Chemically resistant encapsulant to enable a novel MEMS fabrication process

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Abstract

We have proposed and demonstrated a novel sequence in MEMS fabrication process flow. The novel MEMS fabrication process flow can be shortly described as a “packaging first, MEMS release second”, whereas a standard process starts form MEMS release and ends up with packaging. The process is explored on a 3D capacitive MEMS sensor (3 x 3 mm²). Unreleased wafer is singulated by sawing on individual dies, then the individual sensor is mounted to the package, wire bonded and encapsulated. Because the sensors are still unreleased there is no damage occurred during the assembly. However the choice for the encapsulant material is not evident. The encapsulant must survive the chemical attack during the MEMS release process (mixture of 73%HF and IPA (isopropanol)), followed by a triple rinse in IPA. We pre-selected 6 different encapsulants: a silicone-, an epoxy- and an urethane-based. At least one encapsulant passed the acceptance criteria: there is no delamination, there is no texture change and the encapsulant maintains a sufficient mechanical adhesion. Additionally to that we measured micro-hardness of the encapsulant before and after the HF release test. We also performed an electrical characterization of the flow meter sensor before and after the HF release and we detected no changes in the sensor’s performance caused by HF exposure. We have proposed and demonstrated a novel sequence for MEMS fabrication. We packaged the sensor first, and performed the release after that. The key enabler for the novel process is the encapsulant which can withstand exposure to the release solution (73%HF:IPA).

Key words: MEMS fabrication, HF release, MEMS packaging.

Introduction

Microsys lab, ULg (University of Liege, Belgium) and ICTEAM department, UCL (Université Catholique de Louvain) work many years together on R&D and processing of working prototypes of different type of MEMS (micro-electromechanical systems) based sensors. Our goal is to develop and to demonstrate a working prototype of the sensor for specific application and to ensure that the sensor can be manufactured in mass-scale production environment. In many specific cases, the standard sequence [1] in MEMS fabrication process flow cannot be implemented neither in production environment nor in the laboratory. In response to that we developed and demonstrated a novel MEMS fabrication process flow that can be shortly described as a “packaging first, MEMS release second”, whereas a standard process starts from MEMS release and ends up with packaging [2].

Many MEMS unlikely as a classic IC comprises moving parts that are originally supported by a sacrificial layer. The last step of MEMS fabrication is a MEMS release, this is to remove the sacrificial layer supporting the moving part of the MEMS, and as a result of that the moving parts become released. Till the point of the sacrificial layer release the MEMS device is still robust enough to withstand any post-processing. After the MEMS release the device becomes vulnerable to any physical and chemical exposure. Such exposure can occur and effectively occurs during transportation, handling or any post-processing (including the packaging).

Beside our approach namely the “packaging first, MEMS release second”, there are different approaches known to overcome such hurdles [2]. They have specific advantages and disadvantages.

The idea to perform a post-processing on the die level and /or on assembled dies not really new for us. For example, in our later paper on the influenza virus detector development, we already explored and reported a post-processing sequence similar to that approach. There, first we assembled the system, and as a last step was a bio-

functionalization using a bio-material of the already assembled sensor die. The bio-material was applied locally by the micro-dispenser [3, 4]. The bio-material one side has a limited self-life, and on another side cannot withstand the impact of processing occurred during the sensor die assembly.

This paper proceeds as following. The MEMS features and manufacturing process flow are introduced briefly, with extra explanations of the MEMS release process and process optimization. Then the MEMS assembly process flow described in details. A special attention is paid for the encapsulation. In the following section we introduced the specification for the encapsulant material and we explained the selection criteria and gave details on the encapsulant screening matrix. Then, we describe the test method and the result of the test is demonstrated. We showed an effect of the release on selected mechanical properties of the encapsulant material and on electrical behaviour of the MEMS structure. In the last section we draw a conclusion.

Sensor assembly process flow

The novel MEMS fabrication process flow has been explored on a three-dimensional (3-D) MEMS capacitive sensor. The sensor die of 3 x 3 mm² lateral dimensions is fabricated on a 3-inch silicon wafer at the WINFAB clean room (UCL, Belgium).

