MEMS Packaging – Current Issues and Approaches*

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Abstract

The assembly and packaging of MEMS (Microelectromechanical Systems) devices raise a number of issues over and above those normally associated with the assembly of standard microelectronic circuits. MEMS components include a variety of sensors, microengines, optical components, and other devices. They often have exposed mechanical structures which during assembly require particulate control, free space in the package, non-contact handling procedures, low-stress die attach, precision die placement, unique process schedules, hermetic sealing in controlled environments (including vacuum), and other special constraints. These constraints force changes in the techniques used to separate die on a wafer, in the types of packages which can be used, in the assembly processes and materials, and in the sealing environment and process. This paper discusses a number of these issues and provides information on approaches being taken or proposed to address them.

Key words: MEMS, packaging, assembly, die separation, wafer bonding, stress, hermeticity

Introduction

Microelectromechanical systems (MEMS) have received a great deal of interest and attention from research institutions, industrial firms, and the popular press, particularly in the last decade. Much of this attention has been focused on the devices or technology; much less emphasis has been placed on the assembly and packaging of the devices. However, in order for such devices to be used in systems and applications, they must be placed into packages that protect the device and allow it to interface appropriately with the rest of the system and the environment.

Packages for microelectronic devices perform four major functions – signal distribution, power distribution, heat dissipation, and protection of the device from external mechanical, chemical, electromagnetic, and other environmental influences. MEMS devices are generally sensors or actuators, and impose an additional set of requirements on their packaging. Such devices include mechanical sensors (force, rate, pressure), chemical (both gas and liquid) sensors, optical sensors, thermal detectors, microengines, and mechanical actuators. They often must have direct access to and interact with the environment, and thus may be exposed to stresses, chemicals, or other stimuli which are intentionally excluded from microelectronic packages. Another consideration is that MEMS packaging is frequently application specific, making it difficult to develop or utilize generic processes or methodologies.

Given the wide variety of device types, applications, and requirements for MEMS devices and systems, covering the full breadth of assembly and packaging issues and approaches in a brief manuscript is not possible. In this work we will focus on several specific packaging issues and approaches of particular interest and concern for silicon surface and bulk micromachined devices. The literature contains several other reviews of packaging approaches for MEMS (e.g., refs. [1, 2, 3]), and the reader is referred to those for aspects not covered here.

We will first discuss some general considerations for MEMS packaging. Next we will go into more detail on aspects associated with the separation of die on the wafer, assembly processes and materials, and control of the internal package environment.

General Considerations

Most MEMS devices contain moving structures. Free space in the package around those structures is needed, implying that cavity-style packages or another approach to provide this free space is required. The moving structures make the concern for particulate contamination during assembly more severe than for standard

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microelectronic devices. The gaps between moving parts can be of the order of a micron or less (as illustrated in Fig. 1), so that very small particles can prevent functionality (much smaller than those which are problematic for microelectronic structures). For example, a significantly limiter to yield for the Texas Instruments Digital Mirror Device (TI DMD) was particle contamination, and particles are the primary cause for device failure in the field [4].

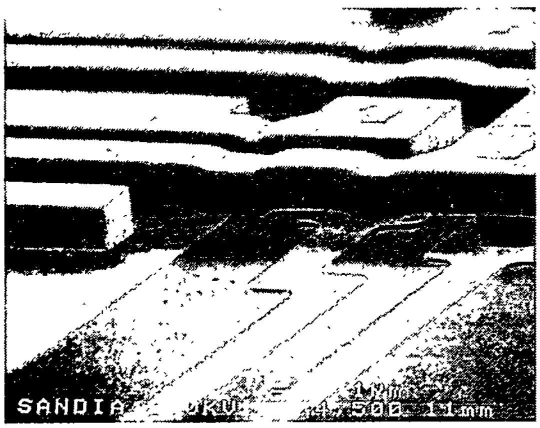

Figure 1. MEMS device structure illustrating the small spaces between moving parts.

