MEMS Device Sealing in a High Vacuum Atmosphere Achieving Long Term Reliable Vacuum Levels

Paul W. Barnes
SST International
9801 Everest Street, Downey CA 90242
Phone: 562-803-3361 ext. 212, Fax: 562-803-4043
Email: pwbarnes@sstinternational.com

Abstract

Microeletromechanical Systems (MEMS) require encapsulation of delicate microelements in a controlled atmosphere or vacuum environment. In order to achieve proper device operation and protection from harsh environments, these packages must be hermetically sealed and the internal atmosphere must be maintained to prevent degradation of the device over it's lifetime. Controlled atmospheres and vacuum levels can change over time due to improper consideration of material and their outgassing characteristics. Packaging of MEMS has been and continues to be a major challenge unless all of the materials comprising of a sealed package are evaluated at the initial design phase. This paper will address the issues related to a ceramic package with a gold metallization seal ring, the importance of using low outgassing sensor attach materials, incorporating a getter material to be sealed in the package cavity, and the proper handling of the hermetic lid. In order to achieve the best and highest entrapped vacuum in the package, materials must be prepared before processing. This will involve proper vacuum baking and activating the getter film prior to sealing the MEMS device. By controlling the vacuum levels with aggressive bake outs, fully activating the getter, addressing all material out gassing rates, and optimizing the high vacuum sealing process profile a MEMS device with a controlled vacuum level can be obtained.

Keywords: reliable high vacuum levels, long term life cycles, high vacuum sealing process

Introduction

As MEMS sensor applications have continued to advance, the demands and requirements for sensor performance have increased. There is more focus and design being considered in the packaging of these devices. Packaging is proving to be more difficult and costly compared to the development and manufacture of the device. For this reason, packaging must be considered as an important aspect in achieving and controlling the device performance. According to Wikipedia, the following is the definition of packaging "packaging is the science, art, and technology of enclosing or protecting products for distribution, storage, sale and use. Packaging also refers to the process of design, evaluation, and production of packages." Packaging provides the interface between the sensor and the system application. As the applications are expanded and as they approach the different markets, cost, weight, mass, size, performance and reliability are the key issues. One of the major challenges in developing the next generation of MEMS, is mainly related to the materials selected and issues related to those materials. The materials used should be selected to withstand manufacturing processes, assembly handling, testing and above all else, the harsh environments the final product will be subjected to. The reliability depends on the package type, ceramic, plastic, or metal. For this paper and study, ceramic packages were selected because they have several features that make them useful for MEMS. They are easily mass produced, can be low in cost, have low mass, available with different sizes, and can be, in some applications, commercial off the shelf (cots) components.

Ceramic Packages

Ceramic was chosen because it brings forth the maximum effect of the device characteristics and has easy assembly/interconnection and low cost, for practical use. [1] Ceramic is a rigid material, withstands harsh environments, high temperatures, mechanical shock, and vibration. The coefficient of thermal expansion (CTE) value is fairly close to the sensor CTE and there are minimal stress differences between the two components. The ceramic package has an internal cavity where the sensor is located and a seal ring where the lid will be attached to obtain a hermetic/vacuum seal. Both the inside cavity and seal ring are gold plated, that will allow proper attach for the sensor with a solder alloy and will also allow the use of a solder alloy reflow process to hermetically seal the package. See figure 1.