The sensor consists of a movable 3-D membrane above a split bottom electrode [5, 6], where the initial polyimide layer acting as both anchor and sacrificial layer is replaced by an oxide layer. The gap between the top electrode (membrane) and the bottom electrode can be controlled by capacitive actuation depending on the application. Such device aims at gas ionization sensing and it is achieved by incorporating or not nanowires on the bottom electrode in order to locally enhance the electric field [7, 8].

Another possible application for the MEMS capacitive sensor is a selective detection of hydrogen, it is achieved by introduction an extra features a bimorph palladium/aluminium (Pd/Al) as part of the top membrane build material. The hydrogen adsorption in palladium induces tensile stress in the Pd/Al bimorph and causes change in the deflection of the movable 3-D membrane depending on the concentration [9]. This change in deflection is then converted into electrical signal and that is read-out.

Figure 1 shows a schematic (cross-section view and top view) of the tested device (3-D MEMS capacitive sensor), before and after release.

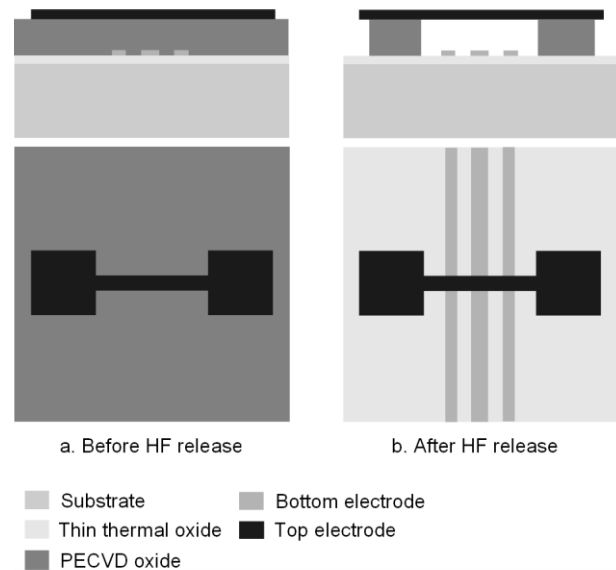

Figure 1: Top and cross-section schematic of the test 3D MEMS device, before (a) and after (b) release.

Since our last publication [2] we did not change sensor assembly process flow, more details can be found in the mentioned above publication. After manufacturing the sensor wafer, the wafer is singulated on the individual MEMS device and transferred to Microsys laboratory (ULg, Belgium) for the assembly. Remarkably, that the sensors are not yet released. As a result of that, the individual sensor can without any damage undergoes the standard assembly process flow that is normally used for the assembly CMOS IC. The individual sensor is mounted to the ceramic DIL24 package to order to enable a test procedure and electrical characterization. The assembly process comprises following steps: sensor mounting that includes adhesive dispensing, die attach, adhesive curing, and wire bonding and encapsulation. The most critical step in the process flow is the encapsulation.

Selection of the encapsulant and the encapsulation process

The encapsulant must meet following specific criteria. First, the encapsulant must survive the chemical attack taking place during the MEMS release process. The release process is relatively harsh and combines a 10 min exposure to the release solution (mixture of 75%HF and IPA in 1:1 ratio), followed by a triple rinse of 5min each in a rinsing solution (IPA). Normally, the encapsulant [10] is not designed to withstand an attack of aggressive chemical substances. The purpose of the encapsulation is just to protect the die against environment and to increase its reliability. In the previous paper on the subject we already reported on the details of the encapsulant selection procedure, it total we examined 20 encapsulation materials of different chemistry. As a result of that, is that we selected 2 encapsulants that pass the acceptance

criteria: there is no delamination, there is no texture change and the encapsulant maintains a sufficient mechanical adhesion. However, then we performed the same test of the working prototype some parts of the MEMS structure or all of them, namely the cantilever, the conductive trucks and other fine features were attacked during exposure to the release solution.

MEMS release optimization

On the first phase of the research we used following release procedure: 10 min exposure to the release solution (mixture of 75%HF and IPA in 1:1 ratio). We performed multiple tests to minimize effect of the release process on MEMS device. To achieve that, we explored two main routes: to minimize the exposure time to the release solution and to minimize the concentration of the HF in the release solution.

