Feasibility of polymers for wafer scale capping of RF MEMS

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Abstract

This paper concerns the feasibility of polymer capping of RF-MEMS devices, replacing traditional silicon solutions. The advantage would be less costs and potential for both further miniaturisation and integration of electrical functions in the cap. One of the challenges is the resistance against expoxy overmoulding as part of the traditional back-end process chain. This involves temperatures of 175°C and pressures of 10MPa, which the cap has to withstand. Calculations are made and experiments carried out to investigate the feasibility of selected polymers. It is shown that nanofillers will lift the polymers mechanical properties comfortably above the minimum established demands.

Keywords: polymer, capping, RF MEMS, simulation, materials testing

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1. Introduction

A growth market is RF-MEMS filters for telecommunication. These are made in silicon fabs on waferscale. The actual RF filter structures often need a clearance (air cavity) between the filter and the package. The latter is normally made by moulding over of the die with an epoxy.

In order to preserve this air cavity in the overmoulding process, a protective cap is used that can withstand overmoulding pressures between 8 and 10MPa and temperatures between 160 and 200°C. Another demand is to resist reflow temperatures for lead free solder (soldering profiles up to 260°C peak temperature). Typical the air cavities have lateral dimensions in the range from a few 100μm to 1000μm. The total height of the cap should preferably not exceed 100μm. Other technical demands are that the capping doesn't interfere with the RF properties of the devices and provides sufficient hermiticity to keep the internal conditions (pressure, composition of internal atmosphere) stable. Often care must be taken that metal coatings on the filter elements are not corroded by gases from the capping material. In such cases halogens should not be present in the capping material.

The capping is a mid-end process, i.e. directly after fabrication of the filter wafer and before (compatible with conventional) back-end processing. State of the art in RF-MEMS capping are flat silicon caps which are positioned with pick and place techniques. For future generation of products, capping technologies are looked for, which reduce costs and allow further miniaturization (footprint reduction).

An alternative is wafer scale capping with a silicon capping wafer, which has to be processed for enabling (wire bonding or flip chip) interconnects. Both from ease of processing and cost perspective, use of polymer wafer level capping would be attractive here. Although the importance of polymers in MEMS is growing [1], their application is not established for this application.

Polymers that are used in semiconductor industry for e.g. structural (gap fill, stress buffer for passivation layers) or electric (dielectric interlayer) purposes are mostly applied as dry or wet films and patterned with lithographic techniques. Photosensitive poly-imides and epoxies are commonly used for this purpose. Very common is the use of thermosetting epoxies for packages, encapsulants and underfills. Thermoplastic liquid crystal polymers receive recently attention because of their hermitic and RF properties [2, 3].

With regard to capping of RF-MEMS, the feasibility of SU-8 epoxy capping was shown in [4], applied by a sacrificial layer method. Because SU-8 contains halogens, it will however not generally be applicable.

TNO carries out a study into the feasibility of polymer caps, with regard to both functional demands as well as the embedding in the process chain. This paper reports on one aspect, the strength to withstand the overmoulding step. Model system was an air cavity of 300μm x 600μm.

Firstly, a numerical analysis was carried out into the effect of thickness and shape on the deflection of a cap when overmoulded. It showed that a material with 2.5GPa Young's modulus should suffice for capping the 300μm x 600μm area.

Of primary importance is the softening of the cap during the overmoulding process. Because of lack of data in literature as well as from material suppliers, the effect of temperature on the stiffness was measured for commercial films, made out two types of candidate materials, LCP and poly-imide. Also, for a poly-imide precursor solution the effect of nanofillers on the high temperature stiffness was measured.

Finally, LCP and poly-imide film were used in experiments in which overmoulding was simulated with a purposely built apparatus.

2. Numerical analysis

FEM simulations of the cap deformation under a 9MPa external pressure were performed, see Fig. 1. Inner dimensions were 300μm x 600μm, the wall width was 20μm and height was 35μm. FEM code was MSC.Marc and 2005r3, linear elastic eight node isoparametric brick elements (type 7), were used. The Young's modulus was set at 2.5 GPa and the Poisson ratio at 0.25.

