POST-PACKAGING RELEASE A NEW CONCEPT FOR SURFACE-MICROMACHINED DEVICES.

Balaji Sridharan, Chang-Jin "CJ" Kim and Long-Sun Huang
Mechanical and Aerospace Engineering Department
University of California, Los Angeles, CA 90095-1597

ABSTRACT

A novel procedure of post-packaging release, i.e., releasing surface-micromachined elements "after" packaging has been performed, is presented in this paper. This new concept of "post-packaging release" makes MEMS packaging considerably less demanding and thus much cheaper by completing most of the packaging steps "before" the delicate microstructures are released (freed). The concept has been successfully demonstrated with two types of test chips (MCNC MUMPs processed) by sublimation release after packaging. The concept of post-packaging release is even more attractive if the sacrificial layer can be removed by vapor-phase etchants such as HF vapor (for oxide) or XeF_2 or BrF_3 (for silicon), since a full spectrum of bonding methods are compatible.

INTRODUCTION

Packaging of MEMS devices starts usually after micromachining is complete, i.e., after microstructures are released (freed). During packaging the microstructures are free to move and are susceptible to damage as a result of improper handling. This paper presents a unique concept which makes devices more rugged during packaging and hence less susceptible to damage. This concept coined "post-packaging release" refers to releasing microelements on the chip after it is housed by a cap and protected. Two methods of post-packaging release are discussed, and the concept has been successfully verified using one of the methods.

Concept

Post-packaging release using sublimation release technique: In this method, the sacrificial layer is removed in wet chemicals but, without ever being dried, the microstructures are embedded in a coating that can be sublimated after packaging has been performed. Release holes are provided on the cap wafer for this purpose. This concept is schematically illustrated in Figure 1(a) and will be experimentally verified in this paper.

Post-packaging release using vapor-phase release technique: In this method of performing post-packaging release, the sacrificial layer is not removed until packaging has been performed.

Figure 1. Post-packaging release: concept (a) Sublimation release, (b) Vapor-phase release

Examples are removing oxide with HF vapor [1] or removing silicon with XeF_2 [2] or BrF_3 [3]. This concept is being proposed as schematically shown in Figure 1(b) but yet to be experimentally tested. The advantage is that a whole spectrum of bonding methods can be employed, whereas the sublimation technique is restricted by the melting point of the sublimation solid.

Sublimation

Sublimation release procedure was initially developed in MEMS community as a method to prevent stiction of microelements during the process of releasing surface-micromachined devices (e.g. [4]). While freeing microstructures by drying, the devices are pulled down to the substrate as a result of surface tension. If the devices contact the substrate, permanent sticking of the devices to the substrate may be brought about by molecular range interactions (e.g. hydrogen bonding and van der Waals forces). One method of preventing this phenomenon of stiction is to avoid the formation of liquid-air interface between the microstructures and the substrate. The sublimation release procedure avoids the formation of liquid-air interface by forming a solid-air interface and thus completely avoids the pull down force and thereby prevents stiction during release. Two convenient sublimation materials are p-dichlorobenzene [4] and t-butyl alcohol [5].

EXPERIMENT

Fabrication of base and cap wafer

Figure 2. Fabrication of cap wafer

The cap wafer for post-packaging release has to be fabricated to provide release holes for sublimating the solid substance and also to provide a transparent window on the top for demonstration purposes to observe the released microstructures after packaging has been performed. The fabrication of the cap wafer starts by growing a thermal oxide on a (100) silicon wafer and deposition of a silicon nitride by LPCVD as an etch mask for KOH. The mask for the release holes is then patterned on the top side of the cap wafer, and the mask for the cavity to enclose the microdevices is

patterned on the bottom side using a front-to-back side aligner (Karl Suss). After this process of double side alignment and patterning, the cap wafer is sculptured by etching in KOH to complete the formation of release holes and the cavity. If a viewing window is used, a large extra hole is made on the cap wafer and covered with a thin cover glass as shown in Figure 2.