Table 1: Release process optimization test matrix.

Sample number	HF test conditions	Result
1	73%HF:IPA =1:0 30sec	Encapsulant OK, Al and/or oxide attacked, release
2	73%HF:IPA =1:0 3min	Encapsulant OK, Al and/or oxide attacked, release
3	73%HF:IPA =1:0 5min	Encapsulant OK, Al and/or oxide attacked, release
4	73%HF:IPA =1:1 60sec	Encapsulant OK Al and/or oxide attacked, release
5	73%HF:IPA =1:1 5min	Encapsulant OK Al and/or oxide attacked, release
6	Not tested witness	Not applicable

On all samples we observed the acceptable colour change of the tested encapsulant, ranging from colour change to light colour change depends of the exposure time and concentration of the HF. Evidently, that the encapsulant survive the test on all tested samples.

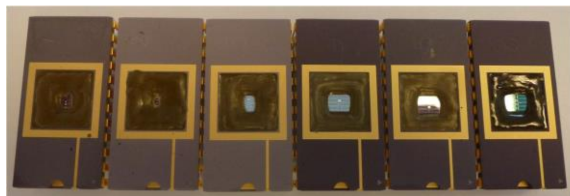

Figure 2: Visual observation after HF test, from left to right: sample 1 to sample 6. The sample 6 is not tested for reference purpose.

Figure 3: Capture of the partially encapsulated sensor (the encapsulant is in black), Al is not attacked during the test on the sample 4 (left,), whereas Al track is attacked on the sample 5 (right).

Remarkably, that on all tested samples (Table 1), there is no visually detected (by optical microscope) damage (such crack, delamination and etc) and other irregularities on the encapsulant surface caused by the release solution attack. On the early stage of our investigation [2], specifically on the encapsulant screening stage, we used a scanning electron microscope (SEM) to detect fine irregularities in the encapsulant, such as micro-cracks, micro-pits, delamination etc. and surface roughness characterization. Since that early stage the 2 selected encapsulants exhibits repeatable resistances to the release process, we used only optical microscope high magnification observations.

Finally the samples are released using the optimized recipe: the release solution composition (mixture of 75%HF and IPA in 1:1 ratio) and the release time of 30 sec. After the exposure to the release solution, the samples are subjected to rinse of 5 min each in rinsing solution IPA. The last step of the process flow was drying the samples by the automegasonic supercritical point dryer, this is to prevent an eventual stiction of the MEMS suspended part.

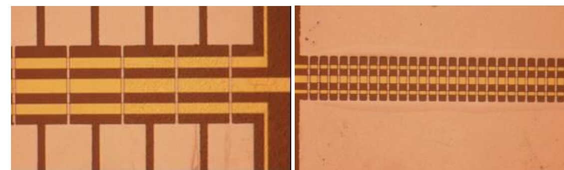

Figure 4: Capture of the suspended part of the sensor after release at optimized conditions, Al is not attacked during the test, and all suspended parts are released.

Micro-hardness study

Additionally to a visual inspection by microscope and SEM study, we used micro-hardness characterization to check if the encapsulant changed its mechanical properties during the release process. For that the micro-hardness study is performed by means of a nano-indentation. It is known that micro-hardness is impacted by the surface conditions and it is sensitive to any surface modification. The idea of the characterization is conceptually simple and the results are easy to interpret. To measure the sample properties before and after the treatment in the HF release solution and to compare both results, finally based on that is to indentify changes if any appears there.

The selected encapsulant is applied by dispensing in the form of 5 mm diameter droplets on the cleaved blanket silicon wafers and then sequentially tested. We considered 2 different wafer configurations Si /SIO2 /Si3N4 and Si /SIO2 /Si3N4 /Al.

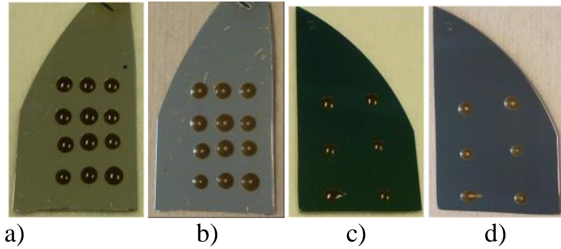

Figure 1: Test samples set for the micro-hardness study: a) and b) on Si /SIO2 /Si3N4 /Al wafer before and after the release correspondingly, c) and d) Si /SIO2 /Si3N4 wafer before and after the release correspondingly.