Multi-Material Micro Manufacture
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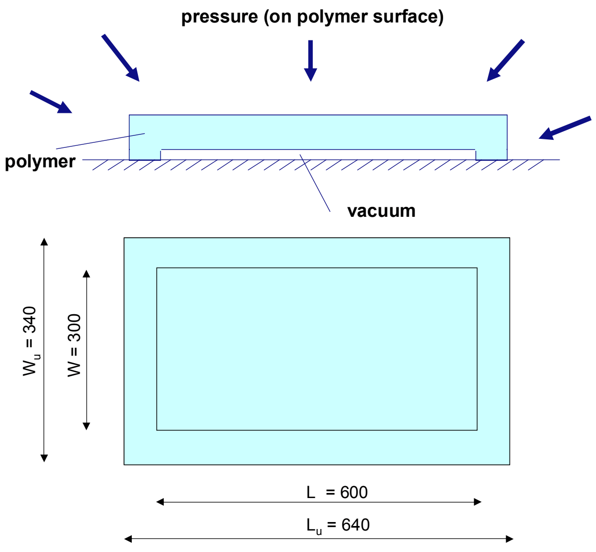

Fig. 1. Geometry of CAP deflection FEM calculations

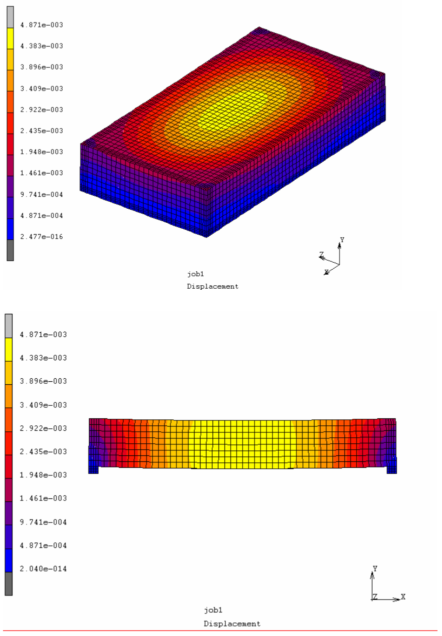

Fig. 2. Simulated displacement [mm]

Table 1
. Calculated deflection (in µm) of the cap centre

cap tickness	cap deflection
50	21
75	9.4
100	5.7

Fig. 2 depicts an example of a deformed cap geometry and Table 1 shows calculated deflections at the cap centre. It should be noticed that the geometry of the wall or rim which are part of the cap structure or on which the cap rests, affects the results. In case of a wall height of 15µm instead of 35µm, the deflection of a 100µm thick cap would be 4.8µm (and 8.2µm for a 75µm thick cap). If a large single 100µm thick cap is considered covering a matrix of cavities (with a 15µm high rim), the deflection would be reduced to 3.3µm.

Deflections were also calculated analytically for an unclamped thin plate, see Fig. 3. For reference, a 100µm thick plate results in a deflection of 3.2µm.

Further optimization is possible if the cap is given a concave dome shape, which will not be elaborated here.

How thinner the cap, how larger the deflection, which determines the minimum wall height. There is an optimum thickness, for a minimum total height of the cap. According to Fig. 3 this is for a cap thickness of 56µm, resulting in a total height of 74µm. A thicker cap however has the advantage of less strain in the cap and less shear stress at the surface with the die.

A remark has to be made on the effect of thermal expansion when the cap is heated. The cap will deform and deflect outwards due to the CTE mismatch with the silicon substrate. If this is taken into account, FEM calculations showed that the total deformation is reduced by a factor of two.

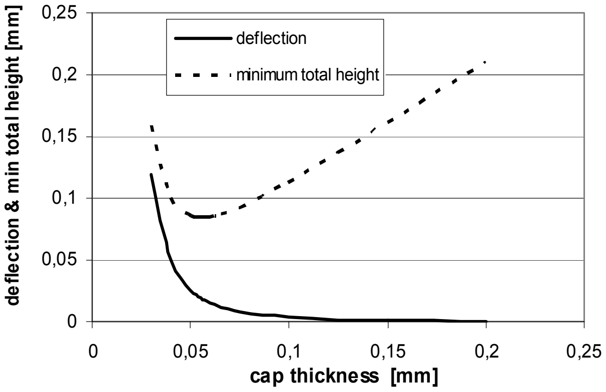

Fig. 3. Deflection and sum of deflection and cap thickness (minimum total height of cap) versus plate thickness.

3. Materials testing

3.1. LCP and poly-imide film

The calculations so far suggest that a Young's modulus of 2.5GPa (at the overmoulding temperature) should be large enough for a 100µm thick cap to withstand the overmoulding pressure without unacceptable deformation.

Two types of materials had emerged as first candidates for the capping application, namely LCP and poly-imides. Because of lack of experimental data, these were subjected to dynamic mechanical analysis (or DMA) for assessing the effect of temperature on their elastic properties. The samples were analyzed at a heating rate of 5 ºC/min.

