Polyimide reinforcement of capped MEMS devices: soft and simple

PROEFONTWERP

ter verkrijging van de graad van doctor aan de Technische Universiteit Eindhoven, op gezag van de rector magnificus, prof.dr.ir. C.J. van Duijn, voor een commissie aangewezen door het College voor Promoties in het openbaar te verdedigen op dinsdag 21 januari 2014 om 16.00 uur

door

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geboren te Chennai, India
De documentatie van het proefontwerp is goedgekeurd door de promotoren:

prof.dr. H.C.W. Beijerinck
en
prof.dr. P.J. French

Published by: Uitgeverij BOXPress, ’s-Hertogenbosch
NUR: 926

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Chapter 1
Introduction

The MEMS dog-bone-shaped resonators developed at NXP Research and the associated thin-film silicon-nitride wafer-level encapsulation are introduced. We present the inherent problems during packaging that hamper the resonators to be manufactured as products. To solve these crucial issues, the need for a reinforcement layer is emphasized. The project deliverables are listed, keeping in mind, the goals of the project. The outline of this ‘PhD on Design’ thesis is given, based on a project carried out full-time at NXP Semiconductors.

1.1. MEMS resonator

Micro electro-mechanical systems (MEMS), functioning as electro-mechanical sensors, actuators and transducers for a wide range of industrial applications, are delicate structures sensitive to damage from handling or environmental influences [1, 2, 3, 4, 5, 6, 7]. Their functionality may furthermore depend on the operating environment. Factors such as stress, moisture and contaminants may impact their characteristics. Packaging technology that has been employed for microelectronic devices cannot be directly implemented for MEMS devices due to their fragility. Therefore, it can be challenging to extend from microelectronics toward MEMS, focusing on product release. Today's approaches to launch MEMS products rely on modified single-chip packages derived from the microelectronics industry. It is wise to employ the so called wafer-level capping to provide protection to the fragile MEMS structure and to enable the device to be packaged like an integrated circuit [4]. Therefore, selecting the proper packaging method plays a crucial role toward product success. In Fig. 1, the top view of NXP’s MEMS dog-bone-shaped resonator is illustrated.
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Figure 1: SEM picture of the 56MHz MEMS dog-bone-shaped resonator\(^1\): a free-standing silicon-on-insulator (SOI) structure that resembles a dog bone. Anchor, mass, springs and excitation electrodes are indicated. The direction of vibration is in-plane as indicated by the double-ended arrows.

The dog-bone resonator is set to an in-plane vibrational mode when it is electro-statically actuated. The resonator works in the lateral ‘thickness extensional’ mode. Upon capacitive excitation by a small AC voltage superimposed on a DC offset voltage, the mass is actuated at the excitation frequency. Resonance occurs when the excitation frequency matches with the frequency of a vibrational mode (also called Eigen mode) of the MEMS dog-bone element. This resonance is sensed by a change in the frequency-modulated electrical resistance of the springs, termed as piezoresistive effect. For this device to operate successfully, two chief electrical parameters are crucial for good device functionality: the quality factor Q and the resonance frequency \( f_0 \) \(^5, \, \, 10\). In Fig. 2, the method of capacitive excitation and piezoresistive sensing is illustrated. The amplitude versus frequency plot is shown in Fig. 3. In daily life, for example, a bell has high Q, such that after it is struck the sound can be heard for quite some time. A plastic cup has low Q, such that after the cup is struck the audio energy almost instantly dissipates. The quality factor Q determines how sharp the resonance frequency response is, a measure of how well a resonator retains its energy.

The signal output (admittance) based on piezoresistive sensing can be expressed \(^10, \, \, 11\) as

\[
\text{i}_{out} = I_d \cdot (\Delta R/R) = I_d \cdot \Delta F \cdot \gamma_d = \beta \cdot I_d \cdot V_g \cdot V_{in},
\]

(1)

where \( \text{i}_{out} \) is the sensed current output of the modulated resistance, \( \Delta F \) denotes the change (increase) in force due to electrostatic attraction, \( V_g \) is the DC offset voltage at the actuation gap, \( V_{in} \) is the AC supply voltage, and \( I_d \) is the current applied to the spring of the resonator. \( \Delta R/R \), the change in the dog bone resistance and \( \beta = (A^2/d^4) \cdot \varepsilon_0 \cdot \gamma_d \). Here, the parameter \( \gamma_d \) is a combination of material constant of the dog bone (compressibility and parameter relating strain to an increase in resistance) and the geometry of the dogbone. The parameter \( A \) is the area of the resonator, \( d \) the resonator-electrode gap, and \( \varepsilon_0 \) the permittivity of free space.

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Chapter 1

Figure 2: Excitation and sensing of mechanical resonance in the free-standing dog-bone-shaped MEMS resonator [6]. Typical gap dimension is 100 nm compared to a tens of microns scale of the structure.

Figure 3: Amplitude response of the impedance or admittance transfer function versus the normalized scan frequency $f/f_{res}$ shows the amplitude peak at mechanical resonance: the simplest form of this resonance is a mass-spring suspended system set to oscillation at a finite frequency $f_0$.

1.2. MEMS resonator as a timing device

Since the early 1980s, significant research efforts have been made by semiconductor firms to replace quartz-crystal oscillators with silicon MEMS-based oscillators as the frequency reference in clock and timing oscillators [1, 5, 9, 10, 11]. Advancements in semiconductor process technology, packaging methodologies, and the miniaturization and integration of circuitry have facilitated the realization of silicon MEMS timing devices. At the core of these oscillators, we find the resonator, which effectively is a time-base generator or time reference, similar in operating principle to the mechanical tuning fork used to tune musical instruments. A separate electronic oscillator provides impetus that forces the resonating element (MEMS) to vibrate at a precise frequency. Those vibrations are captured and output by a gain buffer that amplifies the signal generated by the resonator-oscillator combination.

One of the most promising aspects of MEMS resonators is the realization of integrated circuit (IC) timing circuits. Fabricated in silicon with surface micromachining processes, MEMS resonators can in principal be tied to oscillator circuits and phase-locked loops (PLLs) on the same silicon substrate.
A simplified block diagram is illustrated in Fig. 4. This would allow the clock and timing generators – together with the resonator – to occupy a single low-profile semiconductor package. This package, moreover, would support high-volume assembly techniques. Even where MEMS resonators and oscillators are separate chips, they could occupy the same package – one that would be smaller and easier to handle than the metal cans that currently house crystal oscillators. Thus, silicon MEMS-oscillator combinations are promoted as replacements for crystal oscillators in computers, communications equipment, and digital consumer devices (like set-top boxes). In Fig. 5, the evolution of the MEMS timing device into potential industrial applications is illustrated. The resonance output is sensed by a piezoresistive technique. By providing amplification and the required phase shift, a periodic electronic wave pattern is generated, which can be used in frequency clocks and as a time reference [13, 15].

Figure 4: MEMS oscillator: the core element is a MEMS resonator that is set to mechanical resonance by electrostatic actuation.

A number of startup companies [5, 16, 17, 21, 22] have proposed replacing outboard crystals with silicon-based devices, micro-electromechanical systems (MEMS) resonators, which enables package level integration with IC timing circuits based on a complementary metal-oxide semiconductor (CMOS) technology. Significant efforts are required to solve the challenging technological aspect and promote the product toward industrialization. MEMS resonator manufacturers have not completely resolved key technical and manufacturing issues such as the temperature induced drift in the resonance frequency and a cost effective packaging solution. Consequently, displacement of well-established crystal-based timing sources in systems will be slow. The current market for the MEMS-based oscillators is expected to grow from 10 million USD in 2007 to 190 million USD in 2012 as the MEMS equivalents begin to displace quartz oscillators. In 2009, close to 3 million MEMS oscillators were shipped to end customers [19]. Three companies are delivering such devices: Discera and SiTime are manufacturing silicon MEMS oscillators, while Toyocom (part of Seiko Epson) produces micro-machined quartz MEMS oscillators, leveraging its so-called QMEMS process [15, 16, 19, 22].
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Figure 5: In one single, cost-effective plastic package, MEMS resonators are integrated into oscillators; For NXP, the core element will be a MEMS dog-bone-shaped resonator [10, 15].

Figure 6: Market-share for MEMS-based oscillators from 2007 to 2012, as published in 2010. The high-performance MEMS oscillators applied in mobile handsets (wireless) and GPS today compete with quartz in the XO (crystal oscillator) function. The specifications for temperature stability are becoming easier to meet in the recently developed TCXO’s (Temperature Compensated Crystal Oscillators) [16, 19].

1.3. NXP’s wafer-level thin-film capping approach

Almost all MEMS devices need protection at wafer-level. Hermetic sealing is a stringent design constraint for many contemporary MEMS devices such as accelerometers, gyroscopes, resonators, IR bolometers, and RF devices. MEMS capping technologies using glass frit seals, wafer-to-wafer bonding and die-to-wafer bonding have been widely applied in practice [2, 8, 12]. These methods are usually target-specific and are not cost effective. At NXP Research, a 1.8 µm thin silicon nitride cap is used to encapsulate the MEMS resonator at the wafer level. The thin silicon nitride cap is utilizing front-end technology only, making use of a sacrificial layer. The sequence of steps followed to realize this is illustrated in Fig. 7.
Chapter 1

Figure 7: Simplified version of the process flow, illustrating the MEMS resonator realization, followed by the thin silicon nitride wafer-level capping.

Trenches are etched to define the resonator that is designed. To make the resonator free standing, the underlying buried oxide (BOX) is released. The sacrificial layer for the thin film cap definition is deposited on top of the MEMS and structured. Thin silicon nitride is deposited and holes are defined on it. To ensure low working pressure (approx. 1 mbar) in the micro cavity during its ten-year lifetime, the release holes are sealed with a metal by sputtering.

After the wafer-level thin silicon-nitride capping is realized, the resonators are tested for electrical functionality. The next step is to have these functional resonators assembled in a plastic package. To comply with the package requirements, the silicon-on-insulator (SOI) wafer containing the resonators is thinned down to 150 µm. In Fig. 8, the process of wafer thinning, also known as wafer back-grinding, is illustrated.

After wafer-thinning, the protection tape is removed. The wafer-level capping is vulnerable to the wafer back-grinding operation owing to significant topography. Moreover the peeling force exerted on the front side tape complicates the situation further. Subsequently, the resonators are finally assembled into a package [21, 22].

Figure 8: Wafer thinning operation: a 100µm thick protective tape is applied on top of the wafer-level cap before thinning the wafer to 150 µm, from an original thickness of 525 µm. The tape is peeled from the front side of the wafer. The drawing is not to scale.
Chapter 1

1.4. Crucial issues

The wafer-thinning operation on thin-film encapsulated resonators on full wafer resulted in cracks in the thin silicon-nitride cap. As a next step in the back end (BE) processing, the resonators are extracted from the wafer by the process of dicing. During this process, there was chipping of the thin silicon-nitride cap along the saw lanes. Figure 9 illustrates the thin silicon nitride cracking and the chipping problem. These problems hamper the final thin-film plastic packaging of the resonators. We have to conclude that the thin silicon nitride needs reinforcement or a protection layer to ensure safe back-end handling, to ensure an intact wafer-level cap that is processed at wafer-level. This conclusion is the driving force for the work presented in this PhD thesis on design.

![Figure 9: Optical microscope pictures illustrate the cracking problem during removal of the wafer’s front side tape from the thin silicon-nitride-capped resonator-on-wafer: cracking in the thin film cap (left) and delamination and chipping problem (right) after dicing the wafer, near the saw lanes.]

1.5. Project goals and deliverables

The current thin-film capping process flow is not sufficient to achieve a fully packaged MEMS resonator in the form of a product. The goals of this project, when expanded in milestones, lead to the following deliverables:

1. Realizing a reinforcement material
2. Package-level functionality
3. Package-level reliability

First, we have to enhance the existing thin film silicon nitride capping by adding a reinforcement material and demonstrate feasibility of the process and electrical functionality of the resonators at wafer-level. This must comply with the resonator’s electrical functionality specifications.

Second, by extending to the packaging level, prove that the device survives the packaging (wafer-thinning, wire-bonding, glueing and molding) operations. Investigation of the impact of back-end handling has to be done.