The base wafer has to be fabricated in a way to accommodate a typical surface-micromachined chip. Hence, the base wafer is made by bonding two silicon wafers, one of which is etched through (before bonding) using KOH. The wafer with the through hole is then patterned with gold bonding pads to provide electrical connection through wire bonding to activate the devices on the test chip after packaging has been completed. The bond pads are fabricated by doing a Ti/Au lift-off process. The Ti serves as an adhesion promoter for gold on silicon. This bulk-etched wafer is then bonded to another bare silicon wafer to complete the base wafer assembly.

Procedure

After the completion of the base and cap wafer as outlined in the earlier section, a test chip (MCNC's Multi-User MEMS Processes) is released using HF (49%) for 2-2.5 minutes. This time is usually more than sufficient to completely etch away the sacrificial PSG (phosphosilicate glass) and release the microstructures. After two successive rinses are carried out in DI water for 10 minutes each, the chip is then transferred to a methanol bath. The reason for this rinse step is that the p-dichlorobenzene is soluble in methanol and it is necessary to replace the DI water from the previous step with methanol before introducing p-dichlorobenzene. After this the chip is transferred to another bath with methanol maintained at around 60°C as the elevation in temperature helps the solubility of methanol in p-dichlorobenzene. For the purpose of post-packaging release it is necessary that only a thin coating of sublimation solid remains on the surface. Thin coating is necessary to ensure that the chip with the coating can be accommodated in the cavity provided in the cap wafer. This thin coating is achieved by the following process. After the final rinse in liquid p-dichlorobenzene, the chip with a thick coating of p-dichlorobenzene is placed on a Peltier chip [6] maintained at 50°C. This causes the liquid dichlorobenzene to evaporate at a rapid rate, and after a few seconds only a thin film remains on the surface. This liquid film is solidified by cooling the chip down to the room temperature, leaving a thin film of solid p-dichlorobenzene on the chip surface (100-200 µm thick). After this process the chip with the p-dichlorobenzene coating is placed in the cavity provided in the base wafer, and if an external connection is to be made wire bonding is done with the corresponding bond pads on the base wafer at this stage. The cap wafer is then bonded to the base wafer using an adhesive bonding technique such as epoxy bonding. It is desirable to limit the temperature in the bonding process to a temperature much below the melting point of p-dichlorobenzene (56°C at atmospheric pressure). After packaging the chip, the base-cap wafer assembly with the chip coated with p-dichlorobenzene is placed inside a vacuum chamber and the p-dichlorobenzene is sublimated under vacuum to complete the release procedure. The released chip is then observed through the cover glass window provided in the cap wafer for this purpose to observe the results of the release and packaging procedure.

Need for new sublimation setup

The release of packaged chip, through the release holes located in the cap wafer, took much longer (10 hours) than the regular sublimation release of open chips (30 minutes) [6]. Sublimation was limited by diffusion through these small release

Figure 3. Post packaging release procedure

holes (200 µm x 200 µm). This called for us to investigate the sublimation of the chemical used (p-dichlorobenzene) and propose a method of overcoming this limitation.

The rate of sublimation of a solid can be determined by the following equation,

$$\dot{r} = g_m(m_s - m_e) \quad (1)$$

where g_m = mass transfer conductance

m_s = mass fraction of p-dichlorobenzene

m_e = mass fraction of p-dichlorobenzene at ∞

$$m_s = \left(\frac{P_s}{P} \right) \times \left(\frac{M_d}{M_{air}} \right) \quad (2)$$

while P_s = sublimation pressure of p-dichlorobenzene

P = Total pressure in the vacuum chamber

M_d = molecular mass of p-dichlorobenzene

M_{air} = molecular mass of air.