LCP has good dielectric, barrier and humidity absorption properties and is consequently of large interest for packaging applications. A disadvantage however is their large anisotropy. Tests were carried out on 100 µm gauge (not reinforced) LCP film from Kuraray.

Poly-imides are widely used in semiconductor industry, and are mostly applied on wafers by spincoating followed by curing and lithographic structuring. For these test however, a 130µm gauge Kapton poly-imide film was used.

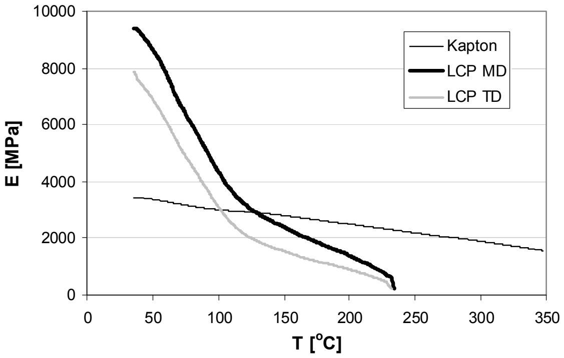

Fig. 4. DMA analysis on poly-imide Kapton and LCP film (latter in two orientations)

Fig. 4 depicts the measured curves. The modulus of Kapton falls in the range that is suitable for plastic capping. Actually, the 2.5GPa used in the calculations in Section 2 coincides well with the 175°C stiffness of Kapton. The stiffness of the tested LCP grade (an extruded film), although starting at a high value at room temperature drops quickly with temperature and will make it difficult to meet the stiffness requirements for overmoulding at 160ºC to 200ºC.

In general, the properties of LCP are strongly anisotropic (with a factor three stiffness variation for some grades), but for the tested grade at room temperature this was reduced significantly due to its manufacturing process (by film extrusion). At high temperatures the anisotropy is however again strong. The graph shows also that the elastic modulus of LCP decreases continuously as the temperature rises. It does not stay relatively level until the glass transition point in order to decrease sharply afterwards as crystalline or amorphous polymers tend to do.

3.2. Poly-imide with nanofillers

Nanofillers are used to improve the strength or other properties (such as hermiticity) of polymers. As part of the present feasibility study, the effect of mixing nanofillers in a precursor for an already relatively stiff poly-imide (dielectric interlayer) film was investigated. Fig. 5 shows that the nanofillers did increase the high temperature stiffness with 40%.

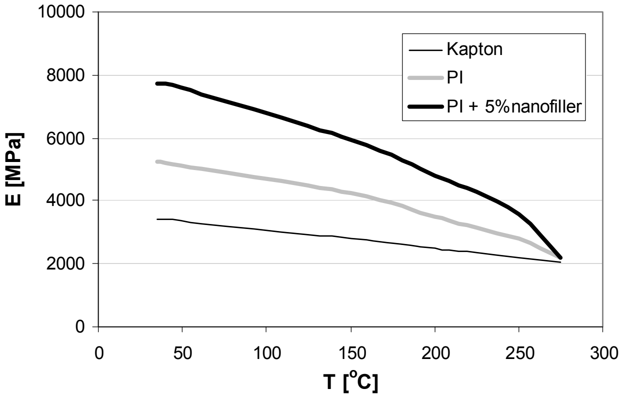

Fig. 5. DMA analysis on poly-imide Kapton film and film from a poly-imide precursor with and without nanofiller.

4. Experimental overmoulding simulations

In order to be able to validate the calculations, and recommendations that results from them, as well as the DMA analyses, a practical test was defined and executed. A tool was made to simulate the overmoulding process, see Fig. 6.

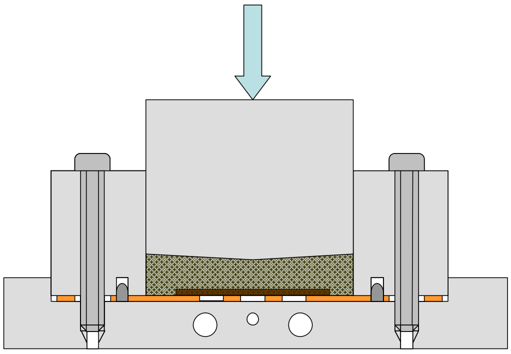

Fig. 6. Overmould simulation apparatus

The polymer capping film is placed on top of a template with a hole pattern, which is fixed on a base plate and under a ring. After heating of the tool (with heat rods in the base plate) the space above the film is filled with an epoxy compound and compressed by a punch. During the curing of the epoxy and subsequent cooling, the punch force and hence internal pressure are kept constant. Afterwards the punch is removed and both the geometry of film and epoxy surface (which has become a negative of the unreleased film surface) are measured, see Fig. 7.

