Design and characterization of thin SiGe membranes for MEMS packaging at wafer level

Pilar Gonzalez, Gert Claes, Kristin De Meyer and Ann Witvrouw

***Abstract*—In this work the use of SiGe layers for wafer-level thin film packaging of MEMS is investigated. The mechanical response of square SiGe packages subjected to molding in standard IC plastic packaging is determined by finite-element simulations. The minimum required cap thickness to withstand the mold pressure is reported together with different methods to stiffen the membrane. The effect of release holes opened in the membrane is also considered.**

***Index Terms*—MEMS packaging, SiGe, FEM simulations, plastic packaging**

I. INTRODUCTION

Packaging is the most critical step in developing and commercializing a MEMS device, accounting for 75% to 95% of the system cost [1]. In addition to the requirements for microelectronics packaging (electrical signal interconnection, electrical power interconnection, heat dissipation, mechanical and environmental protection), MEMS packages must allow for a controlled interaction with the environment to enable sensing and actuation [2]. Moreover, unlike CMOS chips, chips containing MEMS cannot be directly packaged in a plastic or ceramic package (the so-called first level package) as MEMS are often composed of fragile and/or mobile free-standing parts that can easily be harmed during dicing and assembly. To avoid this damage, a MEMS device should be protected on the wafer level before dicing, with the so-called zero-level package [3].

Zero-level or wafer-level packaging is typically done by wafer or chip bonding [4], that involves the bonding of a cap wafer or chip (e.g. glass, silicon or ceramic) with cavity to the MEMS wafer using anodic, fusion, eutectic, solder, adhesive or glass frit bonding techniques. Wafer-to-wafer or chip-to-wafer bonding has several drawbacks [5]. First, the anchor region where the cap seals to the MEMS die must be relatively large to ensure a hermetic seal and tolerate the potential misalignments. This translates into a significant increase in die size and die cost. Second, the bonded die is thicker than the standard IC die; therefore the packaged MEMS device cannot be housed in a thin profile package. Finally, the high temperatures or high voltages required for some of the bonding processes can be detrimental for many devices, which might limit the number of possible applications.

An alternative method is the formation and sealing of surface micro-machined membranes covering the MEMS devices, the so-called thin film encapsulation [3]. In this technique (figure 1) a layer of sacrificial material is deposited on top of the mechanical structures, followed by the deposition of an overcoat that acts as a capping layer. Release holes or perforations are opened in this capping layer to allow the removal of the sacrificial material. Finally the etch holes are sealed either by deposition of a thin layer of overcoat or by a reflow technique [6]. The advantages of thin films caps are the reduced thickness and area (and thus also cost) and the promise of being a lower-cost batch process [3].

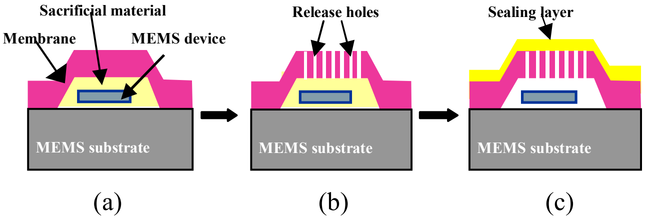

Figure 1 *Process steps for thin film packaging.(a) Deposition of sacrificial layer and capping layer. (b) Opening of release holes in the membrane and (c) removal of sacrificial material followed by sealing of the release holes*

In this paper the use of SiGe layers for wafer-level thin film packaging of MEMS is investigated through finite-element simulations. Polycrystalline SiGe has emerged as a promising MEMS structural material since it provides the desired mechanical properties and reliability at lower temperatures compared to poly-Si, allowing the post-processing of MEMS devices on top of CMOS [7]. Several integrated SiGe MEMS devices have already been realized [8,9]. Moreover, poly-SiGe can also be used as capping material for wafer-level MEMS packaging, forming an area-saving MEMS-device-scale 0-level package. Therefore this process might ultimately enable the creation of highly integrated miniature systems with multiple packaged sensors and actuators post-processed on a single chip [7].

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II. SIMULATIONS

The wafer-level package must protect the MEMS device during conventional post processing, such as dicing, wire bonding and even injection molding in standard IC plastic packaging. This final plastic injection-molding process is the most critical step, where the highest level of mechanical loading is applied. Therefore the package membrane must be robust enough to withstand the high mold pressure of approximately 90 bar [10].