Third, one step further, life-time performance of the device needs to be addressed for a set of relevant reliability testing conditions. The failure of the device to these conditions is studied and the failure mechanisms are analyzed. This has to be performed both on the thin film packaged resonator as well, as on the oscillator samples later to investigate the impact of the accelerated testing.
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1.6. Work flow

Goals are derived from the problem statement. The main goal is to prove that the chosen reinforcement delivers a high yield of electrically functional resonators and oscillators at product-level. The choice of the reinforcement involves selecting and experimenting suitable candidates to function as reinforcement layers for the thin silicon-nitride capping. Front-end capping MEMS resonator is performed on MEMS dog-bone-shaped resonators, taken as a test vehicle. Based on best results, the chosen reinforcement material is applied on to the wafer-level thin silicon-nitride capped resonators. To determine the thickness requirement for the reinforcement layer, mechanical simulations and simple analytical calculations are carried out. Test experiments are performed to realize the process feasibility of the chosen reinforcement material and method, at wafer-level. Back-end testing is carried out to investigate the impact of the wafer handling, while assembling on the resonator performance. This results in thinned wafers for assembly into products. To qualify the electrical performance of the resonators, both at wafer-level and in package, electrical measurements are performed. To check for failures and to understand the possible failure modes, failure analyses are done. The approach to the problem is illustrated in Fig. 10. The choice of reinforcement forms an important block.

Figure 10: Work flow illustrating the modular approach to problem solving.

1.7. Outline of thesis

The scope of this thesis is limited toward implementing an alternative option for the reinforcement of the thin silicon nitride capping. This choice has to result in product-level demonstration at NXP Research. For industrialization, tests on a vast number of samples have to be carried out and proven. This work does not aim to answer all the questions toward industrialization.

Chapter 1 introduces the MEMS dog bone shaped resonators and the NXP’s wafer-level thin film silicon nitride capping approach to encapsulate the resonators. The crucial issues in the encapsulation route are presented. The need for a reinforcement layer and project deliverables are mentioned.

Chapter 2 presents a few available options for the choice of the reinforcement layer. Based on what is viable, the polymer thick films as reinforcement materials are highlighted, along with two other possible candidates. The reasons for selecting this alternative option as a daring choice, to the existing reinforcement approach (thick silicon nitride) are stated.
Chapter 1

Chapter 3 discusses the analytical calculations and mechanical simulations performed to determine the thickness of the polymer reinforcement, required to withstand a molding pressure of 80 bar and all Back-End (BE) assembly steps. A qualitative approach to estimate the stress levels in the capping multi-layer is presented, considering post-molding cure step.

Chapter 4 presents the feasibility experiments to arrive at the final choice for the polymer reinforcement material, out of three possible polymers that were investigated. Focus-exposure matrix (FEM) experiments were used in determining the process window for the polymers.

Chapter 5 presents the risks involved while processing the reinforcement layer at wafer-level. Effects such as thermo-mechanically induced film stress, water diffusion etc, are mentioned with possible risk mitigation measures.

Chapter 6 discusses the effect of pre-assembly operations such as wafer thinning and dicing on the electrical performance of the silicon nitride and polymer reinforced resonators.

Chapter 7 gives some insights into the impact of polymer reinforcement on the electrical performance of the resonator. The deviation in the electrical performance due to the polyimide reinforcement is reported and discussed.

Chapter 8 discusses the results of a few important reliability tests such as thermal cycling, humidity based acceleration tests etc., on fully packaged resonators. Stable electrical performances during these accelerated tests are observed. Based on best results, selection of the final material, namely the polyimide reinforcement is arrived at.

As the final product is a functional oscillator, Chapter 9 discusses the results of packaged oscillators done by assembling the oscillator in 'stacked die’ configuration, in a standard plastic package. Important observations on the aging aspects of MEMS oscillators in package are presented with conclusions.

Not every issue and problem could be solved within the scope of this project work. Chapter 10 gives concluding remarks and possibilities for further work in this subject with some concluding remarks.

Chapter 11 gives the current status of the polymer reinforcement approach to encapsulate the MEMS resonators. The specific topics are discussed in detail in the NXP technical notes with the abbreviation TN – A, B and the P series.

References

Chapter 1


17. Discera product sheet resonator\MOS1-S3-0825-na datasheet.pdf


Chapter 2

Selection of reinforcement material

The MEMS dog-bone-shaped resonators that are designed and fabricated at NXP Research, have a thin silicon nitride capping. Mechanical failure and damage of this thin-film capping during the back-end (BE) handling are observed. To approach and solve these issues, a 5µm thick silicon nitride, is currently employed as a reinforcement material. The choice of alternative reinforcement material(s) is emphasized to support this existing approach. Relevant selection criteria are mentioned, enabling a suitable final choice of the alternative reinforcement material.

2.1 Existing route: thick silicon nitride reinforcement

In July 2009, the existing route to solve the BE issues, such as cracking of the thin silicon-nitride capping during wafer thinning to 150µm, was to apply a low temperature (250°C) plasma-enhanced chemical-vapor-deposited (PECVD) silicon nitride on to the thin silicon nitride. A 5µm thick silicon nitride layer was employed to act as reinforcement. The required strength of this layer is fully determined by the 80 bar molding pressure during the final stage of packaging. The maximum value of the deflection then is on the order of 0.2µm (Chapter 3). The wafer-level capping process is illustrated in Fig. 1 in a simplified form. The reinforcement layer is the last layer in the thin film capping. For electrical contacting, the aluminum bond pads must be opened on the thick silicon nitride. This might lead to processing difficulties. The sequence of steps is rather complex when compared to other materials, e.g., a photo-sensitive polymer, which translates into a higher cost of fabrication.
Chapter 2

Figure 1: Simplified schematic of the wafer-level thin film capping of the MEMS resonator reinforced with thick silicon-nitride.

The purpose is to determine the mechanical robustness of the thin-film capping to 80 bar over-molding pressure. Based on simplified plate deflection theory, assuming that the thin film cap is a 200 x 50 µm² rectangular plate, the deformation at this loading is calculated (Chapter 3). This would result in a 5 µm thick silicon nitride. The choice of the thick silicon nitride reinforcement was still in the experimental phase as of July 2009: no evidence was available that the devices would survive the back-end handling and dicing of the wafers. Moreover, it had the following issues:

- The PECVD silicon-nitride deposition involves various gas precursors, pumping systems, RF generators and safety handling tools, making it a cost-intensive tool. Moreover, silicon nitride is a very good conformal material when deposited by PECVD (not shown in Fig. 1). Therefore, it shall not possess gap-fill characteristics on the capping topography [1]. This attribute is important for the capping, as the topography resulting from processing would be exposed to wafer thinning step. This will pose a risk to the capping and to the resonator on wafer.

- As the PECVD silicon-nitride is a mechanically stiff material, it could have a significant impact on the existing topography (1.8 µm silicon nitride and 5µm sputtered aluminum plug) because of its microstructure-induced stress (residual stress) during the deposition [2, 3, 4]. The severity of metal-line cracking is illustrated in Fig. 2. After Metal 2 is processed, the underlying topography weakens at the edges were the thin silicon nitride is present, resulting in cracks. Due to a very smooth coverage of the polymer, the topography remains intact after Metal 2 is processed.
Chapter 2

- Opening the electrical contacts on the thick silicon nitride involves an additional photoresist processing, defining the bond-pad openings on the photo resist by exposure, patterning the contact opening, removing the photoresist and finally etching the reinforcement silicon nitride to open the contact opening. This would lead to processing difficulties [5]. The sequence of steps is illustrated and compared to the use of an alternative; photosensitive material is emphasized in Fig. 3.

Given these risks and the lack of solid evidence for the success of applying thick silicon nitride as a reinforcement material, there was a major push in NXP to explore alternative materials for this purpose. Ease of handling as compared to the silicon nitride reinforcement and the good gap-filling characteristics (lower panel of Fig. 2) were strong arguments to include these materials in our search. In the next section we compare our final choice for a polymer with other materials.

![Figure 2: Top panel: SEM pictures of two metal layers with PECVD silicon nitride as an inter-layer dielectric between the two metal lines (Metal 1 and Metal 2). Bottom panel: Polyimide is employed as an inter-level dielectric (between Metal 1 and Metal 2) to planarize the surface and fill the gaps to a considerable degree [1]. The size bar is 2 µm for both pictures.](image)

2.2 Available materials

A proper choice of reinforcement material must ensure that the material is compatible with the existing silicon-nitride thin-film capping. Moreover mechanical properties of this material must support the BE handling steps such as wafer-thinning, dicing, assembly and finally over-molding. When it comes to the choice of reinforcement material, there are a few options available [5, 6, 10]. Dielectric materials, both organic and inorganic, as well as metal, seem to be interesting candidates.

2.2.1 Polymers

Polymers have been applied extensively in the microelectronics industry for about three decades for a large variety of applications. Their main application was a role as inter-level low-\(k\) dielectrics and
as stress buffer coating and passivation layers [8, 9]. Thin solid films of polymeric materials used in various microelectronic applications are usually commercially deposited by the spin-coating process.

The semiconductor industry also uses polymers as a high-temperature adhesive. Another application is as a mechanical stress buffer, for example polyimide. Some polymers can be applied for our problems that are photo resists; both "positive" and "negative" types of photo-resist-like polymers exist in the market. An additional use of polymer resin is as an insulating and passivation layer in the manufacture of digital semiconductors and MEMS chips [10]. The polymer films have good mechanical elongation and tensile strength, which also helps to maintain the adhesion between the polymer layers or between polymer layer and deposited metal layer. They are attractive as reinforcement layers due to the following factors:

- Ease of processing: they are photo definable;
- Well-established in the microelectronics packaging industry;
- Cost effective, compared to inorganic dielectric thin-films;
- High degree of reproducibility.

Another major advantage of the polymer reinforcement route is the smaller number of processing steps, minimizing processing issues and a cost-effective fabrication. However, we will not quantify this advantage in terms of a cost analysis. There are some disadvantages in applying polymers. They are known for poor moisture resistance [10, 11]. They sometimes possess high curing temperature, which makes it difficult for some CMOS applications that are temperature sensitive. The thermomechanical load adds stress to the device.

### 2.2.2 Inorganic dielectric materials

Thin-film materials such as silicon nitride and silicon oxide have also been extensively investigated as passivation layers and dielectric materials in the microelectronics industry. Silicon nitride is often used as an insulator and chemical barrier in manufacturing integrated circuits, to electrically isolate different structures or as an etch mask in bulk micromachining [11, 12]. As a passivation layer for microchips, it is superior to silicon dioxide, as it is a significantly better diffusion barrier against water molecules and sodium ions, two major sources of corrosion and instability in microelectronics. It is also used as a dielectric between poly-silicon layers in capacitors in analog chips. Although the advantages of these materials are obvious, we also have to consider the risks involved. These risks of inorganic dielectric materials are:

- Being brittle and exhibiting brittle failure upon tensile loading;
- Having a high intrinsic stress after processing, owing to their microstructure.

An important business disadvantage is the cost of the application of these materials when deposited as thick layers. The work flow of the processes involved is much more complex as for polymers, i.e., the same disadvantage as is the case for the thick silicon nitride reinforcement.

### 2.3 Why polymers?

Polymers are chosen as potential candidates for our problem, based on the following considerations:

First, the problem of thin silicon nitride cracking and de-lamination has to be solved. This behavior is due to the brittleness of silicon nitride when subjected to harsh handling. Therefore a much softer or compliant material shall be a good choice as a reinforcement layer.
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Second, the BE handling involves plastic packaging as the final step before the resonator is available as a product. Over-molding involves the usage of a thermally-curable mold compound that takes the final shape after curing. This results in package-induced stress resulting from shrinkage of the thermosetting mold compound. This effect can be minimized to a huge extent by having a reinforcement material that acts as a stress buffer between the epoxy mold compound and the underlying thin silicon-nitride cap and the MEMS silicon.

Third, incorporating a polymer as a reinforcement layer would reduce the thermal mismatch between the molding compound and the thin-silicon nitride capping and the MEMS silicon. As the polymer is a compliant material, it would act as a ‘shock absorber’ on the interface silicon nitride micro-cap subjected to shear forces resulting from the BE handling.

Finally, applying and patterning of polymer can in principle be done with equipment that can be found in every fabrication facility. This was considered as a mayor advantage for NXP for this daring innovation with its still insecure outcome.

**Lithoglas** is considered as a second option. It involves deposition of a structured borosilicate glass layer by plasma-assisted physical vapor deposition employing photolithographic lift-off-processing. This material has a matched coefficient of thermal expansion (CTE) to MEMS silicon [12]. At the same time it is a hard and very temperature-stable material with high transparency in the visible spectrum, making it the material of choice for long-term reliable encapsulation or sealing of devices and surface materials. The deposition is a low-temperature evaporation process and the thermomechanical properties are matched to the single-crystal silicon or the wafer on which the devices are designed.

Our initial discussions with the company MSG Lithoglas, Germany were successful in coming up with a plan for the test experiment. As the thermal evaporation technique used for depositing the layer on to our test wafers was not available in the MiPlaza facility, the wafers had to be sent to MSG Lithoglas. For this logistic reason, Lithoglas was not experimented as the first option. Moreover, it had to be subcontracted, which was not an option for NXP at that time. Applying Lithoglas in-house another option - would have required both major investments and royalty payments.