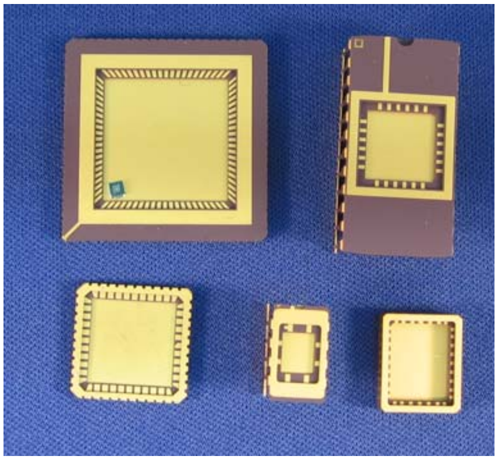

Figure 1: Typical (cots) ceramic packages

Sensor Attach Materials

Most commonly referred to as "die attach" this process provides a mechanical attachment of the sensor to the ceramic package. MEMS packages can use solder alloys, adhesives, or epoxies for die attach. For these tests, a solder preform consisting of 80% gold, 20% tin was used to attach the sensor to the ceramic base. This preform material has a reflow point of 278 °C and was placed between the backside of the sensor and the gold plated bond area of the package. To inhibit oxide formation, gold is usually applied to the back of the sensor. Barrier layers are used to prevent diffusion of the silicon through the gold layer at room temperature, but allow diffusion at bonding temperatures [2]. This is the most dominant method of component attach by the formation of a eutectic bond.

It is important at this stage to achieve a void free solder bond. Voids can reduce the reliability of the device by causing stress locations, will increase the device operating temperature and weaken the die bonds. The main cause of voids in the solder bonds is the segregation and formation of materials such as oxides, carbon and silicon on the molten solder solution [3]. Films formed by the oxides present will prevent wetting at the interfaces of the metallized surfaces. See figure 2 showing an x-ray of a void free sensor attach.

Another source of voids is trapped gas. Air becomes trapped when the components are assembled and the mating surfaces form an effective seal. It's critical to eliminate the trapped gas, because once trapped, it will continue to outgas, and once the package is sealed can be a cause for the vacuum level to rise. Since the attach method was performed in a flux free environment, there is very little outgassing of materials and no cleaning of flux residue required.

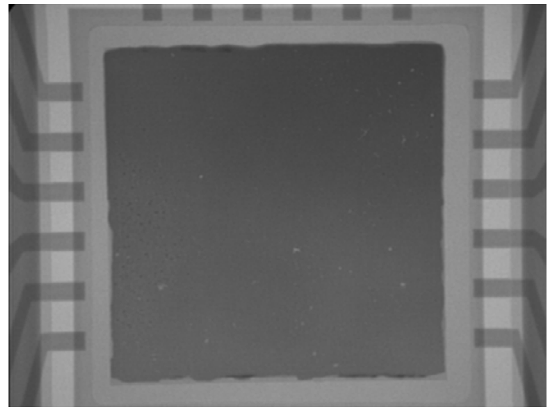

Figure 2: Void free sensor attach to the ceramic package base

Hermetic Lids with Deposited Getter Material

Lids are used as a means to hermetically seal the ceramic packages. The lid material selected is a function and requirement of the MEMS device. There are kovar lids, germanium, sapphire, glass and quartz materials available. Kovar lids are one of the most common materials chosen when the kovar is plated with an under layer of nickel and a final layer of gold. The non-metal lids will typically have a metallized seal ring consisting of a chrome adhesion layer, nickel under layer, and a final gold layer for the solder material to diffuse and make a hermetic bond**.**

The lids will then be processed to incorporate a getter material. See figure 3 for examples of lids with getters. It is generally accepted that using a getter material is the most reliable solution for maintaining and stabilizing pressures in hermetically sealed cavities [4].

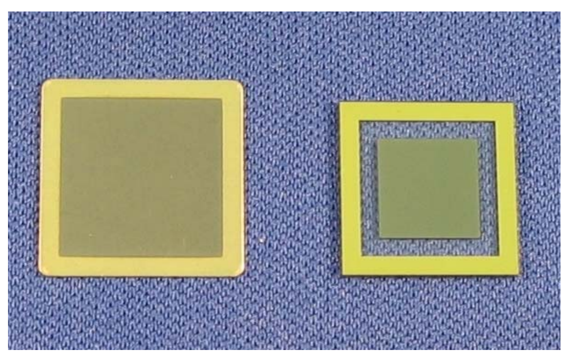

Figure 3: Kovar lid and glass lid with getter

Getters are referred to as materials, which chemically absorb active gases in a vacuum environment. To absorb gases, getters must be heated under high vacuum at high temperatures for a recommended time. A getter is a substance that removes molecules from the gas phase by a chemical reaction on its active surface [5]. Getters are normally selected in terms of their sorption speed and their capacity for various gases.

