A DETAILED STUDY OF YIELD AND RELIABILITY FOR VACUUM PACKAGES FABRICATED IN A WAFER-LEVEL AU-SI EUTECTIC BONDING PROCESS

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ABSTRACT

An Au-Si eutectic wafer-level bonding process was developed for low-temperature vacuum packaging of MEMS devices. Using Au-Si eutectic bonding, devices were encapsulated by bonding a silicon cap wafer to a device wafer. Micromachined Pirani vacuum sensors were encapsulated in order to characterize the packaged pressures. These packages had cavity dimensions of 2.3×2.3 mm with a depth of 90 µm. Yields of 84.6% and 94.1% were achieved in packages with bond ring widths of 100 and 150 µm. With the use of getters and a pre-bond outgassing step, pressures from <3.7 to 23.3 mTorr were achieved. Furthermore, pressures were shown to remain stable to within ±2.5 mTorr for over 4 years of testing.

KEYWORDS

Wafer-level, packaging, eutectic, bonding, vacuum

INTRODUCTION

Packaging and encapsulation are the major roadblocks to the commercialization of emerging microelectromechanical systems (MEMS). Devices like MEMS gyroscopes, infrared arrays, resonators, and micro-switches for wireless circuits require vacuum/hermeticity at pressures from below 10 mTorr to as high as atmospheric pressure with virtually no oxygen or water vapor exposure. Furthermore, these devices need to be packaged at the wafer-level in order to handle the high volume/low unit price demands of growing commercial applications. To the author's knowledge, no papers to date have been presented on package yield and only a few authors have presented detailed reliability studies for wafer-level packaging processes [1-4].

Here we present results from a wafer-level eutectic bonding process for vacuum encapsulating MEMS devices at a temperature of 390°C. Pressures ranging from <3.7 mTorr to 40 Torr where achieved depending on the processing conditions and the use of getters. The effects of process characterization on these measured pressures and the yield over time were observed with 4 years of vacuum/hermeticity data.

Background: Other Approaches

Vacuum/hermetic packaging of devices has been investigated using a number of approaches including thin film encapsulation, anodic bonding, glass frit bonding and various solder bonding techniques. Thin film encapsulation and anodic bonding are each proven and effective bonding techniques which have been used for wafer-level packaging commercial MEMS devices, but can only be applied to specific types of devices and process flows. Glass frit bonding has been used the most extensively for commercial wafer-level hermetic packaging of devices. Frit glass's main limitations are its high processing temperatures (≥450°C), its relatively large bond ring widths (≥150 in addition to room for flow of the frit glass) and its lead content.

Wafer-level packaging using solders and eutectics is an alternative approach. Similar to glass frit bonding, when heated above their melting points, eutectics and solders melt allowing them to conform over non-flat surfaces such as electrical feedthroughs while providing a vacuum tight seal. Furthermore, solder and eutectic processes can be designed at low temperatures ranging from 125°C to 400°C with bond ring widths as small as a few 10s of microns allowing for very small overall package sizes.

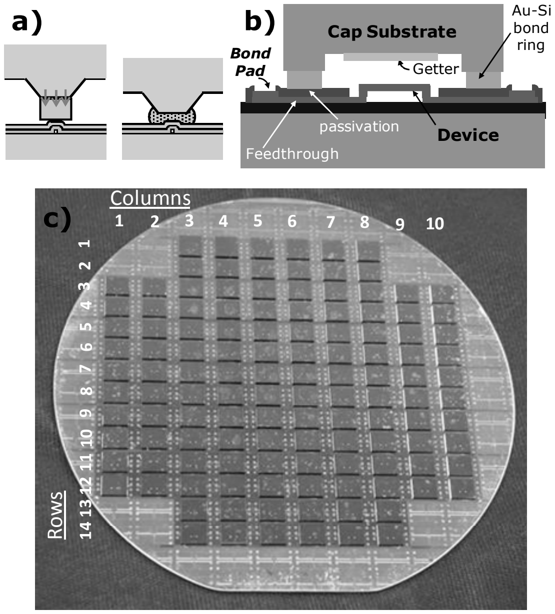

Figure 1: a) A schematic of how silicon diffuses into gold creating the liquid Au-Si alloy, b) of a packaged device, and c) a wafer with 124packaged MEMS devices [1, 2, 4].

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The Au-Si Eutectic Bonding Process

There are many solder alloys available for the wafer-level packaging of MEMS devices. Applying them is generally difficult because of their stringent metallurgy and thermal budget requirements. On the other hand, both the process and metallurgy for Au-Si eutectic bonding are relatively simple.