**Silicon Carbide** is considered as a last option because of its interesting mechanical properties. PECVD deposited silicon carbide has long been known for its excellent mechanical, electrical and chemical properties, making it a viable material for micro-fabricated sensors and actuators designed for environments too harsh for silicon-based devices [13]. However, many of the properties that make this material attractive for harsh environment applications make it a challenging material. High intrinsic stress-related issues shall be the limitations [14, 15, 16]. Table I illustrates the different reinforcement materials, their important mechanical properties (a high Young’s Modulus and low intrinsic stress) and possible applications [7].
Table I: Mechanical properties of possible candidates to be employed as reinforcement layer, together with typical applications and general remarks

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s Modulus, $E$ [GPa]</th>
<th>CTE, $\alpha$ [ppm/K]</th>
<th>Intrinsic Stress $\sigma_i$ [MPa]</th>
<th>Applications</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyimide (Durimide 7500 series®)</td>
<td>2.5</td>
<td>55</td>
<td>32</td>
<td>Stress buffer coat for IC chips(^8).</td>
<td>• Almost a standard in the IC industry. • Available as a negative tone resist.</td>
</tr>
<tr>
<td>Intervia (Intervia 8023-10®)</td>
<td>3.2</td>
<td>62</td>
<td>30</td>
<td>Redistribution layer for interconnect.(^7)</td>
<td>• Used as a low-$K$ dielectric. • Available as a negative tone resist.</td>
</tr>
<tr>
<td>SU8 (SU8-25)</td>
<td>3.8</td>
<td>50</td>
<td>22</td>
<td>MEMS structures, various applications, proved as a good wafer-level cap by Infineon Technologies</td>
<td>• Well-established technology in MEMS world. • negative tone resist.</td>
</tr>
<tr>
<td>Lithoglas© Deposited by evaporation</td>
<td>69</td>
<td>3</td>
<td>-100 to +100</td>
<td>Micro-optics encapsulation and MEMS encapsulation(^11)</td>
<td>• Applied in MOEMS capping. Micro fluidics. • Brittle</td>
</tr>
<tr>
<td>Silicon Carbide PECVD-deposited</td>
<td>165</td>
<td>2</td>
<td>160</td>
<td>Wear-resistant coatings (^{13}) and wafer-level capping for MEMS(^{14,15})</td>
<td>• Applied for micro accelerometers • High intrinsic stress can result in cracking(^2,14)</td>
</tr>
</tbody>
</table>
2.4 Conclusions

The choice of employing polymer thick-films as a reinforcement layer for the thin-film silicon nitride encapsulated MEMS dog-bone shaped resonators is highlighted. The overall merits of this class of materials rank them high, enough reason to investigate these materials. Our objective is to start with a very simple approach like this and then look for process feasibility.

In parallel to this approach, we will also keep track of the reliability of the devices fabricated with the thick silicon-nitride reinforcement. This opens up a maximum flexibility for successful reinforcement options for launching a commercial product based on MEMS oscillators.

References


Chapter 2


Chapter 3
Mechanical simulations

To estimate the required thickness of polymer reinforcement-film in combination with the silicon-nitride thin-film capping, calculations using known analytical expressions and finite-element COMSOL mechanical simulations have been performed. The severity of the maximum capping deflection is emphasized by comparing two different boundary conditions and constraints for the square plate model that is taken as a reference. Scaling rules are applied to arrive at the thickness requirement for the three types of polymer reinforcements. The reinforced silicon-nitride thin-film capping must survive all BE handling steps including a molding pressure of 80 bar. The temperature-dependent change in the elastic modulus of the polymer reinforcement film (softening effect in the polymer) is taken into account.

3.1 Introduction

The required thickness of the reinforcement polymer to withstand the BE-handling and a molding pressure of 80 bar has to be determined. This has to comply with the thin film packaging specifications in NXP [1]. The process technology used to realize this required reinforcement layer thickness is very demanding in terms of the achievable final thickness for the polymer reinforcement layer. At the same time, given the requirement that the capping has to be robust enough, the thickness of the reinforcement shall not be compromised. This leaves us with a major challenge: the optimum choice of the reinforcement layer thickness. Starting with simple assumptions that our capping is an edges-clamped square plate and/or a simply supported plate, the allowable range of the maximum deformation of the capping is calculated. Mechanical simulations are performed in COMSOL multiphysics finite-element modeling (FEM) tool, with information on the known limit to the allowed maximum deformation of the micro-cavity. We also take into account the temperature-dependent change in the elastic modulus of the polymer reinforcement film (softening effect in the polymer at elevated temperatures), for a safe margin in calculating the deformation of the capping.

3.2 Rectangular plate deflection

For our design, we need to know the maximum deflection of the center of our capped structure during the sequence of processing steps in the assembly flow. The maximum mechanical load on the capping that we expect is a molding pressure of 80 bar. It is difficult to imagine how the boundary conditions
and the constraints for our capping structure are in reality. For this reason the influence of different boundary conditions is investigated [2]. Three models are considered:

(1) edge-clamped plate;

(2) pin (corner) -supported rectangular plate;

(3) lid on an open cavity;

The first option will surely result in too small values of the deflection, because the clamped edges imply a derivative of the deflection that is equal to zero at the edges. The second option will result in a too large value of the deflection, because in this case only the corners of the square plate are fixed. The third option is closest to reality, in our opinion, because it takes into account the whole stack including its in-plane stress.

Figure 1: Plane view of a rectangular slab subjected to a load of 80 bar molding pressure.

Edge-clamped plate

For an edge-clamped plate as illustrated in Fig. 1, analytical expressions are available for the maximum deformation \( \Delta d \) of a plate of this member [3, 4]

\[
\Delta d = \beta \cdot (p/E) \cdot (b/d)^{3/2} \cdot b,
\]

where \( p \) is the force per unit area, \( d \) the thickness, \( a \) the length of the plate, \( b \) the width of the plate, \( E \) the elastic modulus and \( \beta \) a numerical constant depending on the length-to-width ratio \( a/b \). The numerical constant for a square plate is given by \( \beta = 0.0138 \); for a rectangular plate with \( a/b = 4 \) we find \( \beta = 0.0284 \). A rectangular footprint is chosen because this is the effective area that suffers a deformation during mechanical loading. This has been adopted in the thick silicon-nitride capping approach. Typical results for our structure are given in Table I. Figure 2 shows the deformation map as calculated with COMSOL.
Figure 2: COMSOL simulation of the maximum deformation of an edge-clamped rectangular plate with dimensions $200 \times 50 \ \mu m^2$. The color scale covers the range of $0 – 38 \ \text{nm}$ when going from blue to red.

**Pin-supported plate**

For the case of pin-supported rectangular plate subjected to a uniform load, we again have analytical results that can be applied in good approximation [4]. The maximum deflection of the plate is given by

$$\Delta d = \frac{4}{\pi^2} \frac{p}{E} \frac{a^4}{bd} \left(1 - \nu^2\right) \left(\frac{a}{b}\right)^2 (1 - \nu^2) \gamma \frac{a}{b} \frac{p}{E} \frac{a}{b} \frac{b}{d} \frac{b}{d}.$$  \hspace{1cm} (2)

In the second expression of Eq (2) we have rephrased the original expression for an easy comparison with Eq (1). The factor $\gamma$ depends on both the length-to-width ratio $a/b$ and Poisson’s ratio $\nu$. For a value $a/b = 4$ we find $\gamma = 0.13$. For a device with dimensions typical for the capping structure, approximately a factor 5 difference in the maximum deformation for the pin-supported case is seen when compared to the prediction of Eq. (1) for the edge-clamped case. An overview of the results for our structure is given in Table I.

**Lid on open cavity**

No analytical expressions are available for the lid or full-stack model. Simulations in COMSOL finite-element modeling tool are performed to determine the maximum deflection of a thick silicon-nitride capping, required to withstand a molding pressure of 80 bar. In COMSOL, the structural mechanics model in *plane stress* mode is chosen for the simulation problem (Fig. 3). All material constants are mentioned in Table II.
Figure 3: Lid structure: the inner rectangle (cap: \(a \times b\)) is a protrusion imitating the rectangular cap. It is fixed at its points and the edges are roller supported. The surrounding plate \((a1 \times b1)\) is fixed at all its edges. The side wall (height) of the lid is 1.5\(\mu\)m. Actual values of the parameters are given in Table I.

Table I: Deflection \(\Delta d\) and geometry parameters \(\beta\) (Eq 1) and \(\gamma\) (Eq 2) for a rectangular plate consisting of \(d = 6\ \mu\)m thick silicon nitride, calculated analytically and with COMSOL for the different boundary conditions

<table>
<thead>
<tr>
<th>Capping shape</th>
<th>Constraint</th>
<th>Constant</th>
<th>(\Delta d\ [\mu\text{m}])</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Analytical</td>
</tr>
<tr>
<td><strong>Plate</strong> (a \times b = 200 \times 50\ \mu\text{m}^2)</td>
<td>Edge-clamped(^a)</td>
<td>(\beta = 0.0284)</td>
<td>0.038</td>
</tr>
<tr>
<td><strong>Plate</strong> (a \times b = 200 \times 50\ \mu\text{m}^2)</td>
<td>Pin-supported(^b)</td>
<td>(\gamma = 0.1399)</td>
<td>0.19</td>
</tr>
<tr>
<td><strong>Plate</strong> (a \times b = 200 \times 50\ \mu\text{m}^2)</td>
<td><em>Lid on open cavity</em>(^c)</td>
<td><em>Not applicable</em></td>
<td>Not available</td>
</tr>
</tbody>
</table>

\(^a\) all edges of plate are clamped (Degree of Freedom, DOF =0) (Eq 1)

\(^b\) corner points of plate are fixed (DOF =0) and edges of plate are free to move (Eq 2)

\(^c\) corner points of lid are fixed (DOF = 0) and edges of the lid are free to move.
Figure 4: COMSOL simulation of the maximum deflection of the lid and the rectangular plate at the center for the 6µm thick silicon nitride cap. The color scale covers the range of 0 – 69 nm when going from blue to red.

The simulated model for the lid is shown in Fig. 4. The edges are not fixed, only the corner points are set to zero degree of freedom; the edges are set to roller-support. The cap has a height of 1.5 µm, emulating the thick silicon nitride capping. The lid has dimensions of 600 x 150 µm². The numerical results for the lid model are given in Table I. We see that the maximum deformation of the lid is twice as large as compared to the edge-clamped rectangular plate.

3.3 Scaling to polymer reinforcement

The maximum deflection of the center of a free-standing Timoshenko square plate representing a thick film capping, that is simply supported (Eq 2), is used for the scaling [2]. This is equivalent to case (2) of the list given in section 3.2. For the same deformation of the rectangular slab with the polymer thick film reinforcement only, assuming that the 1.8µm thin silicon nitride together with the 5µm aluminum plug will not withstand the 80 bar molding pressure, we have to solve

\[
\left\{ \frac{E_{PI}d_{PI}^3}{(12(1-\nu_{PI}^2))} \right\} = \left\{ \frac{E_{SN}d_{SN}^3}{(12(1-\nu_{SN}^2))} \right\}
\]

for the thickness \(d_{PI}\), resulting in

\[
d_{PI} = d_{SN} \cdot \left( \frac{E_{SN}}{E_{PI}} \right)^{1/3}
\]

The cube root dependence on the ratio of the Young’s modulus of both materials saves us for non-acceptable thick layers of polyimide. First we determine the deflection of a 6 µm thick silicon nitride \((a\cdot b = 200 \mu m \times 50 \mu m)\), for the approx.5µm thick silicon nitride as the reinforcement on 1.8µm thin silicon nitride capping. Using Eq. (2), we get a deflection of 0.18µm for the thick silicon nitride reinforcement. Then, we determine the equivalent thickness of polymer reinforcement leading to the
same deflection as that of the thick silicon nitride reinforcement, using Eq.(4). With this information we can determine the thickness of the polyimide layer required in combination with the 1.8 µm silicon nitride thin film capping with COMSOL finite element simulations. In the actual thin film capping, there is a gap of 1.5 µm for the thin film capping to move (and deform), on top of the MEMS device. Our example takes very large safety margins for the polymer thickness because the material constants of the polymer thick film are not exactly determined. Moreover the wafer-level capping shall not be too much pressure sensitive as sufficient vacuum of about 20 mbar is a fundamental requirement.

Table II: Mechanical constants for the materials used: elastic modulus E, Poisson’s number υ and the coefficient of thermal expansion, α (CTE) [2].