In this work, finite element simulations (COMSOL [11]) are used to investigate the mechanical response of square SiGe packages (figure 2) subjected to standard IC plastic molding. A Young's modulus *E*=140GPa [12] and Poisson ratio ν =0.23 for poly-SiGe are used in the simulations. Both the deflection and induced stress in the package membrane when an external and uniform pressure of 90 bars is applied are studied. The minimum necessary membrane thickness for different package sizes to fulfill the chosen requirements of a deflection under 3 µm and a maximum induced stress lower than 1GPa (83% of fracture strength of poly-SiGe [13]), are reported.

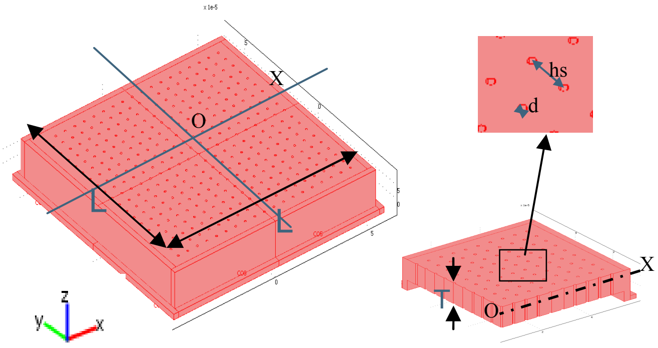


Figure 2 *Generic cross-section of packaged MEMS device and scheme of the square membranes. Length (L), thickness (T), hole diameter (d) and hole spacing (hs) are variable parameters*

As shown later, relatively thick membranes are necessary for the package to withstand plastic injection molding without cracking or deflecting so much that it touches the MEMS device. This translates in a high cost and a long processing time to deposit the thick cap layer. In order to reduce the required cap thickness, different methods to stiffen the membrane are studied: the use of a reinforcement layer on top of the SiGe membrane and the use of supports. SiC, thanks to its high Young's modulus (748 GPa) and low deposition temperature (350ºC), is the selected reinforcement material. The effect of the addition of a SiC layer with varied thickness on membrane deflection and induced stress is studied.

Finally, the effect of the release holes is also evaluated. These release holes are opened in the membrane to allow the removal of the sacrificial layer and the release of the MEMS device. Often, horizontal sacrificial etch channels at the periphery of the cavity are used, but the required release time is high. In order to have a fast sacrificial release process, the etch holes are favorably situated above the device, in the package membrane. These release holes must be sufficiently big to enable efficient release but also small enough such that no or only negligible deposition inside the MEMS cavity takes place during sealing. In this work only circular release holes are considered, and the effect of hole diameter and number of holes is studied.

III. RESULTS

A. Minimum required membrane thickness

The behavior (in terms of membrane deflection and induced stress) of poly-SiGe packages subjected to an external pressure of 90 bar, typical pressure used in plastic injection-molding process is studied using finite-element-modeling. From figure 3 it can be seen that the highest stress occurs at the middle of the four outer edges of the membrane, while the maximum deflection occurs in the centre of the package.

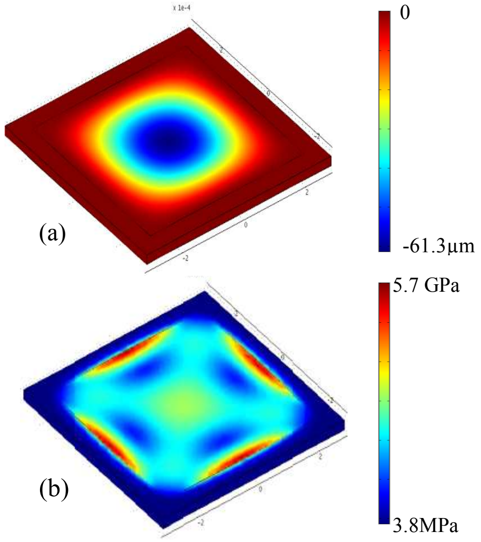


Figure 3 *Simulated (using COMSOL3.3) deflection (a) and Von Misses stress distribution (b) of a 500 µm ×500 µm SiGe package with 10 µm thick membrane.*

The mechanical response of packages with different membrane area and thickness was studied. As expected, both the deflection and the induced stress increase with area and decrease with increasing membrane thickness (figure 4).