A series of tests was carried out with a 130µm thick stainless steel template with a variety of apertures, see Fig. 8, on 100µm gauge LCP and 80µm gauge Kapton poly-imide film. Overmould pressure was 10MPa and temperature was 165°C.

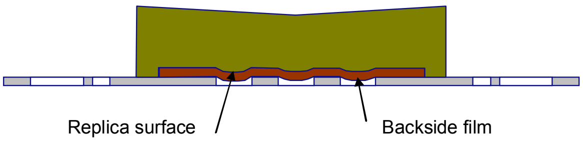

Fig. 7 Template with deformed film and expoxy replica.

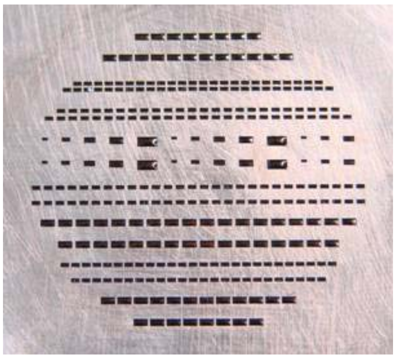

Fig. 8 Template with a pattern of holes ranging from 0.2mm x 0.4mm to 0.7mm x 1.4mm.

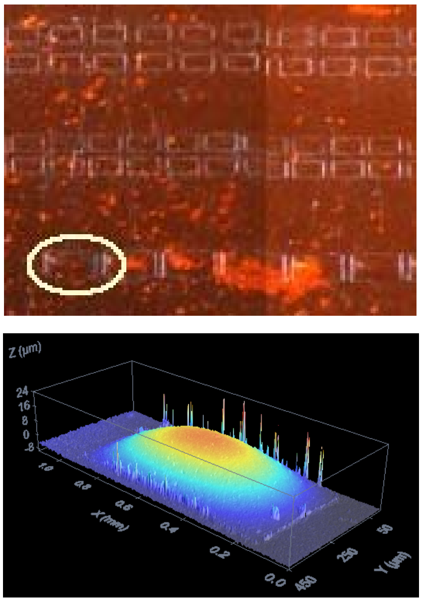

Fig. 9 Top: poly-imide film after overmoulding, with protrusions at site of 0.5mm x 1.0mm holes and 0.3mm x 0.6mm holes.
Bottom: confocal microscope scan of the encircled 0.5mm x 1.0mm protrusion.

Table 2
Measured and calculated deflection of the poly-imide film for various aperture sizes

aperture size [mm]	deflection range [µm]	calculated [µm]
0.2 x 0.4	1 – 1.1	1.4
0.3 x 0.6	2 – 7	7
0.4 x 0.8	n.a.	22
0.5 x 1.0	29 – 49	54
0.7 x 1.4	80 – 104	208 [a]

[a] N.B. experimental value cannot be larger than template gauge of 130µm

In agreement with the measured low stiffness at the test temperature, the LCP film failed. In effect, the film ruptured at the larger holes. The tested poly-imide film remained intact, see Fig. 9. Table 2 shows measured and analytically calculated deflection values, which agree reasonably (though calculated values are too high) except for the largest aperture.

5. Conclusions

Both numerical and analytical analyses of RF-MEMS cavity caps indicate that a modulus of elasticity of 2.5 GPa is large enough to make a cap withstand the overmoulding pressure.

Dynamic mechanical analysis tests show that poly-imides have sufficient high temperature stiffness to fulfil this condition. It was also shown that nanofillers re-inforced poly-imides (added in precursor phase) had a 40% increased high temperature stiffness.

A dedicated test apparatus was built and used for experimental simulation of the overmoulding of polymer film cavity caps. The experiments showed the feasibility of poly-imide as capping material. And last but not least reasonable agreement between measured and calculated deflection of the caps.

As a final conclusion, this study confirmed the feasibility of polymer capping from the mechanical point of view. What follows is the further selection and development of polymers, processing technology and equipment for embedding of wafer level polymer capping technology in the total RF-MEMS production chain.

Of prime importance will be bonding and adhesion technology, the effect of and how to overcome thermal expansion mismatch and barrier properties of the polymers (nanofiller reinforced or with coatings).

Acknowledgements

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