<table>
<thead>
<tr>
<th>Material</th>
<th>E [GPa]</th>
<th>Poisson ratio, υ [-]</th>
<th>α [ppm/K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon nitride</td>
<td>200</td>
<td>0.23</td>
<td>2</td>
</tr>
<tr>
<td>Polyimide</td>
<td>3.5</td>
<td>0.22</td>
<td>62</td>
</tr>
<tr>
<td>Intervia</td>
<td>4</td>
<td>0.23</td>
<td>55</td>
</tr>
<tr>
<td>SU8</td>
<td>5</td>
<td>0.22</td>
<td>53</td>
</tr>
</tbody>
</table>

**Technology challenge**

All three polymers - SU8, Intervia and Polyimide - are processed in a single spin to get the required thickness. This method is demanding in terms of fine-tuning and optimization. There is a gap between what is achievable with the permitted final thickness of the polymer process and what is required for the final thickness for mechanical robustness. The choice of the thickness should always make sure that it closes this gap as reasonably achievable. In our case, the final choice would be based on the best results for the three polymers, as the three polymers have very different chemistries and may behave uniquely in terms of mechanical robustness, in reality. For the three polymers, the required thickness is calculated using Eq. (4). This is then compared to the deformation obtained with the maximum allowed thickness values of the polymers, by the processing (Table III). A gap between the allowed values for the polymer layer thickness, dictated by the processing can impact the mechanical robustness of the reinforced capping.
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Table III: Deformation $\Delta d$ of the 200 x 50 $\mu$m$^2$ reinforced thin film cap for both the required thickness (Eq. 4, for pin supported rectangular plate) and the thickness allowed by the process of spin coating

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Required thickness to obtain the same deformation as thick silicon nitride [$\mu$m]</th>
<th>Deformation $\Delta d_{\text{max}}$ [$\mu$m]</th>
<th>Allowed thickness by spin coating [$\mu$m]</th>
<th>Deformation with the process limited thickness $\Delta d_{\text{spin}}$ [$\mu$m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU-8</td>
<td>20.5</td>
<td>0.172</td>
<td>21</td>
<td>0.16</td>
</tr>
<tr>
<td>Intervia</td>
<td>22</td>
<td>0.174</td>
<td>15</td>
<td>0.55</td>
</tr>
<tr>
<td>Polyimide</td>
<td>23</td>
<td>0.174</td>
<td>20</td>
<td>0.265</td>
</tr>
</tbody>
</table>

3.4 COMSOL simulation of device capping

The wafer-level capping design is adopted from NXP’s wafer-level capping-design mask set [6]. The parameters are mentioned in Table IV. The model in COMSOL is built by mimicking a capping structure consisting of a stack of 1.8 $\mu$m thin silicon nitride and a thick polymer film as shown in Fig. 5. The thickness of this polymer is varied in steps during simulation and a final thickness was chosen based on the value of deformation obtained in the simulations. All material constants such as the elastic modulus, Poisson’s number and the coefficient of thermal expansion (CTE) are supplied to the model (Table II). For the loading conditions, a pressure of 80 bar acting on the cap and a temperature-dependent elastic modulus are supplied [8].

The process of over-molding involves a post-mold curing step, involving a significant temperature step. This can have a significant impact on a compliant material like polyimide, used as a reinforcement layer in the thin-film capping. Therefore, a temperature-dependent elastic modulus has to be used. Figure 6 illustrates the temperature-dependent elastic modulus of polyimide. The value chosen for the elastic modulus in the simulation is 2.1 GPa (at 225 °C) based on softening effect. Although the post mold curing temperature is at 175 °C, this value of elastic modulus has been chosen for any adverse effect the polyimide might cause during the post mold curing, based on the softening effect. Also, the temperature dependent behavior of elastic modulus for the polyimide we used was not determined or known from the processing guide. The other candidates, namely, Kapton and Polyimide with 5% nano-filler have not been considered for the simulations due to their strong temperature dependency. The simulated 3D model in COMSOL of the capping of the actual device is shown in Fig.7. The thickness of the polyimide layer was 20 $\mu$m in the simulated model. The maximum value of the deformation is 0.32 $\mu$m, higher than the value given in Table III for the case of polyimide with the same thickness, on top of 1.8 $\mu$m silicon nitride. This is no surprise, because the simulated model is very different from the previously simulated symmetric structures (section 3.2). In addition to this, 2.1 GPa has been taken for the polyimide elastic modulus assuming adverse effects of post mold curing, assuming it’s stress free state at its glass transition temperature (240 °C).
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Figure 5: 3D model in COMSOL including the grid (seen in the figure as black lines with numbers), depicting the footprint of the thin film cap. The dimensions of the simulated 3D structure are based on the capping that encapsulates the dog bone resonator.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Size [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>260</td>
</tr>
<tr>
<td>B</td>
<td>230</td>
</tr>
<tr>
<td>C</td>
<td>56</td>
</tr>
<tr>
<td>D,F</td>
<td>30</td>
</tr>
<tr>
<td>E,G</td>
<td>145</td>
</tr>
</tbody>
</table>

Table IV: Cap dimension for the actual device

Figure 6: Temperature-dependent elastic modulus of three grades of polyimide films (PI-polyimide, Kapton- a preprocessed polyimide in the form of a tape. There is a drop in elastic modulus of about 30 % going from room temperature to the post-mold curing temperature at 175 ºC for the material of interest with label ‘PI’.
Figure 7: Simulated 3D deflection profile of the footprint of the cap, showing the maximum deformation of the stacked structure (polyimide on thin silicon nitride). It is 0.32 µm and occurs at the area where the capping encapsulates the resonator. The total available room for deflection is 1.5 µm in the actual micro cavity.

3.5 Wafer warpage

Warpage is a measure of convexity or concavity in a wafer due to thickness variation and stresses trapped in the wafer due to the thin functional layers and the resulting interfaces. It occurs due to the difference in lattice constants (intrinsic or residual stress). IC packaging trends demand smaller packaging, which translates to thinner silicon; in some cases as thin as 50µm [8]. For NXP’s MEMS resonators and oscillators that are in a thin film QFN package, wafer thinning to 150 µm from a standard thickness (525µm) is a primary requirement. Thinning the wafer below 300µm induces significant warp in product wafers, which continues to increase as wafers are thinned further [9]. The wafer warpage is illustrated Fig. 8.
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Figure 8: Warpage $w$ in a wafer of diameter $D$ and bending radius $R$.

For the case of a large value of the radius $R$ as compared to the wafer radius $D/2$, i.e., $D/2 \, R \ll 1$, we can approximate the warpage $w$ by the expression [9, 10],

$$w = \frac{D^2}{8R}$$

(5)

with $D$ the wafer diameter, $w$ the warpage, $R$ the radius of curvature and $\varphi$ the bending angle.

The warpage of a 200 mm wafer can be determined using Eq. (5) when $R$ is known, which is determined by the residual stress in the thin film that is deposited on the wafer. We know that the residual stress of our polyimide is +20 MPa (positive value for tensile stress). Also, the bending radius on a full thickness wafer after the polyimide is deposited and finally cured is known [10, 12]. Based on Stoney’s equation relating the radius of curvature $R$ of a wafer induced by the stress $\sigma_f$, in a thin film, we can write the change ($w - w_0$) in the warpage of the wafer due to thinning as

$$w - w_0 = \left\{ \frac{6(1-\nu)}{8E} \right\} \cdot \sigma_f \cdot \left\{ D^2 \cdot \left\{ \frac{d_f}{d_s^2} \right\} \right\}$$

(6)

Here $\sigma_f$ is the thin film stress, $E$ the elastic modulus of silicon (130 GPa), $\nu$ the Poisson’s number for silicon (0.28), $d_s$ the substrate thickness, $d_f$ the film thickness, $R$ the radius of curvature after wafer thinning, and $R_0$ the radius of curvature before grinding. We see that the wafer warpage is directly proportional to the film stress and thickness and inversely proportional to the square of the wafer thickness. All known values for our case are mentioned in Table V.
Table V: Wafer warpage induced by a 20 µm Polyimide layer on a silicon wafer including curing, thinning from 525 µm to 150 µm. We assume a tensile stress $\sigma = 20$ MPa in the Polyimide thin film.

<table>
<thead>
<tr>
<th>Wafer thickness $d_s$ [µm]</th>
<th>Radius of curvature $R_0$ [m]</th>
<th>Radius of curvature $R$ [m]</th>
<th>Warpage $w$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>before thinning</td>
<td>525</td>
<td>1000</td>
<td>16.67</td>
</tr>
<tr>
<td>after thinning</td>
<td>150</td>
<td>35</td>
<td>1.62</td>
</tr>
<tr>
<td></td>
<td>$\infty$</td>
<td>1.69</td>
<td>2.95</td>
</tr>
</tbody>
</table>

The value of warpage of the thinned wafer is determined for our wafer diameter. Also, during the back grinding test in Hamburg, around 3 mm warpage was observed on the thinned wafer [13]. For thinned CMOS wafers targeting different applications in the microelectronics industry with silicon wafers having final thickness $\leq 150$ µm, such a value is not of any surprise [10]. A prior knowledge of this helps in planning design of experiments to adjust the polyimide stress (thickness) to reduce warpage, if required in the future.

3.6 Conclusions

We determine the required thickness of the three polymer reinforcements in combination with the thin silicon nitride. For a 6µm thick silicon nitride, there is factor 5x difference in the calculated maximum deformation between the edges-clamped and the simply supported rectangular plate, for our footprint. However, the simulated lid capping structure exhibits a deformation that lies in between the calculated values of deformation for the two different constraints.

A very safe margin in choosing the polymer reinforcement thickness is used to prevent risks induced by the 80bar over-molding pressure, e.g., capping collapse and stress-induced cracking. In the reinforcement processing experiments, the different polymer reinforcement layers will be processed according to allowable spin processing conditions. All the three polymers, SU8, Intervia and Polyimide, are processed in a single spin to get the required thickness, which is a benefit in terms of processing ease. But it poses a challenge in achieving the required final thickness.

References

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6. A simply supported square plate with a uniformly distributed load.
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(URL: http://structsource.com/analysis/types/plate.htm)


Chapter 4
Feasibility experiments on reinforcement polymers

To investigate the feasibility of the chosen polymer candidates as reinforcement layers, focus-exposure matrix (FEM) experiments are carried out. The objective is to determine the optimum exposure conditions on the three photo-sensitive negative-tone polymers: SU8, Intervia and Polyimide, to open them on aluminum bond pads. This is done to have access to the aluminum bond pads for electrical testing. The process recipes of the polymers are tuned to adapt to the actual conditions of our thin-film silicon nitride capping consisting of a significant topography and the bond pads size. Based on the observations and outcome, choice of reinforcement layers is made.

4.1 Introduction

The three polymers, chosen as potential reinforcement layers for our work, are all negative-tone photo-sensitive polymers. Therefore, focus-exposure matrix (FEM) experiments are carried out to determine the optimum exposure conditions on the three photo-sensitive polymers, SU8, Intervia and Polyimide, to open them on aluminum bond pads. The process flows mentioned in this report are the finalized versions, after feasibility studies that were performed on test wafers [1]. These three polymers are investigated as potential candidates to act as reinforcement for the existing wafer-level capping approach, consisting of a thin 1.8µm silicon nitride capping that is plugged with a 5µm thick aluminum layer. The cavity height of 1.5µm again adds to the topography of the wafer.

The existing silicon nitride thin-film wafer-level capping thus has a significant topography that can play an important role in accommodating the reinforcement layer. There could be processing difficulties induced by the different materials of the existing thin-film capping, like aluminum (causing reflections during exposure of the polymer) and silicon nitride (could lead to adhesion problems with the reinforcement layer). A FEM experiment is required to achieve the necessary process settings, to properly realize the polymer reinforcement.
4.2 Reinforcement processing

The simplified version of the process sequence is as follows. Starting with an SOI wafer, the MEMS resonator is realized in the 1.5µm thick silicon layer by a surface micro-machining technique. Then, at wafer level, the thin-film silicon nitride capping is carried out. Finally, the aluminum is applied for the bond pads and the plugs in the capping (upper part Fig.1). Owing to the confidentiality (NDA) of the project, the detailed sequence and the process recipe are only reported in the confidential NXP technical notes, and not mentioned in this text [1]. The objective is to spin-coat the polymer on the wafer following the processing conditions as given by the product vendor, pattern it lithographically, and finally open the bond-pad region. The sequence of steps to pattern the polymers is reported elsewhere [2].

The topography for the test experiment with the defined layers is illustrated in Fig. 1 [3]. Initially, only a blanket silicon wafer, mimicking the silicon-on-insulator is used to spin process the three photo-sensitive polymers namely SU8, Intervia and Polyimide (not drawn to scale). The sacrificial layer and the silicon nitride are deposited and patterned, holes and contact opening are defined on silicon nitride, the sacrificial layer is released and the silicon nitride is finally plugged with aluminum. Polymer is spin-processed and opened on the aluminum bond pads for electrical contact to the resonator.

