Lead Frame Packaging of MEMS Devices Using Wafer-Level, Air-gap Structures

Nathan Fritz, Rajarshi Saha, Sue Ann Bidstrup Allen, and Paul A. Kohl

Georgia Institute of Technology
School of Chemical and Biomolecular Engineering
311 Ferst Drive, Atlanta, GA 30332 nathan.fritz@chbe.gatech.edu

ABSTRACT

Air-gap structures are of particular interest for the packaging of microelectromechanical systems (MEMS). In this work, an overcoat material is used to cover a sacrificial polymer, polypropylene carbonate (PPC), which protects the MEMS device during the packaging process. Once the overcoat is in place, the sacrificial polymer is thermally decomposed freeing the MEMS structure while the overcoat dielectric remains to provide mechanical protection and isolation from the environment.

This packaging mechanism can be adapted for a range of MEMS device sizes and operating environments. However, the air-cavity structures require rigidity to withstand chip level packaging conditions. Current work is focused on implementing a wafer level air-cavity package into a lead-frame packaging scheme for MEMS devices. Air-gap structures have been studied with regards to metal overcoat for increased rigidity. Finite element models and analytical models were used to understand mechanical testing results with regard to cavity deformation as well as provide a useful tool for designing larger structures.

Keywords: MEMS packaging, air-gap structures, sacrificial polymers, lead frame molding

1 INTRODUCTION

Recent advances in microelectromechanical systems (MEMS) technology have expanded their possible applications and potential market use. However, MEMS packaging presents a pivotal challenge to their overall potential. For typical MEMS-based products, packaging expenses can be up to 20% to 40% of the product's total material and assembly cost.[1] While certain MEMS devices require specialized conditions for operation, a cost efficient, IC compatible packaging process would vastly improve cost and application for a large variety of MEMS devices. In this work, a polymer-based air-gap structure process is being investigated to provide a cost efficient method for lead frame packaging of MEMS devices.[2-4] The air-gap structure utilizes a photolithography process where the sacrifical material is thermally decomposed and the volatile products permeate out of the cavity through a polymer overcoat. The design of the cavity can be tailored to fit a range of devices of various sizes and shapes. Packages may also be designed to prevent or allow interaction with environment by the heremtic sealing of the cavity with a metal or introducing microfluidic ports. Previous work has demonstrated that this process can be used to package MEMS devices such as gyroscopes and resonators on the wafer level.[3-4]

However, the package must be able to withstand the pressure and temperature conditions for chip-level packaging. This work focused on the mechanical compliance of the wafer level air-gap package for epoxy molding. If the cavity lacks the rigidity and strength, the cavity will collapse under pressure during the molding phase. There are two main forms of molding used in chip level packaging today. An injection or transfer molding is the predominantly used technology for lead frame package. The chip typically experiences conditions of 100 atm and a temperature around 175°C during the molding process. Compression molding is an emerging technology designed to package the top side of the substrate for thin packaging or chip stacking. During the compression molding, the chip experiences lower pressure conditions than with injection molding. For this reason, the study focused primarily on the higher pressure injection molding system. In order to improve the cavity rigidity for the molding process, metallization of the polymer overcoat was used to provide a high modulus material. This metallization could also be used as the hermetic seal for the package. Air-gap structures were investigated for the type of metal and thickness required for rigidity during injection molding. Finite element models and analytical models were used in comparison with experimental results with regard to cavity deformation as well as provide a useful tool for designing future packages.

2 MATERIALS

Polypropylene carbonate (PPC) was used as the sacrificial polymer in the air-gap structure. PPC, shown in Fig. 1, thermally decomposes completely at 220°C. The primary volatile products of decomposition are acetone and carbon dioxide and can permeate through many dielectrics at the decomposition temperature.

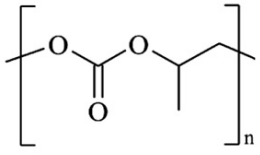

Figure 1: Structure of Polypropylene Carbonate.

The PPC films were made by dissolving the polymer in γ-butyrolactone, typically 18 wt% polymer. No photodefineable additives were added to the mixture to improve residue but requires a dry oxygen plasma patterning step.

An epoxycylcohexyl polyhedral oligomeric silsesquioxane (POSS) photodefineable dielectric was chosen for use as the overcoat material in the wafer-level package.[2] The POSS structrure consists of a silicon oxide cage structure with an epoxycyclohexyl group on each corner, $(C8H13O2)_n(SiO1.5)_n$, where n = 8, 10 or 12. The formulation is a mixture of 8-, 10-, and 12-cornered POSS molecules and corresponding epoxy groups. An example of the 8-cornered POSS is shown in Fig. 2.