The mechanical structures are also quite fragile (at least in a macro-world sense), so that standard die handling procedures (such as vacuum pickup heads) cannot be used. Techniques that handle the die only by the edges or protect the regions with mechanical structures in some other way must be used. This requires modification of standard assembly tooling (e.g., pick-and-place tools have been modified for assembly of the MEMS accelerometers manufactured by Analog Devices [5]). In addition, force sensors may require precise three-dimensional orientation with respect to a package fiducial to assure accurate measurements in the system.

The adhesion of contacting surfaces (often called stiction) can occur in MEMS devices because the forces to restore structures to their original positions are usually quite small. Surfaces may come into contact after release (the freeing of the structure by etching away the sacrificial layers) and drying because capillary forces from the liquid etchant draw moveable surfaces together. Also during operation surfaces may intentionally be brought into contact, or unintentional occurrences (such as shock or overvoltage stress) may force surfaces together. In all these cases the surfaces may remain in contact because of adhesion forces (e.g., van der Waal, capillary, electrostatic) and cause device failure.

There have been a variety of approaches demonstrating stiction-free drying in the release process. These include freeze sublimation [6], supercritical CO_2 drying [7], and the use of polymer spacers so that final release can be done in a dry (plasma) environment [8]. However, none of these approaches helps with stiction occurring during operation. Preventing operational stiction may require the use of a lubrication film, which can be a self-assembled monolayer (SAM) coating [9], fluid, or solid lubricant. (Note that the SAM coatings can also help prevent stiction during the release and drying process.)

The use of lubricant coatings places additional constraints on the packaging process. An oxygen plasma will remove organic coatings, so this cannot be used as a cleaning step in the assembly process after such a coating is applied. The coating may degrade at the temperatures of typical assembly processes [9], requiring modification of those processes. They may desorb at operating temperatures [10], requiring special precautions to prevent failure. For example, the TI DMD device is packaged with an overpressure of its SAM lubricant material so that coating integrity is maintained during operational temperature excursions [10].

Material interactions between assembly materials and lubricant coatings can also cause problems. Such an adverse reaction occurred during development of the TI DMD device, where the primary source of particles was found to be from a chemical interaction between the die attach adhesive and the lubricant coating used [4].

Die Separation

Standard microelectronic die are separated on the wafer by a dicing procedure consisting of sawing the wafer with a diamond blade while passing a coolant stream over the mounting fixture and wafer. For exposed MEMS structures which have been released, this procedure can be extremely damaging. The coolant stream can break the devices, particles generated during the process can prevent functionality, and the liquid can cause structures to stick together. Alternative approaches for separating the die are required.

The approaches pursued tend to take one of two paths. Either an alternative technique is used to "cut" through the wafer between die, or the mechanical structures are protected by some sort of cap during a relatively standard sawing process.

An example of an alternative technique for separating die is that developed for the TI DMD [11]. In this case a standard saw is used to cut part way through the wafer before the structures are released.

After cleaning and release, the wafer is placed face down on a special vacuum fixture with cavities where the mechanical structures are located. The wafer is then ground from the backside down to the partial saw kerfs to separate the die. Alternatives to back grinding include sawing the wafer down to the partial kerfs or breaking the wafer along the kerfs.

Scribing and cleaving is a technique that is often used to separate die on compound semiconductor (III-V) wafers. We have shown that it can be used on silicon MEMS wafers to separate die without causing mechanical damage to the devices or generating significant particulate contamination. However, a number of details remain to be worked out before this technique could be used in production.

Laser "sawing" has also been proposed as an alternative way to separate released MEMS die [3] without generating particulate contamination.

An example of the approach of protecting the released MEMS device during sawing is that developed by Analog Devices [12]. A plastic adhesive film with holes punched in the region of the mechanical structures is placed on the front of the wafer as a spacer layer. A second adhesive film is placed on top of this layer, forming a protective cavity over the mechanical structures. The wafer is then sawn on the back side to separate the die. The adhesive film protects the die from the sawing debris and liquid from the sawing and cleaning processes.

The approach of using a permanent cap to form a cavity over the mechanical structures is also utilized and takes several different forms. Typically another wafer (silicon, glass, or other compatible material) is used for the cap, so that all the MEMS devices on a wafer are capped simultaneously in a type of wafer-level packaging process. There are a number of different techniques that have been developed to join the device wafer and cap wafer.