In the Au-Si eutectic process, a cap wafer with Au bond rings is bonded to a device wafer with either poly-Si or gold bond rings that encircle the MEMS devices [1, 4]. Figure 1a shows how when raising the bond temperature above the eutectic temperature of 363°C, silicon diffuses into the Au layer. Above this temperature, at 19 atomic percent Si in Au, this layer becomes a liquid (eutectic) solder and reacts with the Au or Si bond ring layer on the device wafer. Finally, after bonding, part of the cap wafer is diced away allowing for electrical contact to the device as illustrated in Figure 1b. Figure 1b and 1c show a schematic of an Au-Si eutectic package and a wafer with 124 packages arrayed across it. As illustrated in Figure 1b, the packaged device is connected to a bond pad outside of the package via an electric feedthrough which is insulated by a passivation layer. This process is detailed in [1, 4].

Figures 2a and 2b show photographs of the final package which had a total volume of 2.3×2.3× 0.9mm and bond ring widths ranging from 100 to 300 µm.

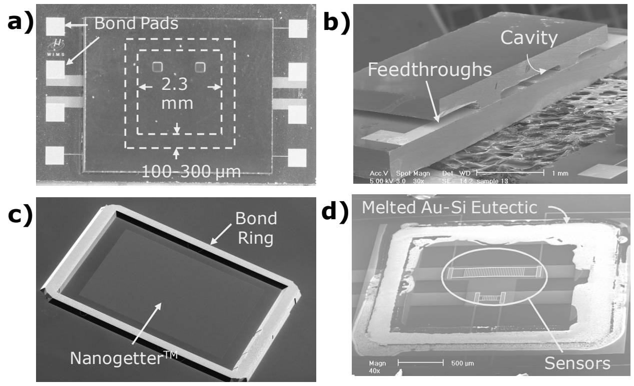

Figure 2: a) A package, b) a package cross-section, c) the bond ring and Nanogetter^{TM} on the cap wafer, and d) the two encapsulated Pirani gauges after the cap was pulled off.

Outgassing & Getters

Outgassing involves desorption of molecules (such as H_2O, H_2, N, O and CO_2) from the inside surface and bulk of vacuum chambers. Outgassing has a much larger affect on pressures inside of a sealed micro-cavity than in macro-scale vacuum chambers because: 1) the micro-cavity is not continuously pumped, and, 2) the surface to volume ratios are much higher. As a result, although packages in this work were sealed at 10 µTorr, pressures were observed at >1 Torr after bonding. Similar results have been reported using anodic, solder and frit bonding [6, 7].

Lower pressures can be achieved using two methods: 1) heating the wafers in a vacuum chamber in order to desorb atoms from the inside cavity directly before bonding/sealing, and 2) using getters which are thin metal films or alloys that react with trapped gasses in order to lower the pressure. In this work, we included an outgassing step in the bonding process at 345°C for an hour directly before applying the bond force and bond temperature of 390°C. We also deposited a commercial getter, Nanogetters^{TM} [5], provided by ISYSS, Inc (shown in Figure 2c).

VACUUM CHARACTERIZATION

Vacuum sensors were encapsulated inside of each package in order to characterize their hermeticity and reliability. Figure 2d shows these vacuum sensors which had pressure measurement ranges of 1 mTorr to 5 Torr and 1 Torr to 760 Torr.

Table 1 shows the pressure ranges measured across 6 different wafer bonding experiments. As illustrated, pressures from 2 to 50 Torr, 77 to 980 mTorr; and <3.7 to 25 mTorr where achieved depending on the use of getters and the outgassing step.

Table 1: Measured pressure for 6 different bonds (wafers) as a function of different parameters and use of getter.

Bond #	Bond Ring width (µm)	Getter/ Outgas Step	Pressure Range	Pass Criteria	Yield
67	300	No/Yes	2T-12T	<50 T	17/17(**)
100	300	No/No	2T- 44T	<50 T	80.4%
103	150	Yes/No	150mT-980T	<1 T	94.8%
105	100	Yes/No	77mT-670mT	<1 T	76.9%
71	300	Yes/Yes	<3.7mT-16mT	<25mT	81.0%
78	300	Yes/Yes	<3.7mT-23mT	<25mT	34.0%

**Not enough test data to determine the yield

Results: No Getter (>1 Torr)

As shown in Table 1, getters were not used in bonds #67 and #100. The main difference between these two bonds was that bond #67 used an outgassing step and bond #100 did not. As a result, bond #100 had a wider pressure range, from 2 to 44 Torr, then bond #67 which had a pressure range from 2 to 12 Torr.