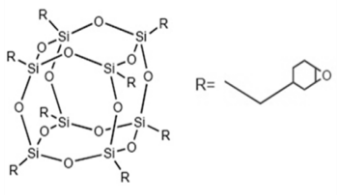

Figure 2: Structure of epoxycyclohexyl POSS.

The epoxy POSS was chosen for its oxygen plasma selectivity when patterning the sacrificial layer as well as a high modulus, rigid polymeric overcoat. Epoxycylcohexyl POSS cage mixture was dissolved in mesitylene, making 40 wt.% or 60 wt.% solids solutions. An iodonium photo-acid generator (PAG) was added at 1 wt% of POSS and sensitizer at 0.33 wt% of POSS so as to make the formulation photosensitive at 365 nm.

3 PROCESSING

Deep silicon trenches were fabricated on 4" Si(100) wafers using the Bosch process. These trenches resembled actual MEMS resonator devices that are currently being fabricated. Trench widths varied between 2 to 6µm, and the trenchdepth was approximately 6µm. Each simulated device had between 2-6 trenches depending on the type of device, and each wafer had close to few hundred simulated devices. Wafer-level packaging process (Fig. 3) was then carried out on these simulated devices.

The air-gap process uses an overcoat material to cover a sacrificial polymer which protects the MEMS device during packaging. Once the overcoat is in place, the sacrificial polymer is thermally decomposed freeing the MEMS structure while the overcoat dielectric provides mechanical and chemical protection from the environment. The decomposition process and the overcoat material have been designed for clean removal of the PC material without damaging the cavity formed during the process.

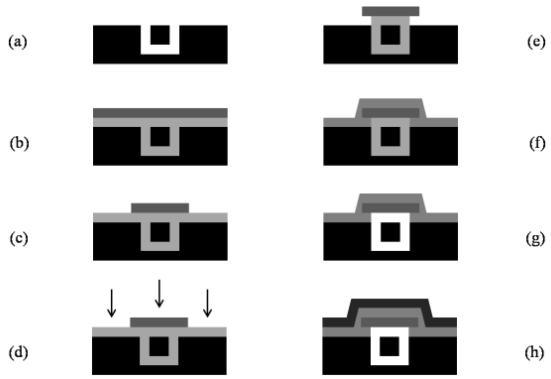

Figure 3: Schematic of the fabrication process for a MEMS package cavity. (a) Fabricated MEMS device (black). (b) Spin-coat PPC (light gray) and POSS (medium gray) layers. (c) Pattern POSS mask. (d, e) Pattern PPC using the POSS mask in RIE. (f) Apply overcoat material. (g) Decompose PPC and cure polymers. (h) Evaporate metal layer (dark gray).

For this MEMS Package, PPC was spin-coated on the silicon trenches and soft-baked on a hot-plate at 100°C for 5 mins. Several coats were required over deeper/wider trenches in order to have a complete conformal coating. The PPC thickness varied between 3-6 µm. To pattern the PPC, POSS was used as an etching mask. The POSS was spin-coated at 4000 rpm resulting in a 0.6 µm thick film. POSS was pre-baked at 85°C for 5 minutes, patterned at 365nm and post-baked at 85°C for 5 minutes again to cross-link the polymer. POSS was then spray developed using isopropyl alcohol. PPC was then RIE etched using a 6% CHF_3/ 94% oxygen plasma that resulted in a PPC/POSS etch rate selectivity of 24. The PPC etch rate was 0.66 µm/min. The overcoat POSS was then spun to a thickness of 3-6 µm and patterned. Finally, the PPC was decomposed through the overcoat at 240°C for 6-8 hrs in N_2 enviroment.

To prevent cavity cracking, rupture or adhesive loss, the decomposition process was modified from a constant heat rate to a constant weight percent decomposition rate. By using a constant decomposition rate process, the diffusion of material through the overcoat is relatively constant, and therefore a pressure imbalance is less likely to occur. To redesign the decomposition recipe, thermogravimetric analysis of the polymer was conducted to determine the kinetic parameters as recommended by Wu et al.[5] The reaction kinetics for the thermal decomposition of PPC was expressed as the nth order Arrhenius relationship shown in Eq. (1), and the decomposition rate was assumed to be equal to a constant r.

$$r = Ae^{\frac{-Ea}{RT}}(1 - rt)^n \qquad (1)$$

The decomposition reaction was determined to be first order (n) with the pre-exponential factor (A) and activation energy (Ea) to be $9x10^{12}$ min^{-1} and 120 kJ/mol, respectively. Eq. (1) was rearranged for temperature (T) vs.

decomposition time (t) as shown in Eq. (2). A rate of 0.25 wt.%/min for the decomposition was successful in decomposing the PPC and maintaining the cavity.