Silicon fusion bonding or direct wafer bonding joins two clean silicon wafers together by bringing them into intimate contact and then fusing them at high temperatures (~1000°C). It has been used to fabricate a variety of MEMS sensors, including accelerometers [13] and pressure sensors [14]. Although the high temperatures historically required for this type of bonding can prevent its use for many devices, recent work has demonstrated low temperature bonding (down to ~150°C) [15] which may greatly increase its range of applicability.

Anodic bonding uses charge migration to bond a silicon wafer to a glass wafer having a high content of alkali metals. The wafers are brought into contact, a high electric field is applied and the temperature is elevated to ~300°-500°C. The alkali metal ions migrate under these conditions to form a space charge at the silicon/oxide interface, which creates a strong electrostatic force to hold the wafers together. This technique has been used in the assembly of accelerometers [16] and pressure sensors [17]. Although in this case the temperatures required are more moderate, the high voltages often required (500-1000V) can be a problem for many devices. Again recent work has mitigated this constraint, demonstrating anodic bonding at room temperature and 50V by the use of an intermediate layer of low melting point glass [18].

A number of other techniques use intermediate layers between the silicon and cap wafer to form the bond. The intermediate layer acts as an adhesive after the wafers are brought together under pressure and raised to an elevated temperature (typically 200-500°C). Materials used for the intermediate layer in the assembly of MEMS sensors include Au-Si eutectics [19], Pb-Sn solders [20], organic adhesives [21], and low-melting-point inorganic oxide glasses (glass frit) [22].

Microriveting is a recently demonstrated technique to join wafers at room temperature, with low voltage, and relaxed requirements for surface preparation [23]. In this case electroplating is used to form rivets through holes in the cap wafer, thereby holding the wafers together. One potential disadvantage of this technique relative to those discussed above is its lack of hermeticity.

There is also a capping technique which is an extension of the wafer fabrication process used to make the MEMS devices. This approach uses chemically vapor deposited (CVD) thin films to encapsulate the mechanical structures [24]. A structural "cover" layer is deposited and patterned over the last sacrificial layer on top of the mechanical structures. A hole is left in this layer so that the release etch can penetrate underneath to remove the sacrificial layers around the mechanical structures and form a cavity around them. After drying, the hole is sealed by a CVD film.

The advantage of these permanent capping techniques is that after they are completed, the wafer may subsequently be handled during assembly in much the same manner as standard microelectronic devices. Plastic molding can even be used to form the final package. Some disadvantages are that the cap wafer often requires processing to create a recessed cavity, ground planes, vias, or other features needed for the device to operate properly. Provision to transmit electrical signals to and/or from the mechanical structure is also necessary. This may require special isolation for signal lines under the edge of the cap. Permanent capping also requires a different set of assembly procedures and constraints to reach the point where it can be treated as a standard microelectronic device would be.

Assembly Issues

Since MEMS devices often have free mechanical structures or contain piezoresistive elements, they are sensitive to stress and/or bending induced in the die by the die attach material or process. (Note: They are similarly sensitive to stresses induced by other packaging processes, such as plastic encapsulation, or from differences in the thermal coefficient of expansion of package materials under thermal cycling.) Figure 2 shows the maximum shear stress at the die edge and the maximum compressive stress at the die center for a 27 mil thick silicon die. The calculation follows reference [25], and assumes a 1 mil thick epoxy attach to a 100 mil thick alumina package. The stresses can be quite large (up to 30 MPa) and vary significantly with temperature.