Depending on the application and package designs, one can activate getters thermally or electrically. Thermal activation is performed at higher temperatures, which can have an adverse effect on materials, plating, solders and most important, temperature sensitive MEMS or sensors. For these tests the PaGe getter from SAES was used. Activation times and temperatures were selected according to the activation efficiency curve outlined in Figure 4.

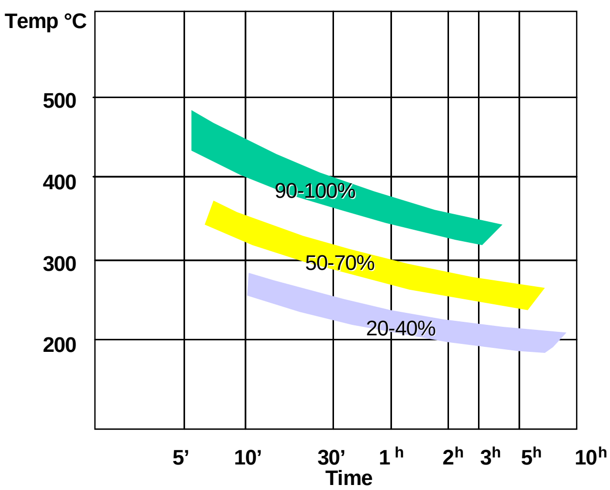

Figure 4 : Typical Getter Activation Efficiency Curves (Courtesy of SAES Getters)

Since the activation process is a function of both time and temperature, based on the process requirements or sensor temperature sensitivity, the full getter activation can be achieved at lower temperatures by extending the activation time.

Material Preparation

When the ceramic packages are processed and then plated with nickel followed by gold, there is a large amount of hydrogen trapped in the metals. If this hydrogen is still present once the package is sealed, this hydrogen could outgas and be a major cause for the contained vacuum level to rise. Material outgassing is one of the most important aspects to be addressed when designing a package. Kovar lids are also a source of trapped hydrogen because they are plated with nickel and gold. Another factor not to be overlooked is when kovar material is drawn, hydrogen gas is used during the process to improve ductility. This hydrogen gas is then trapped within the material and when subjected to elevated temperatures, will outgass. According to Saito et al., the major source of hydrogen gas in an hermetically sealed package is from electroplated nickel in the package housing [6]. Another source of hydrogen entrapment is the capture of hydrogen released during the gold plating process which will later outgass into the cavity destroying the desired vacuum level.

Once the packages and lids are received from the supplier, it is ideal to subject these materials to a high vacuum bake out. It has been found through experimentation that the temperature must be higher than 350 °C to bake out hydrogen from the iron base alloys [6]. It has been empirically derived that a more practical bake out temperature of 400 °C for one hour in a high vacuum environment of 1×10^{-5} Torr results in adequate reduction of the hydrogen which will not impact the sealing process [5].

During this initial hydrogen depletion process, careful consideration must be realized that too high a temperature can cause the nickel underlayer to diffuse or migrate to the top of the gold surface. As the nickel migrates to the gold surface it is possible it could generate a nickel oxide which will have an adverse effect on the sealing process. Nickel beneath a 50 micro inch gold film will diffuse to the surface per the following temperatures and times.

200 °C – in 31 days
275 °C – in 15 hours
340 °C – in 1 hour
450 °C – in 30 minutes

Package Assembly

Once all the materials are properly prepared and baked out, it is at this point the package needs to be assembled per the following steps. All of the following steps should be performed in a clean room environment to eliminate or reduce particles and any contaminants from being trapped in the sealed package cavity.