Based on the outcome, full topography wafers including the thin-film silicon nitride wafer-level capping are then used. The polymer then is spin-processed and opened to contact the aluminum bond pads for electrical testing [4].

Figure 1: Process sequence for the test experiment: Cross-section of the device before (top) and after deposition of the polymer reinforcement layer including the opening of the bond pads (bottom).
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4.3 Focus Exposure Matrix experiments

The focus exposure matrix (FEM) parameters are the exposure dose $E$ of the UV light (I-line 369 nm) and the focus offset (FO), mapped in a matrix where $E$ is varied along each row and (FO) is varied along the columns to achieve the required critical dimension and photo-resist definability on wafer [4]. For our case, the FEM experiment is done to achieve the exposure optimum for opening the reinforcement layer on the aluminum bond pads. The small bond pads are 60 x 60 µm² and the large bond pads are 100x100 µm². Table I lists the chosen FEM settings for the three polymers, first following the product guide of the polymers and then tuning the settings based on the outcome with the standard settings. A Cartesian index system $(x, y) = (i, j)$ is used to identify the device areas on the wafer, centered at the midpoint of the wafer. The FEM settings for the different areas are given by

$$E_x = E_0 + i \cdot \Delta E, \quad -8 < i < 8,$$

$$\text{FO}_y = \text{FO}_0 + j \cdot \Delta (\text{FO}), \quad -9 < j < 9,$$

Where $E_0$ and $(\text{FO})_0$ at location $(0, 0)$ are the central values of the range to be investigated and $\Delta E$ and $\Delta (\text{FO})$ are the discrete steps determining the span of our search, respectively.

Initially, the standard setting is followed from the process manual, supplied for all the three polymers by the vendor (Table I). First, the reinforcement polymers are processed on blanket wafers (SOI wafer, 1.8 µm silicon nitride and 5µm aluminum as the outer of the stack). Next, the reinforcement layers are processed on topography wafers, consisting of the real thin-film capping on dummy resonators (Fig. 1). A good photo-definition of the polymer on the thin-film-silicon-nitride capping, complete removal of the polymer in the bond-pad area after exposure and development, and a good adhesion to the underlying topography are the criteria to choose optimum settings for the exposure dose. The focus offset was kept at the same value for the initial and final experiments on the optimization.

The diagnostics used for deciding on the optimum value are twofold. First, we use optical inspection, to look for the opening of the polymer on the aluminum bond pads (both small and large) after exposure and development, for swept barriers between bond pads, and swollen and wavy patterns on the whole device. Second, with a profilometer we scan over the opened bond pads to check if they are fully open and to investigate the profile of the opening in the polymer. A flat curve at the bottom confirms that the bond pad is fully opened. Skewed or tapered profiles indicate softening and stress in the polymer layer, respectively. The resolution of the Dektak 6M stylus profilometer is 0.1µm in the horizontal direction and the vertical resolution is in the range of 1 Å to 160 Å if extended. from the tip of the stylus. The shape of the tip is rectangular, which allows us to measure steep steps in a profile with a depth less than 21µm. The typical step size is 100 nm.
Table I: FEM settings (Eq. 1) for the scan of the exposure dose $E$ and the focus-offset (FO) for the three polymers, together with the optimum values determined in our search process.

<table>
<thead>
<tr>
<th>Polymer</th>
<th>$E_0$ (mJ/cm$^2$)</th>
<th>$+\Delta E$ (mJ/cm$^2$)</th>
<th>(FO)$_0$ (µm)</th>
<th>$+\Delta($FO$)$ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Process manual</td>
<td>This work</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SU8-25</td>
<td>400</td>
<td>120</td>
<td>10</td>
<td>0.00</td>
</tr>
<tr>
<td>Intervia</td>
<td>500</td>
<td>500</td>
<td>15</td>
<td>0.00</td>
</tr>
<tr>
<td>Polyimide</td>
<td>310</td>
<td>240</td>
<td>20</td>
<td>0.00</td>
</tr>
</tbody>
</table>

4.4. SU8-25

For this polymer it was cumbersome to arrive at the optimum exposure settings. Consulting the process manual of the polymer vendor, we find a recommended value of the exposure dose equal to $E = 400 \ J/cm^2$, a surprisingly high value when compared to other polymers. At this value of the exposure dose, SU8 was not opened on the bond pads. Partial reflections occurring at the aluminum-to-silicon nitride interface (the edges of aluminum covered by the polymer) upon exposure at the prescribed exposure dose were identified as the most likely explanation for this effect [2]. Moreover, at the recommended exposure dose, cross-linking was observed in the unexposed regions. Therefore, a much lower exposure dose was chosen for this polymer, as mentioned in Table I as the central value $E_0 = 120 \ mJ/cm^2$ of our scan.

Blanket wafer

The first FEM experiment has been carried out on a blanket wafer, mimicking the actual stack of the thin-film silicon nitride capping without the cost of the topography wafer. The resulting value for the exposure optimum is $E = 80 \ mJ/cm^2$, to open a 25µm thick SU8-25 on the small aluminum bond pad. In Fig. 4 we show a bird’s eye view with the optical microscope of a set of small and large bond pads of our test wafer, processed at the optimum exposure setting. In the soft-bake step, instead of following the procedure in the process manual, the temperature was controlled in a two-step process [1] to minimize the effect of thermal loading induced by soft-baking.

As indicated in Fig. 2, for $E = 80 \ mJ/cm^2$ the polymer is fully open on aluminum. But the pattern of the polymer is shifted. We see that the SU8 polymer becomes soft upon going to low exposure energy because of poor cross-linking and solvent-induced swelling after development at the contact opening.

Topography wafer

Figure 3 illustrates the step-height measurements on SU8-25 after the second FEM experiment on the actual topography [5]. By looking at the flat profile at the bottom, we conclude that the bond pads are completely open at $E = 80 \ mJ/cm^2$. This optimum setting is used for the next experiment on capping structures. From the spin-curve optimization experiments [2], it is known that the thickness of SU8-25 is around 24 µm. The profilometer measurements also show this thickness, as demonstrated in Fig. 3 for a small bond pad. A similar value in thickness was observed for the large bond pad. There is a mild skewness and tapering of the profile in the polymer layer after opening it.
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on aluminum. The tapering can indicate stress in the SU8 layer; the skewness can be due to a remaining softness of the polymer.

After obtaining the exposure optimum with the FEM experiments, polymer reinforcement experiments are done on topography wafers containing a 1.8 µm silicon nitride capping plugged with aluminum. The objective is to investigate whether the thick polymer reinforcement shows a good adherence and definition after patterning on the significant topography that comes from the 5µm thick aluminum plug metal and the first silicon nitride capping layer itself [7]. For the trial experiments, the optimum exposure dose was used. After exposure and before final curing (optional for SU8), the polymer becomes very soft and shows a tendency to shift its form (pattern) around the aluminum bond pad area. Swelling is observed (Fig. 4), which is caused by the developer solution used to remove the unexposed polymer on the aluminum bond pads, leading to swelling.

![Image of optical microscope pictures of FEM on SU8-25 at E = 80 mJ/cm².](image)

**Figure 2:** Optical microscope pictures of FEM on SU8-25 at E = 80 mJ/cm².

![Image of step profile measurement.](image)

**Figure 3:** Step profile measurement of a small bond pad produced at E = 80 mJ/cm² showing a 24µm step height. The unit of the vertical scale is 1 kÅ = 0.1µm.
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4.5 Intervia

**Topography wafer**

The opening at the aluminum bond pads with the recommended exposure settings for Intervia was good on blanket wafers. Therefore, another experiment was carried on a topography wafer to check whether it is feasible to obtain the same definition on the topography and to determine if the polymer exhibits good adhesion.

On the topography wafer, the polymer exhibited swelling both before and after the final cure. Figure 5 illustrates the patterns after exposure and after final curing. It must be mentioned that due to the unavailability of the prescribed oven, the cure was done for the first time in a radiation oven\(^2\), as opposed to a convection oven which is the standard for Intervia. Following this, the step height was measured. The measured profile in Fig. 6 illustrates the obtained thickness of Intervia 8023-10 after final curing. The ear shaped protrusions result from the shrinkage of the polymer. The polymer is wavy and swollen because of the absence of a convective heat transfer to achieve a stable polymer.

On another wafer, curing of Intervia 8023-10 was experimented in the convection oven (Heraeus, MiPlaza). A FEM experiment was carried out, with \(E = 500\) mJ/cm\(^2\) at the wafer centre following the exposure settings in the process catalogue for the polymer as the optimum exposure dose [5] (Table I). Focus-offset did not play a major role for the thick Intervia. Therefore, in the topography experiments, the given settings are chosen as the optimum.

Figure 7 illustrates the profilometer measurements, indicating that thickness of Intervia 8023-10 after final curing is around 16µm. This value is in agreement with the experience at NXP. The protrusions seen in the step height do not result from stress induced swelling or waviness, but they result from the thin silicon nitride overlap with the aluminum bond pad on which the Intervia is processed.

In Fig. 8, the resonator is feebly visible through Intervia as the layer is semi-transparent. In the zoom-in optical microscope picture on the right-hand side, the bond gap opening is shown and it is

\(^{2}\) Heraeus ATV Radiation oven, Mi Plaza
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focused on the surface of Intervia. We see that, the underlying topography is intact and a good definition of the polymer after opening the bond pads is achieved.

Figure 5: Opened aluminum bond pads on Intervia 8023-10 after curing at $E = 500 \text{ mJ/cm}^2$.

Figure 6: Intervia thickness after final curing on topography, after opening on small bond pads. The unit of the vertical scale is $1 \text{kÅ} = 0.1\mu\text{m}$.

Figure 7: Step height measurement of Intervia 8023-10 after final curing step, resulting in 15 $\mu\text{m}$ thick layer. The unit of the vertical scale is $1 \text{kÅ} = 0.1\mu\text{m}$.
4.6 Polyimide

**Blanket wafer**

The first FEM experiment was done by choosing the exposure dose suggested in the process manual of the vendor (Table I). The exposure energy was too high to open the bond pads after spin-processing a 21µm thick polyimide layer. The most likely cause again can be found in the occurrence of reflections of the light at the polymer to aluminum edges, resulting in partial cross-linking of the polymer in the non-exposed regions [3].

So, a second FEM experiment was carried out by lowering the central value $E_0$ of the exposure dose by nearly 30% (Table I). The test structure is a blanket wafer with the top aluminum layer opened as squares on silicon nitride. These experiments are done to study the interaction of polyimide on silicon nitride only, while opening the polymer. The small aluminum bond pads are not completely open after the final curing step at the optimum exposure dose. Figure 9 illustrates the optical microscope images of two different cases where all the aluminum bond pads are completely open (Fig. 9, left) at the optimum exposure energy $E = 80 \text{ mJ/cm}^2$. But, for a higher exposure energy $E = 105 \text{ mJ/cm}^2$, the small bond pads (Fig. 9, right), we see that there are reflections at the aluminum to polyimide edge. Whereas the small bond pad opening on silicon nitride does not show this behavior. The profile in Fig 10 indicates a step height of about 21µm after final cure, which is a regular value for the final thickness of the cured polymer (approx. 50% shrinkage after curing from the original thickness after spinning, 42 µm). Ear-like protrusions are seen at the edges of the profile. We believe this is due to the mechanical stress in the polyimide after curing it.

**Topography wafer**

The topography wafer consisted of patterned silicon nitride, sealed with aluminum, after releasing the initially deposited and patterned sacrificial layer [2]. On this, the polyimide was spin processed, following the standard steps and finally cured. The optimum exposure dose was used (Table I). Figure 11 illustrates the fully opened bond-pads after spin-processing and patterning the Polyimide. In our experiments we observe that (FO) variations do not have any impact on the definition of the size of the bond-pad opening [3, 5]. The polymer exhibits rounded corners, a natural outcome after patterning when we take into account the tendency to relax its stress after curing.
All bond pads are open and the underlying topography is intact after curing the polyimide. Following this, the final thickness was measured using the profilometer. After the final curing step, it is found to be 21-µm (Fig.12). This is a realistic value considering the shrinkage of this polyimide after curing. This is a regular value for spin-coating polyimide. Moreover, we observe tapered profiles and ear-shaped protrusions at the edges of the profile. This could be due to stress in the cured polyimide on the thin silicon nitride and aluminum. The underlying topography is devoid of cracks, chipping and delamination, as seen in the optical microscope.