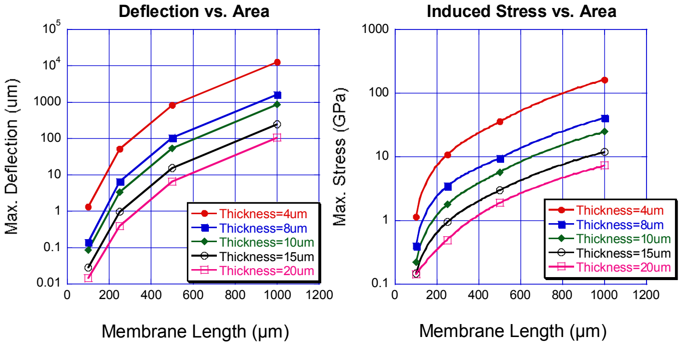
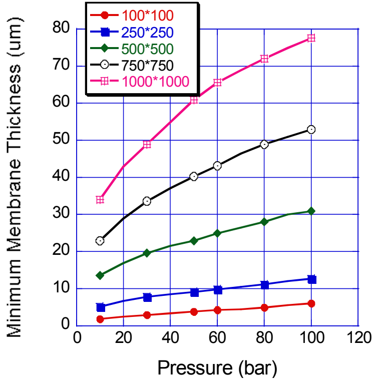


Figure 4 *Deflection and maximum stress induced in the package membrane for different membrane area and thickness. P=90 bar*

The package must be sufficiently robust to withstand the high mold pressure without breaking or collapsing on top of the MEMS device. To ensure this, the membrane must be thick enough to fulfill the desired requirements in deflection and stress. In our case we impose a deflection smaller than 3 µm and a maximum induced stress lower than 1GPa, which represents 83% of fracture strength of poly-SiGe. Figure 5 shows the minimum membrane thickness needed for different package sizes to withstand the 90 bar molding pressure while fulfilling the mentioned requirements. It was observed that for packages larger than 100 µm ×100 µm, the maximum allowed deflection was the most restrictive requirement, which dictated the minimum required membrane thickness. For smaller packages, the maximum allowed induced stress in the membrane was the limiting factor.



Area (μm^2)	Min. Thickness (for 90 bar)
100×100	6 µm
250×250	12 µm
500×500	30 µm
750×750	51 µm
1000×1000	75 µm

Figure 5 *Minimum membrane thickness to fulfill requirements (deflection<3µm and stress<1GPa) for different package areas (µm^2) and applied pressure. The minimum required membrane thicknesses to withstand 90 bar are listed in the table.*

As can be observed from figure 5, for large packages relatively thick membranes are necessary. For instance membranes thicker than 30 µm are necessary for packages bigger than 500 µm ×500 µm. This requirement for thick caps translates into a high cost and a long processing time. To improve the bending strength and reduce the minimum necessary membrane thickness, two different methods were studied: the use of a reinforcement layer (SiC) deposited on top of the SiGe membrane and the use of supports.

B. *Reinforcement layer*

In figure 6 the deflection and maximum stress for a SiGe membrane with an additional SiC reinforcement on top of a 500 µm ×500 µm cavity subjected to plastic molding is shown. It can be seen that by depositing a 2 µm SiC layer on top of a 23 µm thick SiGe membrane, the required thickness reduces from 30 µm to 25 um.

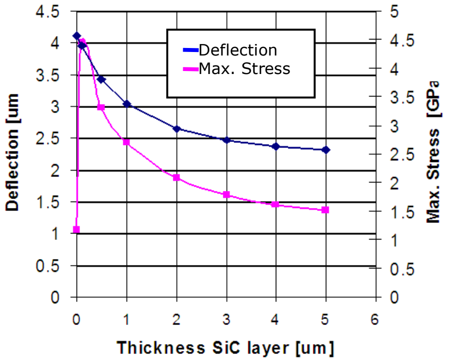


Figure 6 *Deflection and maximum stress (on top of the SiC) for different thickness of the SiC layer. Pressure=90 bar and area= 500×500µm^2.The total membrane thickness (SiGe+SiC) is always 25µm*

C. *Supports*

The addition of supports proved to be more efficient as reinforcement method. With careful placement of supports (figure 7) the minimum required membrane thickness for a 500 µm × 500 µm package can be reduced to 20 µm or less. However this method has the drawback that supports must be taken into account during the design of the MEMS device.

D. *Release holes*

The effect of the release holes opened in the membrane to allow the removal of the sacrificial material was also considered. Simulations with etch-holes (figure 8) show that stress is higher on the edges of centrally located holes, and this stress is independent from the number and size of the holes. Nevertheless, the addition of etch-holes does not modify the deflection or the maximum Von Misses stress (that remains at the middle of the four outer edges, fig. 3) observed in the membrane.