1. die attach sensor to the package using a gold tin solder preform
2. wire bonding to connect the sensor to the package
3. tack weld the solder preform to the package seal ring
4. sputter the getter onto the lid
5. design and manufacture fixturing to align and hold the materials in place

High Vacuum Sealing Chamber

Materials within the high vacuum chamber as well as the materials used to construct the chamber will have a large impact on pumping speeds and ultimate vacuum levels. For these tests a turbo molecular vacuum pump was used. It was selected because of it's high compression ratio for hydrogen gas, high pumping speeds, and low ultimate pressure. Turbomolecular pumps do not backstream hydrocarbons from the lubricating fluid or mechanical dry pump and are well suited to pump gas cleanly at high flow rates or low pressures [7].

All materials used within the system should have low outgassing rates and low permeability to the lighter gases such as hydrogen and helium. One of the most important factors affecting the performance of vacuum systems is the amount of water vapor adsorbed on all surfaces within the chamber. Figure 5 shows a residual gas analyzer (RGA) scan of a high vacuum system during the initial stages of pump down. Having this type of gas analysis available will help determine the bake out time required to lower the moisture and hydrogen gas during the initial pumping sequence.

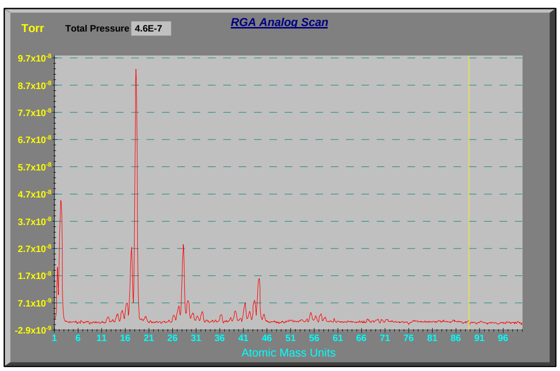

Figure 5: RGA Scan of High Vacuum Chamber

High Vacuum Sealing Process

A key consideration for successful soldering is to ensure that surfaces are free from oxides and other films that can inhibit wetting by the molten solder alloy. Vacuum is primarily used to reduce the oxygen partial pressure of the system. The prevention of oxidation also results in the reduction of voids. The oxygen partial pressure in a vacuum system can be reduced below the gas pressure in the vacuum by repeatedly pumping out and backfilling with dry inert gas. Vacuum is correctly defined as a state which exists in a completely sealed space from which all gases and vapors have been removed. Behavior of gases and vapors becomes more involved as conditions of pressure and temperature change. Vacuum is created when molecules of gas are removed from a chamber until as few as possible remain [8]. MEMS typically have moving parts that are sensitive to the operating pressure. Figure 6 is a ceramic package with die and gold tin preform tacked in place along with a kovar lid with a deposited getter ready to be loaded in the fixturing for the final seal process.

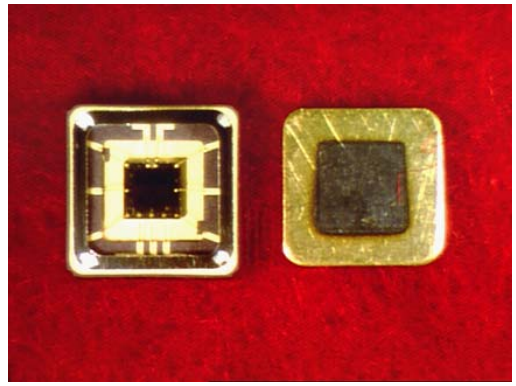

Figure 6: Ceramic Package and Kovar Lid

The fixturing consists of graphite heating elements that are placed in the high vacuum chamber on a pair of copper electrodes. The tooling is configured as a holding/locating device as well as the heating source. Electrical current is passed from the electrode to the graphite via the transformer and a phase fired controlled power pack. A thermocouple inserted into the graphite provides feed back to the temperature processor, determines the appropriate temperature ramp rates and provides accurate temperature set points and dwell times.