Pressures for 15 of the packages from bond #67 were monitored in 360 days of testing. As illustrated in Figure 3a, 9 of these packages had relatively stable pressures over time with measured pressure fluctuations from ±0.10 to ±0.51 Torr. A part of this fluctuation likely resulted from measurement error given the calculated measurement error ranging from ±0.031 to ±0.16 Torr. A possible additional source of these measured pressure fluctuations may have been from adsorption and desorption of gases to and from the inside cavities (chemisorption and outgassing).

Figure 3b shows data for 4 of the packages in which the pressures changed by >3 Torr over time. The observed slow increase in pressure over time is likely caused by outgassing. Graphing this data in terms of outgassing flow rates per unit area ($\dot{Q}/A$) verses time (see [2, 4] for detailed calculations), power law decreases in the outgassing rate were observed. These trends are typical of those measured for outgassing in the literature.

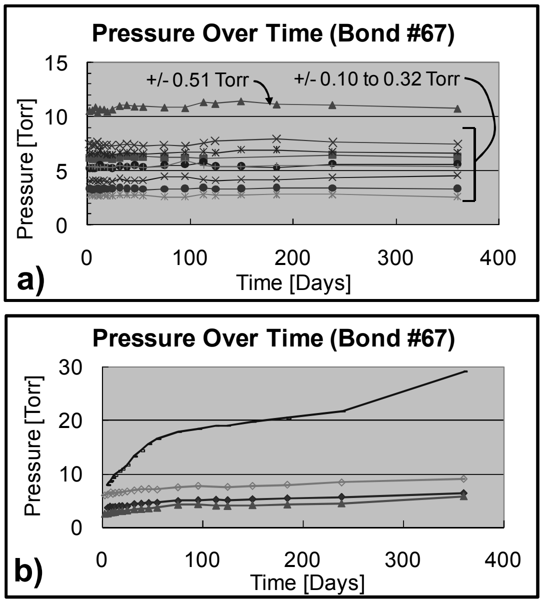

Figure 3: Package pressures measured over 360 days in which a) the pressures remained stable with in ±0.1 to 0.51 Torr and b) those which had >3 Torr increases in pressure over time.

Results: With Getter & No Outgassing Step (<1 Torr)

As was shown in Table 1, in bonds #103 and #105 getters were used but without an outgassing step. In these experiments, 150 and 100 µm bond ring widths were used as compared to 300 µm widths in the other bond tests. Across these bonds 58 and 52 packages were tested where 94.8% and 76.9% of the packages respectively had pressures in the mTorr range. Pressures from 150 to 980 mTorr and 77 to 650 mTorr were observed. A majority of the packages from both of these bonds had stable pressures over time (with graphs similar to Figure 3a) with fluctuations ranging from ±1 to ±25 mTorr in 1 ¾ years of testing. The calculated measurement error ranging from ±4 to ±33 mTorr potentially accounts for all of these observed pressure fluctuations.

A number of different trends were observed for packages with significant increases in pressure over time. A few of them showed failures with pressures going all of the way to atmospheric pressure (760 Torr) after anywhere from 21 days of testing to 614 days of testing. The majority of the failures involved smaller changes in pressure from +0.25 to +1.5 Torr.

Results: With Getter & an Outgassing Step (<25mT)

As was shown in Table 1 in bonds #71 and #78, getters were used along with a 345ºC, 1 hour pre-bond outgassing step. Most of the packages across these wafers demonstrated pressures below 25 mTorr. Across these bonds 63 and 47 packages were tested where 81.0% and 34.0% of the packages respectively had pressures below 25 mTorr. Pressures in this range were near the limit of the operating range of the Pirani guage used for pressure measurement and as a result, each gauge needed to be individually calibrated for accurate pressure measurement. In order to do this, 8 packages from bond #71 and 4 packages from bond #78 were de-capped after packaging and the sensors were then calibrated. As illustrated from Table 1, the pressures for these packages ranged from <3.7 to 16.3 mTorr and <3.7 to 23 mTorr respectively.

In our analysis of bond #71, the 8 calibrated sensors across the wafer were used to interpolate the calibration curves of the sensors which were still encapsulated (see [4] for detailed calculations). Using this interpolation data, Figures 4a shows data for packages which demonstrated pressure variations of less than ±2.5 mTorr in 4 years of testing. The calculated measurement error of ±3.7 mTorr potentially accounts for all of these observed pressure fluctuations.