There is no significant modification in both Young's modulus and hardness on the selected encapsulant is observed after up to 2 min exposure in HF(73%:IPA) solution. The mean value of Young's modulus from sample to sample is ranging from 4.5 to 5.5 GPa and the mean hardness is between 0.35 and 0.45 GPa, with a large standard deviation, respectively up to 2 GPa and up to 0.15 GPa, due to the measurement conditions

Electrical characterization

The last step in the evaluation procedure was electrical characterization. The samples were measured before and after the HF release procedure. The equivalent electrical circuit of the tested structure is represented on Figure 5.

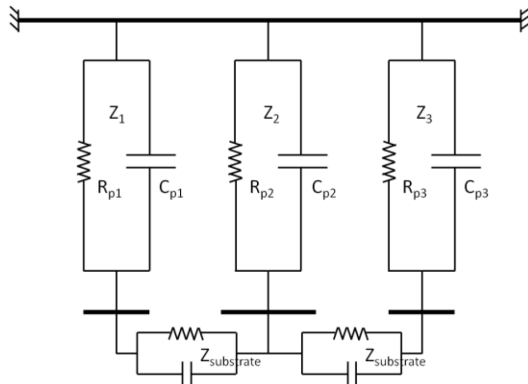

Figure 5: Equivalent electrical circuit of the tested 3D capacitive MEMS sensor

This electrical characterization is performed using a LCR 4284A meter. The LCR meter is connected between the upper electrode and the split bottom electrode of the MEMS. By neglecting the substrate effect, from $1/Z_{total} = 1/Z_1 + 1/Z_2 + 1/Z_3$, we then extract the equivalent parallel capacitance $C_p = C_{p1} + C_{p2} + C_{p3}$. Figure 6 shows the equivalent capacitance as a function of the frequency (up to 1MHz), before and after the release.

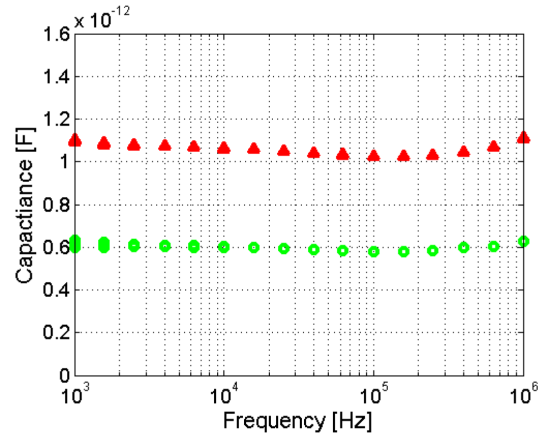

Figure 6: Capacitance measurement before (red triangles) and after (green circles) release.

As predicted, the capacitance of the measured MEMS is decreasing, this is because of the dielectric is removed during MEMS release process.

A parasitic capacitance of about 400 ftF seems to be present, as the theoretical permittivity of undensified PECVD SiO_2 is about 3.5, and not 1.8 as observed. Though, the buckling of the upper membrane can also explain this shift in capacitance value.

Conclusion

We have proposed and demonstrated a novel sequence in MEMS fabrication process flow. The novel MEMS fabrication process flow can be shortly described as a "packaging first, MEMS release second". We propose to package the MEMS device first (die mount, wire bonding and encapsulation) and to perform the MEMS release as the last step in the fabrication process flow. The novel MEMS fabrication process flow has been demonstrated on a flow meter sensor. The sensor of 3mmx3mm is fabricated on a silicon wafer. The released wafer is singulated by sawing on individual dies, then the individual sensor is mounted to the package and wire-bonded. Because the sensors are still unreleased there is no damage observed caused by post-processing. The 6 encapsulants of different chemistry were tested and 2 of them survived the chemical attack of the release solution (75%HF:IPA=1:1). As a by-product on the research we optimized the MEMS release process.

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