$$T = \frac{Ea}{R}\left[ln\frac{A(1-rt)^n}{r}\right]^{-1} \quad (2)$$

After the decomposition was complete the surface was cleaned using RIE and metallized. A chromium layer was sputtered for adhesion followed by a copper seed layer. The copper was then electroplated to the appropriate thickness. Cu was chosen for its modulus of 140 GPa but moderate film stress levels for a crack free overcoat. The samples were then annealed at 180°C for an hour. The wafers were diced with a diamond saw to separate the MEMS devices. A sampling of wafer level packages were characterized for quality before chip packaging using scanning electron microscopy (SEM) and tape adhesion test. The remaining samples were lead frame packaged using injection molding. The injection molding process was carried out at 175°C and 100 atm for 100 seconds. The samples were then cured for eight hours at 175°C. A few samples were completed with compression molding at 175°C and 40 atm for 100 seconds. All chip level packakges were cross-sectioned and inspected using an SEM.

4 MODELING

To predict the cavity deflection under pressure, analytical models of a bulge test were used. The bulge test is used to determine the modulus and stress of a thin film over a pressurized window, as seen in Figure 4.[6] The elastic modulus can then be solved for from the deflection of the film.

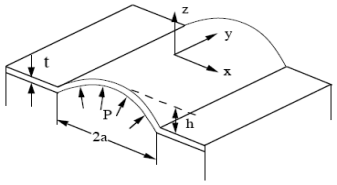

Figure 4: Schematic of the Bulge experiment.[6]

The analytical solution for a rectangular bulge test (equation 3)[6] was used for comparison to the rectangular MEMs package.

$$P = \frac{2ht\sigma_0}{a^2} + \frac{4h^3Et}{3a^4(1-\nu^2)} \quad (3)$$

In Equation 3, the cavity's polymer overcoat was neglected and the metal overcoat was determined to be the thin film since the elastic modulus of the metal is 30 times greater than that of the polymer. Since the metal film is annealed the initial film stress, σ_0, and the first term was assumed to be neglible. For the packages, the pressure is set by the molding process and the modulus to the choice of metal. The two controllable factors for design is the metal thickness and adjustment of the cavity height to prevent total deflection. As can be seen in Equation 3, the width of the cavity plays a crucial role in the amount of deflection of the cavity and will be a primary component in determining the metal thickness and cavity height.

Finite element modeling (ANSYS) was also used to determine the cavity deflection under pressure. The cavities were created using both the polymer and metal layers. The mechanical properties in the model were limited to be linear, elastic, and isotropic. To compare the model with the bulge equation, a 40 µm wide cavities with a 3 µm aluminum overcoat was tested to determine the pressure required to deflect the cavity 3 µm. The ANSYS model prdeicts the pressure to be 500 atm, while the analyitcal solution to equation 3 predicts a pressure of 506 atm.

5 RESULTS

Wafer level packages were fabricated on a simulated device for a capacitive resonator. Cavities for this particular device set range from 20 µm to 150 µm in characteristic width. Metal adhesion was excellent as determined by a cross hatched tape test. The cavities were cross-sectioned and viewed under SEM. The cavity dimension for the simulated capacitive devices in Figure 5 was approximately 20 x 200 µm. Cavities were approximately 5 um tall. The cavity was able to retain the shape of the PPC coating underneath. The side-walls were clearly defined, and the cavities were debris-free. The initial cavities utilized a 1 µm Al overcoat for the metal hermetic seal and metal support.

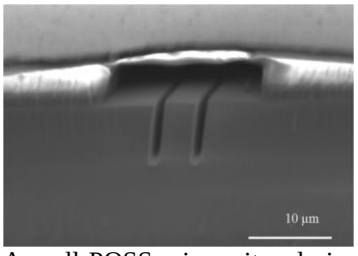

Figure 5: An all-POSS air-cavity designed for a resonator package. A 1 µm Al layer is on top of the 2 µm POSS overcoat. The trenches in the wafer show where the resonator would be located.

Injection molding was carried out on the cavities as part of molding experiments for lead-frame packaging of actual devices. Molding temperature was set at 175°C for 105 s, transfer pressure at 100 atm and post mold cure at 175°C for 8 hr. Cross sections were studied under SEM to evaluate cavity damage. At 100 atm, cavities were observed to be completely flattened. The material located in the trench was determined to be aluminum oxide due to polishing of the sample. (Fig. 6(a)). The Al support layer lacked the mechanical rigidity required for the injection molding process.

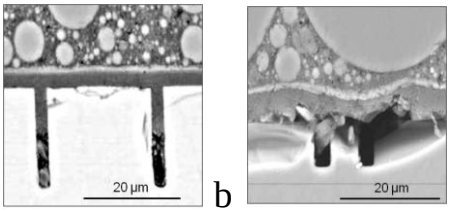

Figure 6: Injection molding of cavities show complete cavity collapse at 100 atm molding pressure (a). In (b) pressure was reduced to 40 atm using compression molding and cavities were intact. Both cavities had a 1 µm Al overcoat.