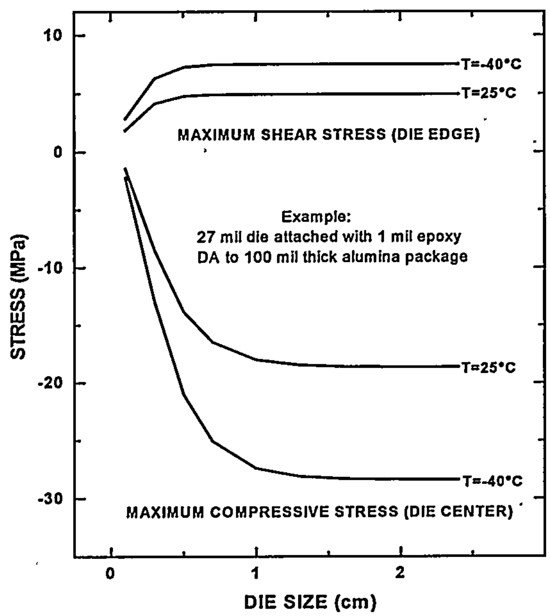

Fig. 2. Maximum shear stress at die edge and maximum compressive stress at die center induced by the die attach as a function of die size.

Much of the error in commercial piezoresistive-based sensors is caused by package-induced stress [26], since the sensor element is basically a strain gage. A significant consideration in the assembly of MEMS accelerometers is the minimization of stress [2]. Packaging-induced mechanical stress has even been demonstrated to be the cause of cracking in the silicon membrane in a MEMS micro-pump [27].

One way to minimize stress induced or transmitted to the die is to use organic materials rather than inorganic for the die attach. However, MEMS devices may have unpassivated surfaces whose properties can be affected by small amounts of contaminants, such as those from the outgassing of organic materials. This places constraints on the materials and processes that can be used in many situations.

An example of types and quantities of gases left in a package after lid sealing is shown in Fig. 3. Illustrated are the results from residual gas analysis (RGA) from packages using different die attach materials and processes and sealed in a belt furnace in a nitrogen environment.

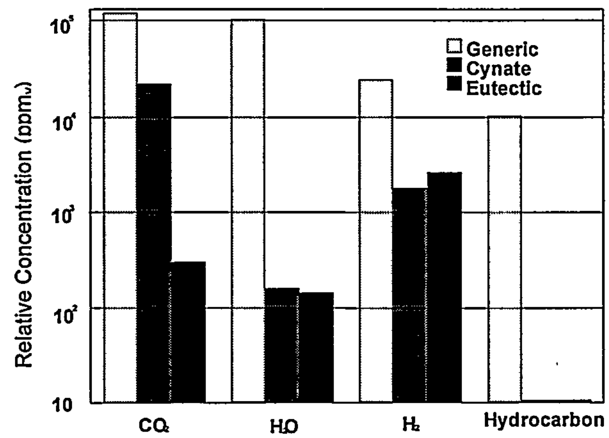

Fig. 3. Comparison of RGA results from packages using different die attach materials and processes.

The inorganic gold/silicon eutectic die attach provided the lowest levels of contaminant gases, but can cause high stress in die (and requires high temperatures which can degrade lubricant coatings). The epoxy die attach has more compliance, but showed high levels of carbon dioxide, hydrocarbons and water vapor (well above the mil-spec limit of 5000 ppm). The cyanate ester was processed so that it showed levels of contaminant gases comparable to that of the eutectic (except for carbon dioxide, which is believed to be relatively benign). This figure illustrates that with proper material choices and processes, the outgassing of harmful materials can be minimized.

As mentioned earlier, MEMS devices are sometimes coated with a lubricant film to improve their performance and properties. This coating can cause poor adhesion between the die and the package substrate. We have observed assembled parts that have such a coating can fail mechanical shock testing by the die breaking loose from the package. To prevent such failures, the coating must be either removed before die attach or applied after die attach.

The lubricant coating can interfere with the formation of reliable wire bonds. From the perspective of wire bonding, such films act as a contaminant, and can degrade the yield and reliability of the wire bond [28]. The coating should be removed from the bond pads before wire bonding or applied after the bonding is completed.

Internal Environment

Since some MEMS devices must interact directly with the external gaseous environment (e.g., pressure sensors), it may not be possible to fully control the environment to which the part is exposed. In other cases (e.g. accelerometers, resonators, or optical devices), the gaseous environment of the device is critical to its performance and reliability and must be tightly controlled.

