absorb significant amount of moisture. The moisture may be trapped inside the package if the package is hermetically sealed. The trapped moisture acts as a debonding agent, which degrades the adhesion between die and the substrate, and eventually causes delamination.

One study shows the effect of moisture on Digital Micromirror Device (DMD). DMD is simply an array of microscopic mirrors or pixels (see figure 3). These mirrors can move if enough energy is applied to each pixel. In addition, each mirror has a corresponding stiction force (resistant force) which exists between the released micromirror and silicon substrate. Stiction force resists against the movement of the micromirror. Under normal operation, DMD applies extra force to the micromirrors to overcome stiction. However, moisture in the package significantly increases stiction force and as a result the pixels do not move [14].

One way to test the hermeticity of the package is to monitor inside of the package for moisture condensation. This can be done by making two electrodes (two MEMS cantilever beams) formed by the top metal layer of the MEMS structure. The two electrodes are connected to outside through wire lines. Any condensation of moisture on the surface causes a decrease in the impedance between the electrodes which can be detected from outside of the package [15].

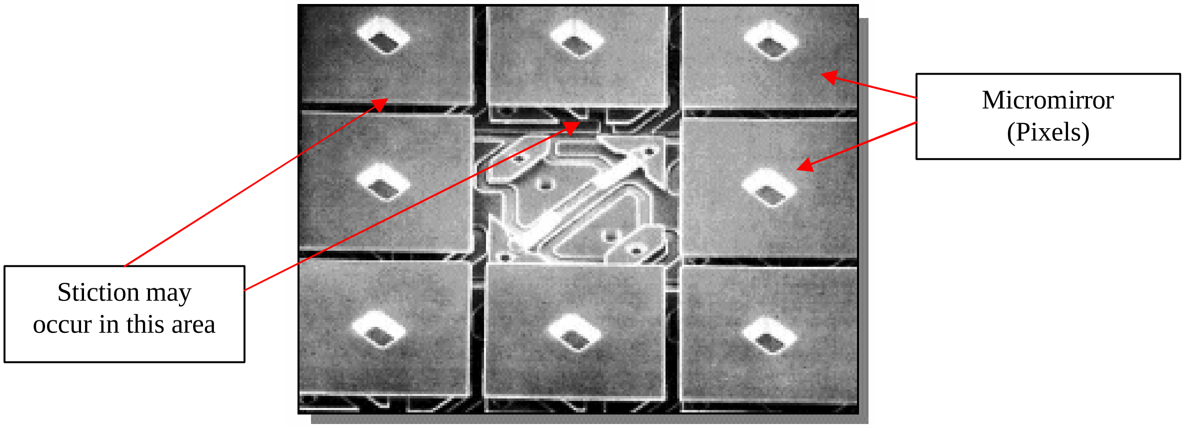


Figure 3: A 3*3 array of DMDs

3.2 Ceramic Substrate Reliability Issue

CTE mismatch between the ceramic substrate and the MEMS silicon die may induce stress on the die. Die cracking or bending may occur due to the induced stress. To reduce the effect of stress on the die, the substrate CTE must be as close to silicon CTE as possible.

3.3 Released MEMS Structures Issue

One major difference between IC packaging and MEMS packaging is that ICs are passivated (SiO_2 is used as the passivation layer) after fabrication; therefore they are protected during the packaging. However, extreme care must be taken when released MEMS structures are packaged. Released mechanical structures are susceptible to mechanical shock, contamination, excessive handling, and moisture induced stiction (refer to 3.1.3), which may cause reliability issues. One way to protect release structures is to do wafer level vacuum packaging. Before wafer level vacuum packaging, the entire wafer will be passivated to protect the MEMS structures from contamination. Then, each die on the wafer will be surrounded by a metal seal ring with the corresponding seal ring on a silicon lid wafer. The MEMS and lid wafer will be placed in a vacuum chamber and baked. Finally the structures will be released, and wafers will be sealed using a solder seal or a thermocompression bond seal, or anodic seal [16, 17, 18, 19]. One study showed that 100% of thermal actuators, 94% of torsional actuators, and 70% of microengines functioned after wafer level vacuum packaging with anodic bonding [18].

4.0 Conclusion

MEMS industry is growing very fast. Because of the various applications of MEMS devices, greater emphasis is placed on improving MEMS packaging since the package protects the MEMS structure. Types of the package and materials used for MEMS packaging should be studied carefully. Organic and inorganic die attach materials can be used to attach for MEMS packaging. CTE of the die attach material and substrate should be considered because CTE mismatch may induce stress on the MEMS structure. Also, moisture absorption by die attach may cause delamination or stiction. In addition, outgassing by organic die attach materials may cause reliability issues. Released MEMS structures should be handled carefully. Wafer level vacuum packaging should be used to minimize contamination and excessive handling.

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