However, an alternative compression molding process was also tested for packaging. This process lowered the molding pressure to 40 atm, and the cavities stayed intact (Fig. 6(b)). The cavities showed some deflection of the cavity roof, but was several micrometers from the wafer surface preventing contact with the simulated device. Some debris accumulated inside the cavity due to aggressive cross-sectioning.

The experimental results and models were compared to check compliance of the model for future cavity design. The cavities were modeled in ANSYS for both the injection and compression molding. Figure 7(a) shows the injection molding cavity to be collapsed to the surface. The model did not completely collapse the wafer as seen in the experimental results due to the restrictions imposed by linear, elastic properties within the model. Figure 8(b) shows the compression molding model deflecting 1.5 µm and in good comparison with the experimental compression of the samples.

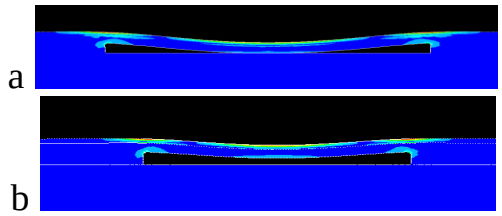

Figure 8: Finite element models of Injection molded cavities showed complete cavity collapse at 100 atm (a). In (b) pressure was reduced to 40 atm and cavities were intact.

A second set of wafer level packages were designed to test improvements on the wafer level package for injection molding. The cavities range in size from 20 x 200 µm to 150 x 500 µm. Cavities were designed to be 6 µm tall and formed using the air-gap process shown in Figure 3. The 1 µm aluminum metal support was switched for a thicker, higher modulus, 3 µm copper support. The new cavities were injection molded at 175°C for 105 s, using a transfer pressure of 100 atm and post mold cure at 175°C for 8 hr. Cross sections were studied using SEM to evaluate cavity damage. Cavities that were 70 µm wide (Fig. 9) and smaller showed minimal deflection, with the top of the cavity not interacting with the device surface. The residue in the cavity was due to the cross-sectioning and polishing. The 150 µm wide cavity did collapse under the pressure of the molding . Equation 3 was used to predict the collapse of the 150 µm cavity, due to the increased width being to the fourth power in the equation.

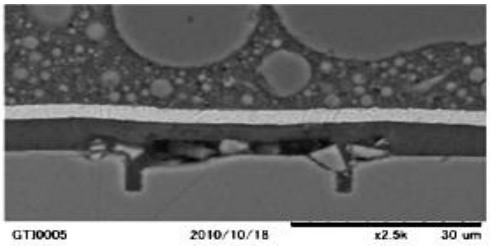

Figure 9: A 70µm X 200 µm resonator cavity cross-sectioned after injection molding. The residue in the cavity is due to dicing damage.

6 CONCLUSION

An innovative air-gap process was used to create a clean, wafer level package for MEMs devices of various dimensions on silicon wafers. The wafer level package demonstrated design flexibility to package a wide variety of devices. The air-gap package utilized a metal overcoat to provide rigidity during the injection molding process in lead frame packaging. The strength of the cavity was effectively improved by increasing the thickness of the metal layer as well as using a high strength metal. Air-gap MEMS packages demonstrated mechanical reliability in injection molding conditions for package sizes up to 70 µm in width. Finite element models and analytical tools were developed to predict deflection and collapse during the molding process for future package designs.

REFERENCES

[1] Grace, R.; Maher, M. A. *Hearst Electronic Products*, http://www2.electronicproducts.com/PageSearch.aspx?FName=farc_softmems_nov2010.html, 2010.

[2] Fritz, N.; Saha, R.; Allen, S.; Kohl, P. A. *Journal of Electronic Materials*, *39*, pp 149–156, 2010.

[3] Joseph, P.J.; Monajemi, P.; Ayazi, F.; Kohl P.A. *IEEE Transactions on Advanced Packaging*, *30* (1), pp 19–26, 2007.

[4] Monajemi, P.; Joseph, P.J.; Kohl, P.A.; Ayazi, F. *Journal of Microelectromechanics and Microengineering*, *16*, pp 742–750, 2006.

[5] Wu, X.; Reed, H.A.; Wang, Y.; Rhodes, L.F.; Elce, E.; Ravikiran, R.; Shick, R.A.; Henderson, C.L.; Allen, S.A.; Kohl, P.A. *Journal of the Electrochemical Society,150* (9), pp H205–H213, 2003.

[6] Nix, W. D. http://imechanica.org/files/353%20Class%20Notes%202005.pdf, 2005.