![Patterned polyimide on a blanket wafer with dummy bond pads, after final curing. Left panel at E = 80 mJ/cm², on aluminum, right panel at E = 105 mJ/cm² at the silicon nitride after opening aluminum.](image)

*Figure 9: Patterned polyimide on a blanket wafer with dummy bond pads, after final curing. Left panel at E = 80 mJ/cm², on aluminum, right panel at E = 105 mJ/cm² at the silicon nitride after opening aluminum.*

![Profile measurement of Polyimide at a small bond pad opening. At the barrier between two bond pads, the polymer shrinks resulting in an ear-like structure. The unit of the vertical scale is 1 kÅ = 0.1 µm.](image)

*Figure 10: Profile measurement of Polyimide at a small bond pad opening. At the barrier between two bond pads, the polymer shrinks resulting in an ear-like structure. The unit of the vertical scale is 1 kÅ = 0.1 µm.*
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Figure 11: Polyimide on the silicon nitride resonator cavities, after patterning at $E = 80 \text{ mJ/cm}^2$ and curing (left panel), showing the final result of a small bond pad opening (right panel).

Figure 12: Profile of polyimide for a small bond-pad opening after curing, on a full-topography wafer at $E = 80 \text{ mJ/cm}^2$. The unit of the vertical scale is $1 \text{ kÅ} = 0.1 \mu\text{m}$.

4.7 Conclusions

For SU8-25, the optimized exposure energy is very low to enable complete cross-linking. The polymer becomes very soft after exposure. Moreover, the polymer swells after opening the bond pads, performed with solution development in a wet process, due to poor cross-linking. There is pattern shift on the full-topography dummy-cavity wafer. Therefore, this polymer is not a good candidate to be used as a reinforcement layer.

We see a good definition of Polyimide and Intervia on the topography wafers. The micro-cavities on wafer are intact after processing, on visual inspection. For Intervia 8023-10, a convection oven is a standard way to cure. The final thickness is 16µm after curing, with the optimized exposure settings. No ‘corner rounding’ is observed. Polyimide results in a thickness of 21µm. We observe ‘corner rounding’ for this polymer. We attribute this to the stress exerted by the polymer to the underlying topography.

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For both Polyimide and Intervia reinforcement thick films, the underlying topography is devoid of cracks, chipping and delamination, as seen in the optical microscope. Therefore, both Polyimide and Intervia are still in the race as good candidates to be experimented with as reinforcement layers in the actual capped MEMS resonator wafers.
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References


Chapter 5
Risks of thin-film capping

Thin-film capping is prone to a number of risks during the back-end handling of capped resonators on wafer. Also, processing the additional layer for reinforcing the thin silicon-nitride capping for the resonators is a challenging task, since it involves thermal loading with the associated stresses and strains that the MEMS and its capping environment need to endure. Key qualities such as minimal stress-uptake during packaging and good moisture-barrier capability of the reinforcement layer decide on the effectiveness of the thin-film capping for a good resonator performance during its operating life. Early assessment of the risks helps us to come up with mitigation measures and target toward functional specifications of our final product: the packaged oscillator.

5.1 Motivation
Assessing the potential risks of the thin-film capping and the associated processing to achieve the reinforced capping for the resonators can prepare us to take necessary mitigation measures in achieving a successful end product, the packaged oscillator. We state the possible risks that are foreseeable considering the BE-compatibility of the reinforcement processing. A few important mitigation measures are mentioned that help achieving reliable resonators and oscillator products.

5.2 Process-induced risks

Complexity
Materials that are suitable candidates to act as reinforcement layer are processed in the clean room, using the standard thin-film deposition techniques such as PECVD, sputtering and spin-coating. An additional layer or coating deposited on the existing thin-film silicon nitride capping would form a stack of materials with very different material properties. Due to the microstructure of the material and different thermal expansion coefficients of the materials that constitute the cap, intrinsic and thermo-mechanical stresses might develop and remain in the capping at room temperature [1, 2].
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Another important factor is the complexity involved in the reinforcement processing. This can impact the vacuum seal of the thin silicon-nitride capping and ultimately the electrical performance of the resonator. Solvents, gases and chemicals used in processing the reinforcement layer can interact with the thin silicon nitride and the aluminum plug. Processing inorganic dielectric reinforcement layers requires additional photo-resist deposition and exposure steps to pattern the layers. This can impact the stability of the thin-film capping layer or the hermeticity of the aluminum plug.

**Outgassing of PECVD silicon nitride**

At NXP Research, the current option for capping consists of a low-temperature (250 °C) PECVD-deposited silicon-nitride reinforcement layer. This process has a high probability for the material to contain volatile residual gases as it is deposited at low temperature. These contaminants might trigger reactions and release hydrogen gas both outside as well as inside the capping, causing additional residual-gas damping of the resonator [3]. It has been reported that, for the resonators used in this project and reinforced by PECVD silicon nitride, out-gassing of this extra layer of silicon nitride degrades the quality factor of the resonators. This outgassing is a thermally-driven mechanism that is activated at or above 400 °C impacting the operation of the resonator over a short time scale (on the order of 5 to 7 days) [3, 4].

**Molding at 80 bar**

The thin-film silicon-nitride capping, together with the sealing metal plug is not mechanically robust and will not survive the 80 bar molding pressure, required for the plastic package encapsulation. Cracking of the thin silicon nitride and the aluminum plug and capping-collapse are the typical failure mechanisms (Chapter 2) leading to resonator failure [5]. There is a need for a mechanically robust thin-film cap that can withstand the pre-assembly operations: wafer-thinning and dicing and finally molding thereby enabling packaged resonator functionality.

**Post-mold curing at 180°C**

Often, microelectronic packages come in a plastic package, such as quad-flat-no-lead (QFN), and the stress resulting from molding can have an impact on the electrical performance of the chip [6]. The post-mold curing is the last step in the assembly of the resonators and the oscillators. Table I illustrates the list of steps involved in molding. The temperature-induced stress exerted by the molding compound on to die and hence on the thin-film capping can influence the overall package stress level owing to the huge difference in CTE.

The mold compound is injected during a three minute interval at 180 °C, where it is still a fluid. After cooling to room temperature within three minutes, the packaged device is cured at 180 °C for another three hours (post mold curing). When cooling down after this final cure of the mold compound to room temperature, a differential stress, going from the stress-free state at post-mold curing temperature to the room temperature will result in a volume change in the capping and therefore cause stress in the capping as well as the final package.
Table I: Sequence of process steps during the final overmolding of the device before its release as a packaged IC for commercial applications.

<table>
<thead>
<tr>
<th>Step #</th>
<th>Process</th>
<th>Risks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>EMC out of deep-freeze for 4 h + cooling for 1 h</td>
<td>Traps and defects in the mold compound can be present.</td>
</tr>
<tr>
<td>2</td>
<td>UV clean of laminate/lead frame in oven (30 m)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Set molding tool (180 °C)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Place laminate/substrate/lead frame</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Close tool and open plunger (180 °C)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Release plunger at 80 bar/180 °C</td>
<td>The pressure at mold compound release and the pressure at which the mold compound fills are different. Moreover, the injection pressure could impact the die on laminate.</td>
</tr>
<tr>
<td>7</td>
<td>Release mold pressure/allow package to cool</td>
<td>The onset of cooling could retain the defects in the mold compound. During cooling, high residual stresses will build up between the die and the mold compound, which could lead to damage of the thin-film capping.</td>
</tr>
<tr>
<td>8</td>
<td>Post-mold cure 4 h at 180 °C</td>
<td>Mold compound shrinks during cure; additional package stress is building up.</td>
</tr>
<tr>
<td>9</td>
<td>Cooling down 180 C to 25 °C</td>
<td>Residual stresses in the mold compound can result in mold compound cracking.</td>
</tr>
</tbody>
</table>

5.3 Shear stress on thin-film capping

The capping has a significant topography that is due to the cavity height and the aluminum plug (Chapter 4, Fig. 1). The thin-film silicon nitride capping is a very fragile structure. This makes the thin-film capping very sensitive to the handling forces (stress) during the BE handling steps namely wafer thinning, dicing, and wire bonding. The vacuum sealing of the capping shall not deteriorate as required for the functionality of the resonator [7]. The main contributor to the topography (capping profile height) is the 5 µm thick aluminum plug. If the shear as well as normal forces act on aluminum, cracks might develop. The vacuum-tight sealing can be lost. Moreover, a molding pressure of 80 bar required for the plastic package could load and collapse the thin-film capping.

5.4 Moisture barrier capabilities of polymer film

Water vapor diffusion

Water vapor diffusion [8] through the thin-film capping is an undesirable effect and can lead to resonator failure. The estimation of the time required for an increase in pressure inside the micro
cavity due to water penetration, the characteristic time, is valuable information. We consider the case illustrated in Fig. 1, water molecules diffusing through the wall of the capping. We consider here the case of a 20 µm polymer slab alone functions as a moisture barrier. The diffusion behavior of a gas or vapor through a solid medium is governed by Fick’s law. The flow density \( \dot{N} \) (m² s⁻¹) is related to the gradient in the slab \( \frac{dn}{dx} \) by the diffusion constant \( D \) (m²/s) of the species of interest, as given by

\[
\dot{N} = D \cdot \frac{dn}{dx}
\]  

To simplify the problem, we consider a 1-D model with a gradient along the x-axis. To determine the time evolution of the density profile \( n(x, t) \), we look at the spatial dependency of the flow density \( \dot{N} \). Equation (1) then becomes

\[
\frac{d \dot{N}}{dx} = D \cdot \frac{d^2 n}{dx^2} = \frac{dn}{dt}
\]  

The density profile \( n(x, t) \) of the diffusing agent is found by solving eq. (2) with appropriate boundary conditions at \( x=0, t=0 \) and \( x=d, t=0 \).

Figure 1: One-dimensional model consisting of a capping layer of thickness \( d \) through which diffusion into the micro-cavity (top spacing \( d_2 \), bottom spacing \( d_1 \)) containing the MEMS can take place.

For a capping reinforcement layer with thickness \( d \), we can define a characteristic time

\[
t_0 = \frac{d^2}{D}
\]  

which is a measure for the evolution of the density profile as can readily be written using Eq. 2 in terms of a scaled variable \( x/d \). The stationary solution for the given slab of material is a linear profile with a gradient equal to \( \frac{dn}{dx} = \frac{n_0}{d} \). Here, \( n_0 \) is the concentration on the outside of the polyimide slab. We neglect the buildup of the concentration at the exit plane of the slab, i.e., at the MEMS device side. This is justified because a small fraction of the water vapor density outside the cavity is already detrimental for the functioning of the oscillator in the cavity. The relevant information to have is to estimate an increase in pressure in the MEMS micro cavity, as a function of time. Using Eq. (1), we find,

\[
\dot{N} = D \cdot \frac{n_0}{d} = n_{cav} \cdot V_{cav},
\]
with $V_{\text{cav}} = A \cdot (d_1 + d_2)$ the volume of the cavity. The increase in pressure $p_{\text{cav}} = n k T$ of the cavity is then equal to

$$p_{\text{cav}} = n_{\text{cav}} k T = \frac{n_0 \cdot D \cdot k T}{(d(d_1 + d_2))^2} = \frac{p_0 \cdot D}{d(d_1 + d_2)},$$

with $k$ Boltzmann’s constant. We observe that for this problem it is nicer to introduce a slightly modified characteristic time $t_1 = (d(d_1 + d_2) / D)$ which leads to the simple relationship,

$$p_{\text{cav}} = (p_0 / t_1)$$

The capping layer that is considered for moisture diffusion calculation is polyimide. This is based on our earlier discussions that polymers are hygroscopic materials (water absorbing) [13] and silicon nitride is a perfect moisture barrier for microelectronic applications [4, 6]. Typical values for $t_1$ are given in Table II, using the polyimide reinforcement as a reference.

Table II: Characteristic time $t_1$ and pressure rise in the micro-cavity per day at room temperature for different values of the diffusion coefficient of the polymer slab, for a cavity with $d_1 = 1.0 \mu m$ and $d_2 = 1.5 \mu m$. We assume normal operating conditions with a partial pressure $p_0 = 10$ mbar of water.

<table>
<thead>
<tr>
<th>$d$ [µm]</th>
<th>$D$ [m²/s]</th>
<th>Characteristic time $t_1$ [h]</th>
<th>Pressure rise [Pa/hour]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>$10^{-15}$</td>
<td>13.9</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>$10^{-13}$</td>
<td>0.139</td>
<td>72</td>
</tr>
</tbody>
</table>

It has been reported in [8] that the room temperature values of diffusion coefficient for the photosensitive polyimide are on the order of $D = 1$ to $5 \cdot 10^{-14}$ m²/s. An exception of this rule of thumb is BPDA-PDA type of polyimide backbone formulation) with a much smaller value $D < 1.10^{-14}$ m²/s. For the temperature dependency of the diffusion coefficient we can use

$$D(T) = D_0 \cdot e^{\frac{E_a}{kT}},$$

with $E_a$, the activation energy. For $E_a = 0.432$ eV (5013 K), this will result in an increase in $D$ by a factor of 100 when going from 293K to 393 K and thus in a decrease by the same factor of the characteristic time $t_1$. We have to conclude that this simple calculation shows that a polyimide as a reinforcement layer is not effective in keeping water vapor out of the micro-cavity.