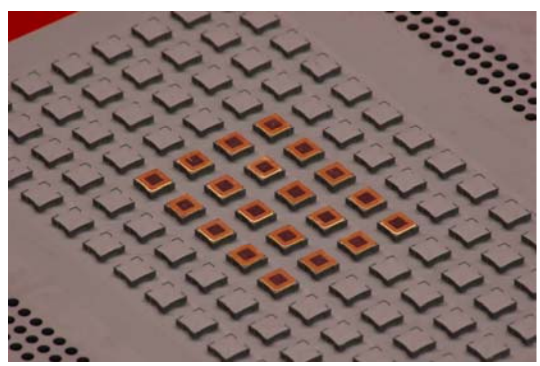

Figure 7: Tooling Locating the Lid with Getter

One key element necessary to achieve and maintain the vacuum levels is proper getter activation. Because the getter is best activated at high temperatures, 400 °C and above, the package with the preform and sensor must be isolated from the heat source so as not to damage the sensor and to avoid reflowing the solder preform that is tacked to the ceramic seal ring. The vacuum system is configured with a linear motion stage and an isolation mechanism to block the radiant heat from reaching the package. This separation and isolation process can maintain a large enough temperature delta to allow proper getter activation temperatures to be reached and not harm the temperature sensitive components.

Once the tooling is loaded with all the components, it is then placed in the high vacuum chamber and the chamber lid is closed. An automatic programmed profile is initiated per the following steps all performed in a high vacuum atmosphere:

- lid and package separation
- high vacuum bake out
- activate isolation mechanism
- ramp to getter activation temperature
- cooldown to a safe temperature
- open isolation mechanism
- bring package and lid together
- ramp to final seal temperature
- cooldown

A package was prepared with a pressure gauge (PG) mounted to the inside ceramic cavity. See figure 8. There will be current passed through the gauge and depending on the vacuum level inside the sealed package, the pressure gauge will heat up. If there is a very good vacuum the pressure gauge will heat up and not have any heat loss to the atmosphere.

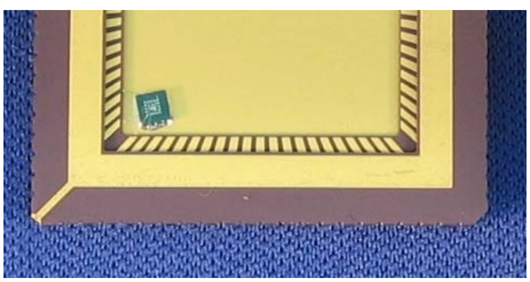

Figure 8: Pressure Gauge Mounted Inside the Package

The pressure gauge was calibrated and several packages were run in different profiles. According to the calibrated curves and based on the power supplied, the pressure gauge will heat up and the corresponding vacuum level will be determined by the calibrated graph. See figure 9. The following are recorded levels of vacuum inside the package.

below 2.56×10^{-4} mbar
below 4.92×10^{-4} mbar
below 7.99×10^{-4} mbar
below 3.36×10^{-4} mbar

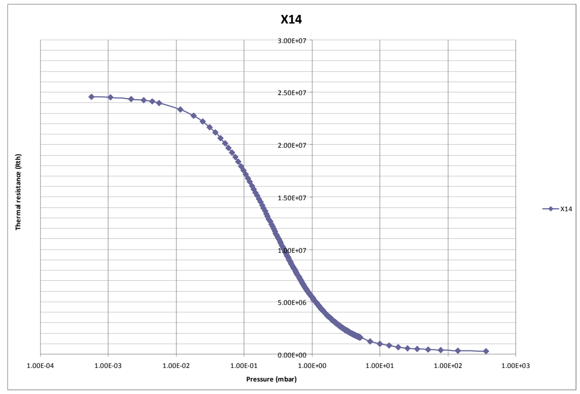

Figure 9: Calibration Curves for Pressure Gauge

Conclusion

By addressing all materials, outgassing rates and activating getters properly, a contained vacuum can be achieved and maintained for an extended period of life. By controlling the process and generating a high vacuum environment through aggressive bake outs, the level of vacuum sealed in the package will meet or exceed the sensor life requirements.

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