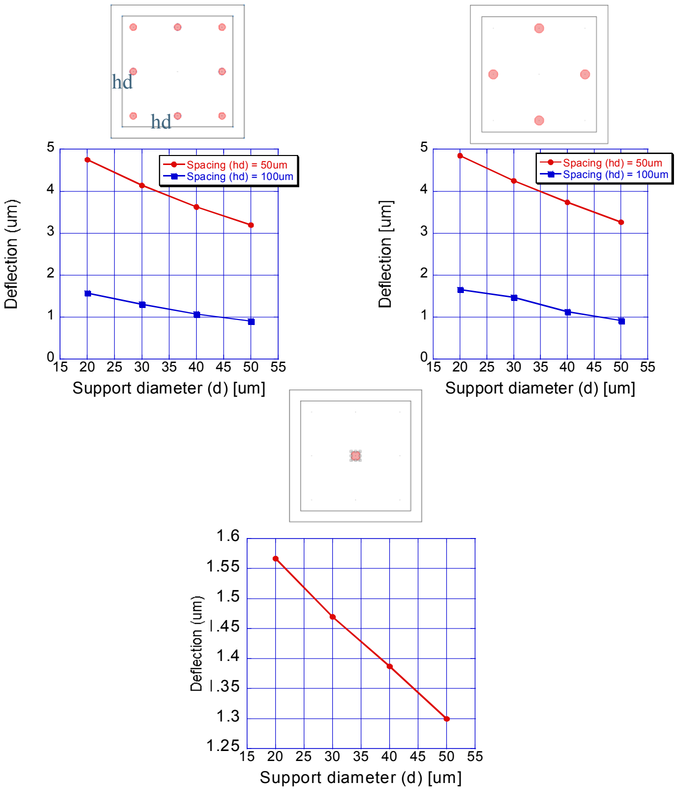
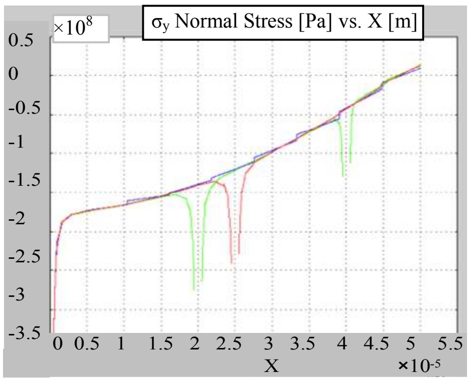
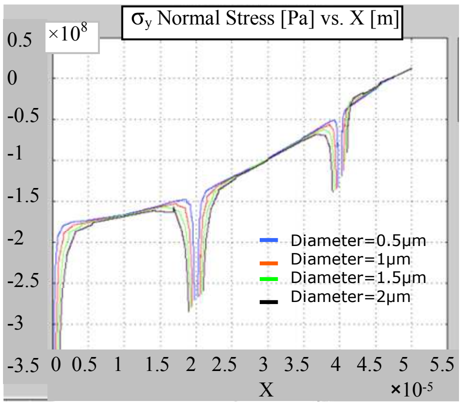


Figure 7 *Different support designs and corresponding membrane deflection for a 500 µm ×500 µm ×20 µm SiGe membrane subjected to 90 bars. hd represents distance from supports to membrane edge*



(a)



(b)

Figure 8 *Normal stress along the y-direction for a cut along the x-direction going from the centre to the edge of the membrane (line O-X, fig. 2), passing through the edge of the holes. Obtained for 10 μm thick 100 μm × 100 μm membranes subjected to 90 bars. (a) represents stress vs. number of holes and (b), stress vs. hole diameter*

IV. CONCLUSIONS

In this paper the mechanical response of SiGe membranes for wafer-level MEMS encapsulation was investigated using finite element simulations. The minimum required membrane thickness to withstand plastic molding in standard IC packaging together with different methods to stiffen the membrane was reported. For instance it was found that for a package of 500 μm×500 μm a membrane with a thickness of at least 30 μm was necessary to withstand the mold pressure. By adding a SiC reinforcement layer or supports the required membrane thickness could be reduced to 25 or 20 μm, respectively. For packages smaller than 200 μm × 200 μm no need of reinforcement methods was encountered since membranes thinner than 10 μm were already sufficient. These results, therefore, prove the potential of using SiGe for MEMS packaging and show that with careful design, robust packages able to withstand the plastic injection-molding process are possible.

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