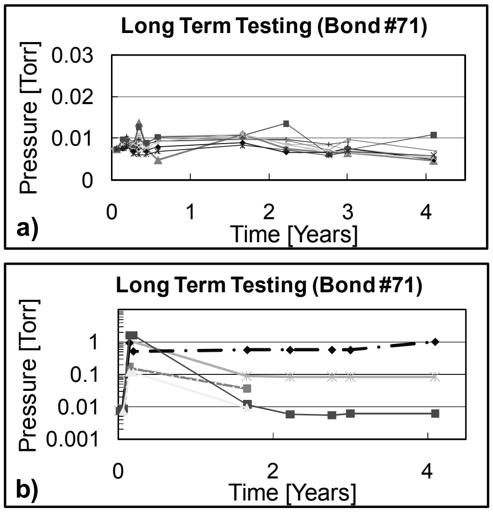

Figure 4: Package pressures measured over more than 4 years where a) pressures stayed constant within ±2.5mTorr and b) those which had larger increases and subsequent decreases in pressure over time.

A number of different trends were observed for packages with significant increases in pressure over time. Some of the packages showed failures with pressures going all of the way to atmospheric pressure (760 Torr). As shown in Figure 4b, several others showed increases in pressure ranging from 100 mTorr to 1 Torr, many of which had subsequent reductions in pressure. This was likely caused by outgassing and subsequent chemisorption of these gasses into the getter. As reported elsewhere [2, 4], several other packages from this wafer which demonstrated similar pressure fluctuations where heat treated at 150°C causing them to stabilize. This may highlight the need for heat treatment or a longer pre-sealing outgassing step in order to drive out all of the trapped gasses.

Failed Packages & Yield Over Time

Table 1 summarizes the pass-fail criteria for each set of bonds. As illustrated, for package processes without getters, with getters/without an outgassing step, and with getters/with an outgassing step, the packages where determined to have failed if they had pressures of >50 Torr, >1 Torr and >25mTorr respectively. Subsequently, for determining the package yield over time, packages were determined to have failed if a pressure fluctuation of ±1 Torr, ±25 mTorr or ±5 mTorr was observed.

Given this pass-fail criterion, Figure 5 shows the yield over time for bonds #103, 105 and #71. As illustrated, bonds #71 and #105 had initial yields of 81 and 76.9%. These yields dropped off significantly in the first few months of testing and seemed to slowly level off at around 55% after 1 ¾ years of testing. Testing continued for bond #71 and after 4 years of testing the yield was measured at 46%. Bond #103 showed the best initial yield at 94.1% and dropped to 73.5% after 1 ¾ of testing.

A number of factors contributed to these differences in yield. The last step for processing all of the device wafers was a buffered hydrofluoric acid (BHF) etch, followed by a distilled water soak and a methanol soak. For bonds #67, #71, #77 and #78 these wafers were dried on a hot plate. In each case some solvent residue was observed after drying. Residue was observed across nearly all of bond #78, likely contributing to the initial yield of 34%. In the other bonds in Table 1, critical point drying was used. This resulted in a cleaner process. Other factors that affected the yield included the bond ring deposition conditions on both the cap and device wafer, and various parameters in the bond recipe [1, 4].

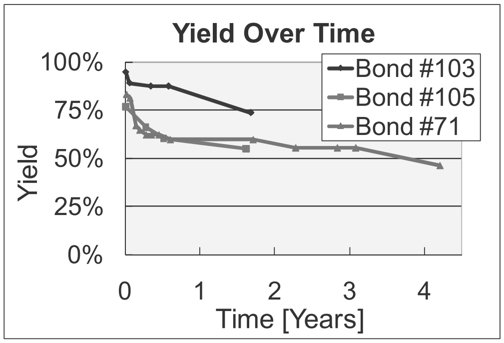

Figure 5: The calculated yield over time across three bonds.

CONCLUSION

Detailed long term hermeticity and vacuum results have been presented for wafer-level packages created in an Au-Si eutectic bonding process. Package pressures ranging from <3.7 to 23 mTorr, 77 to 980 mTorr and 2 to 44 Torr were observed, depending on the use of getters and an outgassing step in the bond recipe. The observed yields depended on a number of factors including the process parameters and bond recipe. Initial yields were observed to drop off significantly after the first few months of testing and then eventually leveled off. An initial yield of 94.8% was achieved and this dropped off to 73.5% after 1 ¾ years of testing. Other tests included 4 years of testing and reliability tests. Future work will include further optimization of the Au-Si eutectic process and its application to a wide range of MEMS applications.

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