Water vapor is a particularly important component of the gaseous environment. For some devices, it is critical that the environment be kept dry. For example, to prevent adhesion caused by the capillary condensation of water vapor, the TI DMD is hermetically packaged with an overpressure of the lubricant film [29]. In some cases it has been found that moisture at an appropriate level (~2000 ppm) can help reduce reduce stiction [30]. For microengines, it has been observed that the wear rate of rubbing surfaces decreases as the humidity increases, so that high humidities (>30%) can be beneficial in minimizing wear [31]. Any small leak in the package seal can rapidly alter the desired level of water vapor.

For example, the rate of ingress for water vapor through a leak in a package seal is illustrated in Fig. 4. This plot shows the length of time it takes for the internal environment (assumed dry nitrogen at 1 atmosphere) in a package cavity of 0.1 cm^3 to reach a particular partial pressure of water vapor for several leak rates into the package (and assuming the external environment is 75% relative humidity at 35°C). The calculation follows reference [32]. The mil-spec limit of 5000 ppm in the package is highlighted. Since the practical limit to helium leak rate testing is $\sim 10^{-8}$ atm-$cm^3 sec^{-1}$, one can see that for a package seal with a leak rate just below the detectable limit, it takes only 36 days for the internal packaging environment to reach 5000 ppm water. If the package cavity were vacuum, the backfilling with ambient air would be much faster.

The pressure of the gas around the MEMS device can be a significant parameter. The dynamic response of accelerometers depends strongly on the pressure; the damping of the accelerometer can be tailored for specific applications by changing the pressure inside the sealed device cavity [2].

Devices such as resonators or gyroscopes function best under vacuum. Vacuum packaging can be done as part of the fabrication process using CVD film sealing [24], by wafer capping techniques such as glass-silicon anodic bonding [16], or by using

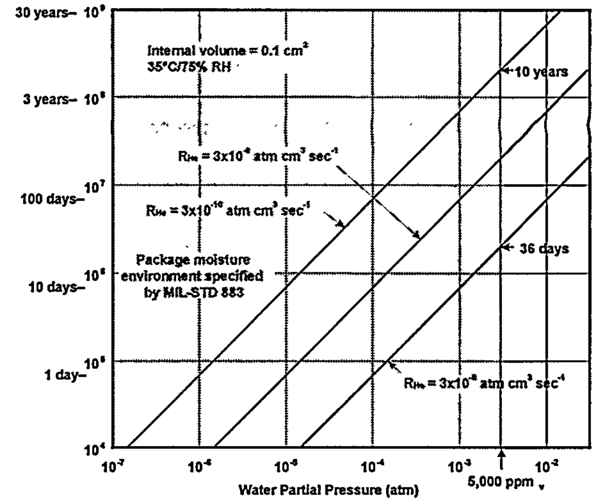

Fig. 4. Time taken for internal package cavity environment to reach a given partial pressure of water for several leak rates.

traditional packages sealed in a vacuum environment [33]. An issue with such techniques is the maintenance of vacuum for long periods of time. Very small leaks in the environmental seal can rapidly degrade the vacuum.

Outgassing of materials inside the package can similarly degrade the cavity vacuum. Outgassing rates for materials range between 10^{-5} cc-torr/cm^2-sec for organics to 10^{-8} cc-torr/cm^2-sec for clean, vacuum degassed metals. An outgas rate of 10^{-6} cc-torr/cm^2-sec within a package cavity will degrade an initially high vacuum to ~1 torr in ~100 days. Controlling the problem of small leaks or outgassing is likely to require the use of getters within the package [16, 34].

Summary

The assembly and packaging of MEMS devices are typically application specific, but in general impose a number of additional constraints and considerations compared to standard microelectronic packaging. To deal with problems arising from traditional methods of wafer sawing and die separation, alternative separation approaches or temporary or permanent "capping" of the mechanical structures have been pursued. To date the optimum approach appears to be specific to a given device and application. MEMS devices can be especially sensitive to particulate contamination, stiction, stress, outgassing within the package, and the internal package environment. These sensitivities require special attention to and changes in standard assembly and packaging processes. Overall a number of issues remain to be addressed to achieve optimum generic approaches for MEMS packaging.

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