**Practical evidence**

The water diffusion isotherms for a class of polyimide thin films have been gravimetrically investigated over the temperature ranges of 5–60°C [8]. The PDA-based polyimide films exhibited a relatively more ordered morphological structure (highly crystalline and good in-plane orientation) than that of the corresponding ODA-based polyimide thin films, which may serve as impenetrable
obstacles for the water diffusion in the out-of-plane direction. Consequently, it would lead to relatively slower water diffusion in the PDA-based polyimide thin films.

The effectiveness of polyimide films in acting as a moisture barrier for microelectronic applications has been reported by a few research groups [9, 10, 20]. Polyimide and Benzo-cylo-butene (BCB) polymer thick films have been applied on tungsten (W) and tungsten-nitride (WN), tungsten-silicon (WSi) and tungsten-silicon nitride (WSiN) as insulator films for MMIC (Monolithic Microwave IC) interconnects [11]. In these applications, polyimide has been found to be effective in combating moisture (as moisture barrier coating).

5.5 Stress in reinforcement layer

During the process of post mold curing, the mold compound (EMC) that has taken the shape of the lead frame upon injection, cross-links (hardens) and takes its final shape as the plastic package. The post-mold curing temperature is very close to the glass-transition (softening) temperature of the polymer reinforcement materials that have been investigated [12].

The molding process and the post-mold curing step (steps 6 and 8, Table I) are the main cause of stress in the packaged device. The stress is transferred from the molding compound to the underlying thin-film capping and reinforcement during over molding and cooling down from 180 to 25 °C [13]. Another important boundary condition is the stress in the silicon nitride plus the polyimide reinforcement when starting the post-mold cure at 180 ºC. The reinforced cap is not stress-free at 25 ºC before the molding. Therefore, the situation at 180 ºC at the start of the cooling down after the molding process can be considered as stress-free and the model holds.

The distribution of stress levels can tell us what order of magnitude of stress can be expected during this process and whether the presence of polymer reinforcement can decrease the build-up of stress during the post molding curing step. To know this, we can apply the analytical model reported in [14]. This model is based on force and moment balances, and it has been developed to predict the residual thermal stress in an elastic multilayer coating system due to differential thermal contraction. Using this model, the stress levels are determined for the cases: (1) thick silicon nitride and (2) polyimide reinforcement layers. For the stacked layers, the values of the layer thickness and stress are mentioned in Table III [15, 16]. For these cases, the thin film stress that results from the molding and post mold curing at 180 ºC is given by

$$\sigma_i = E_i (\alpha_i - \alpha_{EMC}) \cdot (\Delta T) \quad (1 \leq i \leq n)$$

with $E_i$ the elastic modulus of layer $i$ and $\alpha_i$ its coefficient of thermal expansion. This is the stress at the interface for these multi-layers. Not every layer in the stack of thin films connects to the EMC layer (bulk). The stress in the bulk - here the mold compound (EMC) depends on the coordinate in $z$ and - is given by the weighted summation

$$\sigma_{EMC} = -\frac{2(3z+2d)}{d} \sum_{i=1}^{n} \sigma_i \left( \frac{d}{d} \right) \quad (-d \leq z \leq 0)$$

with $n$ the total number of thin-film layers on the bulk, $\Delta T$ the temperature change during the cooling down after EMC curing, $\sigma_i$ and $d_i$ the stress and thickness of layer $i$, and $d$ the thickness
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of the bulk layer. Inserting the values into Eq. (8) and (9), the stress in the EMC for the stack of thin films is known.

Table III lists the stress values due to different types of reinforcement layers used. The interface stress $\sigma_i$ in each thin layer is independent of the film thickness, but depends on the differential CTE with the bulk and the temperature change $\Delta T$. The stress in the EMC depends on the weighted contribution of the stress in the thin layers.

As the coefficient of thermal expansion of polyimide is 32x higher compared to the silicon nitride thin film and nearly 3x higher than the mold compound ($\alpha_{\text{Polyimide}} = 55 \text{ ppm/K}$, $\alpha_{\text{Silicon nitride}} = 1.7 \text{ ppm/K}$, and $\alpha_{\text{EMC}} = 20 \text{ ppm/K}$) it accommodates for the thermal mismatch between the mold compound and thin silicon nitride. With the addition of the polyimide layer, the differential stress in the EMC layer is equal to $\Delta \sigma = 14.8 - (-7.4) = 23 \text{ MPa}$, a factor 4x smaller and thus implying a 4x larger radius of curvature. In both cases, the stress in the silicon nitride layer is the same (567 MPa).

Table III: Stress in the EMC, polyimide and silicon nitride for $\Delta T = 180 - 25 = 155K$ temperature change for (1) thick silicon nitride and (2) polyimide reinforcement

<table>
<thead>
<tr>
<th>Layer</th>
<th>$z$ [µm]</th>
<th>$\sigma$ [MPa]</th>
<th>Layer</th>
<th>$z$ [µm]</th>
<th>$\sigma$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiN</td>
<td>-5</td>
<td>567</td>
<td>SiN</td>
<td>-1.8</td>
<td>567</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Polyimide</td>
<td>20</td>
<td>-13.6</td>
</tr>
<tr>
<td>SiN-EMC interface</td>
<td>0</td>
<td>57</td>
<td>Polyimide–EMC interface</td>
<td>0</td>
<td>14.8</td>
</tr>
<tr>
<td>EMC surface</td>
<td>200</td>
<td>-28.5</td>
<td>EMC (surface)</td>
<td>200</td>
<td>-7.4</td>
</tr>
</tbody>
</table>

With the inclusion of the polyimide layer, the package is nearly flat with no forces on the silicon-nitride to aluminum-plug interface. The nature of stresses is different for the two reinforcements: polymer reinforcement- with compressive stress on the mold compound as well as the polymer coating; silicon nitride reinforcement-with compressive stress on the mold compound and tensile stress on the silicon nitride reinforcement.

5.6 Mitigation measures

Mechanical load

It is necessary to shield the thin silicon-nitride capping from shear stress and shock during the BE handling steps. Providing reinforcement with a soft and compliant material such as polymers would ensure a proper shielding. A compliant polymer reinforcement-layer, thrice as thick as the aluminum plug, would absorb the mechanical vibrations in the aluminum plug, compared to a brittle inorganic dielectric layer. The combination of polymer, aluminum and thin silicon nitride can function as an effective capping layer for our resonators, with the polymer shielding and guarding the aluminum plug and the underlying topography from shear stress and mechanical shock [17].
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Thermal load

To minimize reinforcement processing-induced triggering of outgassing on the thin silicon nitride and also for less thermo mechanically induced stress, polymers that exhibit less residual (coating) stress on wafer are desirable. When the thermal load arising from the curing temperature involved in processing is reduced by choosing polymers that have a lower curing temperature, this would be better for the thin-film capping and thus for the resonators. The polymer SU8 does not require a final curing step. Polyimide needs to be cured at 350 °C, which is comparable to the aluminum plug deposition temperature. Intervia is cured at 190 °C. This has a significantly lower thermal budget compared to Polyimide processing and the reference, the thick silicon nitride deposited at 250 °C.

Moisture

As a passivation layer, standard PECVD silicon nitride is proven to be a good moisture barrier for microelectronic devices, as it is frequently used as a passivation layer [18]. The thin-film silicon nitride capping with the aluminum plug did not survive the accelerated moisture test (UHAST). The resonators-on-wafer that were reinforced with thick low-temperature deposited PECVD silicon nitride (our reference) were also subjected to accelerated moisture testing. Again, these resonators were not functional after the test [19]. Resonator charging was found to be the root cause of failure.

This implies that a 1.8µm layer is either not a good moisture barrier or that a different failure mechanism is operational. The latter seems to be the case in view of the discussions with experts and related experience in the field. A 20µm polyimide reinforcement layer alone will not serve to be a good moisture diffusion barrier, based on our calculations for water diffusion time and pressure increase. In this case, the thin silicon nitride layer must be responsible for avoiding moisture to penetrate the oscillator cavity.

Interface shear

The aluminum-plug to silicon-nitride interface is sensitive to any minor mechanical disturbance, which can result in small leaks and thus in moisture penetration. With a proper choice of reinforcement material with a good conformal adhesion, the aluminum plug in our capping could be stabilized to mechanical shear stress and avoid moisture penetration during harsh reliability tests such as UHAST.

Our option for the NXP’s thin film capping consists of a stack of 1.8 µm silicon nitride, plugged with a 5 µm aluminum and a 20 µm polyimide reinforcement thick film. On the underlying 1.8 µm thick silicon nitride layer, the polyimide could suppress and prevent possible failure modes such as interface shear on the aluminum plug-silicon nitride interface due to a very good encapsulation and coverage on the topography [20].

5.7 Outlook

To approach the problems occurring during molding at 80 bar, thick-film polymers that come with processing ease can be suitable candidates. As advanced technologies such as flip-chip continue to evolve, device manufacturers are faced with several material and processing challenges. Stress buffer-layer materials introduced to the semiconductor packaging industry can be efficiently photo-patterned as thick dielectric films and cured at low temperatures [21]. In our work, these materials can play a role to help over-molding. Adoption of the spin-processing technique, employed to process polymer films, has been feasible to a considerable extent as they pose processing requirements very similar to other front-end semiconductor fabrication processes. Good chances of
future success is likely to depend on a close collaboration between materials and equipment suppliers, working with assembly and packaging service providers to develop practical solutions that can be implemented into an efficient manufacturing process.

References

Chapter 5


Chapter 6  
Effect of pre-assembly on resonator electrical performance

Back-end (BE) handling is one of the crucial steps that determine the end result of the package-level functionality. The results of the two BE tests are presented, namely, wafer back-grinding and dicing, on Polyimide and Intervia reinforcements, processed on dummy micro-caps as well as on thin silicon-nitride encapsulated MEMS resonators on wafer. These results are used to broaden our understanding of these tests on the resonator’s electrical performance. The impact of these back-end handling operations on the electrical performance of the resonators is studied. Also, ways to mitigate these issues are discussed.

6.1 Introduction

With the trend toward smaller and thinner packages for portable and hand-held products, there is an increased need for thinner semiconductor devices. The technology for thinning wafers is becoming more critical than ever before. With the advent of the thicker 200 and 300 millimeter wafers, bumped wafers, stacked-die requirements and ultra-thin packages, wafer back-grinding equipment and processes are becoming critical issues for assembly [1, 2]. Back-end (BE) operation is one of the crucial steps that determine the end result of the package-level functionality. The forces applied during the application of the tape on the front side of the wafer and the pressure applied to the back side of the wafer during grinding can have a significant impact on the functionality of the MEMS dog-bone resonator and the integrity of the thin film capping [3].

The questions to be answered are:

- Is the reinforced silicon nitride cap intact after the operation?
- Are the devices electrically functional?

The results of wafer back-grinding and dicing of resonators on wafer with polyimide reinforcement are presented, which were cured in a non-standard way (section 6.6). The impact of the two back-
end handling operations on the electrical performance of the resonators is understood and ways to mitigate issues are discussed.

6.2 Back-grinding and de-taping test

Figure 1 illustrates the sequence of steps associated with the back-grinding and de-taping operation. The tape is applied on the top (front) side of the wafer to protect the features from the influence of dirt, particles and the forces that come from the wafer back-grinding operation. The adhesive on the tape holds the base film on to the wafer’s front side. The capping experiments have been performed with both dummy cavities (mentioned in chapter 4 of this thesis) and on micro-caps processed on resonator wafers in MiPlaza.

![Diagram of back-grinding, de-taping and dicing process](image)

Figure 1: Standard back-grinding, de-taping and dicing operation on a wafer containing a micro-electronic device. Forces acting on the backside of the wafer are harsh, impacting the devices’ electrical performance [10].

The initial back-grinding and de-taping tests on reinforced dummy micro-caps were carried out in the European Sample Centre (ESC), NXP Nijmegen [4]. For the resonator wafers, taping, back-grinding to 150 µm wafer thickness, and de-taping was performed at the NXP wafer thinning facility in Hamburg [5]. Visual inspection then is the available diagnostic.

The next step in our tests is to apply the back-end handling routines to thin-film capped and reinforced resonators. Again, visual inspection is an easy diagnostic for cracking, etc. However, the electrical functionality after this treatment is the decisive diagnostic for the real impact of the mechanical treatment in the process of fabrication survival.