Combining Eq. (1) and Eq. (2) and since $m_e = 0$.

$$\dot{r} = \left(\frac{P_s}{P} \right) \times \left(\frac{M_d}{M_{air}} \right) \times g_m \quad (3)$$

In the above equation, g_m is a factor dependent on the physical properties of the material, temperature, airflow etc. and can be assumed to be a constant as there is not much of a variation in these factors in our experiments:

$$\dot{r} = \text{const} \times \left(\frac{P_s}{P} \right) \quad (4)$$

From the Equation (4), it is clear that the sublimation rate is a strong function of the ratio of sublimation pressure to the total pressure of the system. This indicates that the sublimation rate can be increased by either increasing the sublimation pressure or by lowering the total pressure of the system. The sublimation pressure

of p-dichlorobenzene has been experimentally determined by Polednick et al. and fitted according to Antonine equation [7].

$$P = \exp\{28.4986 - 6272.86/(T - 32.2741)\} \quad (5)$$

where P is the sublimation pressure of p-dichlorobenzene in Pascals and T is the temperature in Kelvin. The graph of the variation of sublimation pressure with temperature is shown in Figure 4.

Figure 4. Sublimation pressure of p-dichlorobenzene as function of temperature [7]

As seen from the graph, the sublimation pressure of p-dichlorobenzene increases with the temperature. The sublimation rate can thus be improved by raising the temperature. This method of increasing the temperature can be easily performed using the Peltier chip design in the sublimation setup described in [6]. The sublimation rate was observed to increase if the temperature of the substrate was raised to ~40°C (still below the melting point of dichlorobenzene). However the dichlorobenzene sublimated from the chip surface tends to deposit on the inside cavity wall of the cap wafer as the temperature is lower on the cap than the base wafer.

Another method of increasing the sublimation rate is by decreasing the total pressure of the system. This decrease in total pressure was achieved by an improved sublimation setup described below.

New sublimation setup

The new sublimation setup incorporates a high vacuum pump capable of going down to the sublimation pressure of p-dichlorobenzene. A Speedivac 2 rotary vacuum pump which has an ultimate vacuum of 10 Pa was used for this purpose. A foreline trap was installed between the vacuum chamber and the vacuum pump. The vacuum chamber is also fitted with a pressure indicator and valve for regulating the vacuum. The valve serves the purpose of breaking the vacuum in the chamber before shutting off the pump and preventing seeping of the oil from the pump to the vacuum chamber. A cooling tower is also included in the setup to prevent the p-dichlorobenzene vapor from escaping into the atmosphere. The schematic layout of various components of the vacuum setup along with a picture of the setup is shown below.

Figure 5. Sublimation setup (a) schematic, (b) picture

TEST STRUCTURE AND RESULTS

The test structures used for demonstrating the post-packaging release concept were fabricated using MCNC's MUMPs. One set of test structures for verifying the results of post-packaging release consists of a set of polysilicon beam structures. The beams are 2 μm thick and are suspended at a distance of 2 μm from the substrate. The width of the beam structures vary from 2 μm to 12 μm. This varying beam width enables us to compare the data obtained for release length vs. thickness with those previously obtained using the unpackaged chips [6]. In order to further verify the success of this unique method of post-packaging release, another set of structures were fabricated using the MUMPs process. This set incorporated different sets of comb drives, which can be actuated through actuation pads on the chip, which in turn are wire bonded to corresponding bonding pads on the base wafer. The purpose of designing these devices was to drive the packaged comb actuators from outside the package and observe the performance through the viewing window provided on the cap

wafer. The layout of the test chip and picture of the packaged device are shown in Figures 6 and 7 respectively. The results obtained on the chip containing beams of varying width is plotted as a function of detachment length vs. beam width in Figure 8. The data obtained with open (unpackaged) chips [6] is plotted alongside for reference. As seen from the data, there is little difference between the post-packaging release procedure and the sublimation release procedure, implying the success of this method. The comb drive structures released using this method were also actuated to test this method and were found to function without any difficulties.

Figure 6. Layout of a test chip

Figure 7. Picture of a post-packaging release chip

CONCLUSION

In this paper, we have demonstrated a method of releasing the surface-micromachined devices after packaging has been performed, thereby making the overall production procedure much more rugged and economical. An improved setup for sublimation release was also developed during the course of this work, which improves the sublimation rate considerably. Experiments showed no apparent ill effect of packaging to surface-micromachined elements. With the introduction of new room temperature wafer

bonding procedures like the microriveting [8], this method of post-packaging release is believed to improve production of MEMS devices. A method of post-packaging release using vapor-phase etchants was also proposed.

Figure 8. Results of post packaging release

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