6.3 Reinforced dummy micro-caps

For the dummy micro-caps, the back-grinding and de-taping tests were carried out in ESC. These experiments have been done in two separate steps. First, only the taping and de-taping operation was performed in a standard way. After this test was proved to be feasible, taping, back-grinding to 150-µm wafer thickness, and finally detaping was performed at the wafer thinning facility in Hamburg. Figure 2 illustrates the visual inspection results of taping, back-grinding and detaping operation. The Intervia and Polyimide reinforced dummy-cavities survive the back-end operation. No cracking, chipping, and delamination are observed after the test on a full wafer with some 120 resonators.
6.4 Reinforced MEMS resonator wafers

After polymer processing and electrical measurements, the two wafers with Intervia and Polyimide reinforcement were back-grinded in the NXP Hamburg facility, to a thickness of 150 µm, considering the requirements for the stacked die option for the MEMS oscillator demonstration [2]. Images of the visual inspection after wafer back-grinding are shown in Fig. 3. We observe no damage of the devices. In Table I, the optical measurements of the wafer thickness, including the thickness of the polymer reinforcement, are presented. The total thickness variation (TTV) for polyimide is more than a factor two larger than Intervia. We believe this is due to the fact that the polyimide wafer cracked in the delamination tool during pick up.

Figure 2: Dummy cavity and bond pad after taping, back-grinding to 150µm and de-taping operation at Hamburg for Intervia (left) and Polyimide (right) reinforcement. The polymer covers the entire die in both cases. The dummy micro-caps are intact after the operation.

Figure 3: Visual inspection Intervia (left) and Polyimide (right) reinforced dog-bone resonator after wafer back-grinding to 150 µm. The resonator region is not visible on a device with polyimide reinforcement because the 20 µm thick layer is not transparent. For Intervia it is clearly visible due to the transparent nature of this polymer. The polymer covers the entire die in both cases.
Table I: Optical measurement of the wafer thickness before and after the back-grinding operation, given in terms of the mean value and the total thickness variation (TTV). Also, the lower- and upper bounds denoted ‘min’ and ‘max’, respectively, of the range are given [3].

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Intervia</td>
<td>525</td>
<td>148</td>
<td>8.7</td>
<td>143</td>
<td>152</td>
</tr>
<tr>
<td>Polyimide</td>
<td>525</td>
<td>142.5</td>
<td>20.7</td>
<td>132</td>
<td>153</td>
</tr>
</tbody>
</table>

Figure 4 shows some more images of the devices after back-grinding and after electrical measurements. We observe that micro-caps with both types of reinforcement polymers survived the standard back-grinding and detaping operation. The MEMS dog bone resonator is intact and there are no other strange effects seen. Therefore, we conclude positively on the feasibility of the wafer back-grinding operation. For the polyimide reinforced dog bone resonator, probe marks can be seen. They resulted from the RF probing during the electrical measurements. The 20 µm thickness was significant enough to have almost no clearance between the bottom surface of the RF probe and the surface of the polymer. This resulted in scratching of the probe on the polymer.

The wafer with polyimide reinforcement broke during pickup by the robot for de-lamination of the front-side tape that was applied. This was reported to be a BE handling problem. A possible reason could be that the final wafer thickness after back-grinding did not support the 20 µm polymer coating on top of the silicon nitride micro-cap, exhibiting a huge warpage of 1.2 mm. The suggestion from NXP Hamburg wafer-thinning facility was to have the wafer thickness to be 250 µm after back-grinding as standard for a 20 µm thick polymer coat [3].

Figure 4: Visual inspection after back-grinding Polyimide reinforced dog bone resonators after wafer back-grinding. The underlying capping and the resonator are intact. Probe marks can be seen in the vicinity of the bond pads and on the polymer as well.

6.5 Intervia-reinforced resonators

In this section, the results of electrical measurements on Intervia reinforced resonators are presented. These measurements are taken after the back-grinding step. We have investigated 120 devices on wafer. We observe that a large fraction (90 %) of the Intervia reinforced micro-caps survive back-grinding and detaping. Table II gives typical values of the quality factor and resonance frequency shifts before and after the back-grinding operation. Both dicing and back-grinding do not degrade the quality factor of the reinforced resonators. However, the dicing operation has a significant
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impact on the frequency shift. On the wafer with Intervia reinforcement, a center-to-edge variation was observed in the quality factor and resonance frequency.

Table II: Measured typical values of the quality factor \( Q \), the maximum value of the decrease \( \Delta Q \) in quality factor and the frequency shift \( \Delta f/f_0 \) of Intervia reinforced MEMS resonators after the back-grinding operation, as compared to the situation with only Intervia deposited and cured [11].

<table>
<thead>
<tr>
<th>Electrical parameter</th>
<th>Before Intervia</th>
<th>After Intervia incl. cure</th>
<th>After back-grinding</th>
<th>( \Delta Q(\text{max}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality factor ( Q ) [..]</td>
<td>42000</td>
<td>28000</td>
<td>36000</td>
<td>31000</td>
</tr>
<tr>
<td>Frequency shift ( (\Delta f/f_0) ) [ppm]</td>
<td>Before and after cure (max)</td>
<td>22</td>
<td>Before and after back grinding (max)</td>
<td>28</td>
</tr>
</tbody>
</table>

In conclusion we can state that back grinding even can improve the electrical performance in terms of the quality factor. Some devices show a high quality factor after back-grinding and detaping. This is most likely due to the stress relaxation of the wafer-level capping after back-grinding.

6.6 Polyimide-reinforced resonators

**Wafer warpage**

The very first wafer with MEMS resonators on which polyimide was processed in a standard way, was back grinded from its original, standard thickness of 525 µm to 150 µm, for the thin film package application [2]. This resulted in cracking of the wafer due to a very large warpage [3]. It was not possible to measure the electrical parameters of the polyimide-reinforced MEMS resonator wafer in a routine way, as it cracked during the robot pickup after the back-grinding operation. A few resonators at selected sites were measured after manually adjusting the level of the broken wafer in the vacuum chuck. These devices were functional. There is no data available for this test due to logistics and a communication problem. The purpose was to know whether the resonators were functional after the wafer back-grinding.

It is clear that the Polyimide-reinforced resonator wafers have a handling issue. This is not a surprise because we already have investigated the possible warpage of the wafer by the stress in the polymer in chapter 4. Before we decide on the ultimate process to be used, this needs to be explored in more detail by the production facility to be employed.

For the second series of experiments, we did not solve the technology issue but have chosen for back-grinding the wafer to a thickness of 250 µm including the polyimide layer. This avoided the handling problem experienced in the first series. We still observe a huge warpage of about 1.9 mm after the back-grinding. This is mentioned in Table III. Moreover, the wafer took the shape of a saddle. We attribute this to stress build up in the bulk silicon of the SOI wafer and also at the interface between the thin-film capping (Polyimide – Silicon nitride) and the monolithic silicon. With the Stoney’s equation, the stress induced by the polyimide can be determined. We assume that the polyimide coating stress (20 MPa) is the only driver of the warpage. With this known warpage and the mean wafer thickness after back-grinding, the polyimide stress can be calculated using the Stoney’s equation (Eq. 6, chapter 3). This gives us the stress exerted by polyimide, 26 MPa. We confirm that polyimide coating stress is little different from what we have assumed, and is solely responsible for the warpage.
Table III: Average values of warpage and bow ‘before’ and ‘after’ back-grinding a 250 µm thick wafer including the polyimide layer [7]. The total thickness variation (TTV) and the mean value of the wafer thickness without the polyimide layer are mentioned.

<table>
<thead>
<tr>
<th>Case</th>
<th>Bow [µm]</th>
<th>Average warp [µm]</th>
<th>TTV [µm]</th>
<th>Mean wafer thickness [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before back grinding</td>
<td>99</td>
<td>127</td>
<td>Not available</td>
<td>525</td>
</tr>
<tr>
<td>After back grinding</td>
<td>1920</td>
<td>1979</td>
<td>7.65</td>
<td>210</td>
</tr>
</tbody>
</table>

After back-grinding, the wafers are diced in the Nijmegen facility in a standard way, employing a circular diamond blade. The saw lanes are free of debris and there is no chipping. The dicing operation does not pose any problem and the edges appear to be very smooth. In Fig. 5 we show an image of a resonator after dicing. The reinforcement layer, which is an organic material, acts as a good overcoat on top of the thin silicon nitride near the saw lanes. This eliminates the brittle fracture from occurring, owing to the polymer’s compliance.

![Saw lanes free of debris](image)

**Figure 5: Visual inspection after dicing of a polyimide reinforced wafer: the resonator region is intact. The saw lanes are free of debris. No delamination, chipping and cracking are found [8].**

**Electrical parameters**

The electrical parameters quality factor, dog bone resistance and frequency shift are analyzed to understand the accumulated impact of both the back-grinding and the dicing operation on a quarter portion of the wafer. We have investigated a total of 20 resonators. In Fig. 6, the quality factor, dog bone resistance and the frequency is plotted for the different stages of processing the wafer. It is seen that the quality factor drops significantly (30%) after polyimide processing including the curing step. Then it remains almost stable during the back-grinding and dicing operations. Although a little surprising, the quality factor mildly increases after back-grinding. This can perhaps be attributed to relaxation in the thin film capping. After dicing, the quality factor values are acceptable for the intended application of the resonator in the oscillator.
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After polyimide processing including curing, the dog-bone resistance shows a steady increase of approx. 10% for all resonators. Except for the back-grinding phase, where the dog-bone resistance shoots up by approximately 30%, it remains almost constant in all other phases. It is also seen that the effect of wafer dicing removes the fluctuation in the dog bone resistance values that was introduced by the back-grinding operation. The dicing operation is the last step in the back-end operation, before the dies are assembled in a package and molded. The final values of the resistance lie well within the acceptable range that is expected for a good device performance [6].

From Fig. 6, we see that the back-grinding operation does not mechanically load the MEMS resonators on wafer as the frequency shifts are with a few ppm. The effect of dicing is much larger, on the order of 30 ppm and accounts for the full effect of back-end handling. This can be understood by realizing that all forces related to dicing that are applied, are much localized in the sawing lane. But cutting through the polyimide is likely to lead to an overall change in the state of stress; removing of material under stress leads to relaxation. The results for all the electrical parameters are compiled in Table IV.

Spatial distribution on wafer

The impact of back-grinding and dicing on the resonator specifications are separately studied. Figure 7 repeats our discussions so far, but, the intention is to clearly show the spatial distribution of the two most important electrical parameters and to determine the effect of any post processing, such as wafer thinning and dicing on the distribution. A comparison between back-grinding and dicing has been done to know which one of the two has a major impact on the resonator electrical performance. The spatial distributions of the dog bone resistance and the resonance frequency shift are illustrated. We have chosen for an adequate but simple representation with a color coding for the different ranges of experimental results. They are defined as given in Table V.

The values of $R_d$ are higher near the edge of the quartered wafer. This is exactly the region where the wafer had been back-grinded to 250 µm, then quartered with a diamond blade, and later on, diced on this quarter of the wafer. There is an influence of stress due to this operation. The dicing operation induces a stress relaxation, which, implies an additional elastic deformation on the surrounding area of the dog bone springs), impacting the resonance frequency of the dog bone shaped resonators, as we see on the distribution of the resonance-frequency shift for this quarter wafer.
Figure 6: Quality factor $Q$ (top panel) and $R_d$ (middle panel) at different stages of processing the wafer: (1) thin silicon nitride; (2) Polyimide after curing at 250 °C; (3) after back grinding to 250 µm; (4) after dicing. Frequency shift $\Delta f/f_0$ (bottom panel): (1) before back-grinding and after dicing (2) before and after back-grinding to 250 µm. The numbers along the horizontal axis indicate the index of the device.
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Table IV: Typical values of all the electrical parameters (including the standard deviation SD) after the different stages of processing the wafer: thin silicon-nitride encapsulation, polyimide deposition and curing at 250 °C, back-grinding and dicing.

Note: Reference value is always ‘Before back grinding’ situation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Thin Silicon Nitride</th>
<th>Polyimide</th>
<th>Back-grinding</th>
<th>Dicing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Q ($10^3$)</td>
<td>50</td>
<td>7</td>
<td>32</td>
<td>5</td>
</tr>
<tr>
<td>Rd ($\Omega$)</td>
<td>608</td>
<td>2</td>
<td>646</td>
<td>5</td>
</tr>
<tr>
<td>$\Delta f/f$ (ppm)</td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>5</td>
<td>29</td>
<td>4</td>
</tr>
</tbody>
</table>

Table V: Color code representation of electrical parameters distribution on quartered wafer

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Color</th>
<th>Range</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_d$ [$\Omega$]</td>
<td>Red</td>
<td>700 – 800</td>
<td>Out of specification</td>
</tr>
<tr>
<td></td>
<td>Yellow</td>
<td>650 – 700</td>
<td>Meets the specification</td>
</tr>
<tr>
<td></td>
<td>Green</td>
<td>No change</td>
<td>Meets the specification</td>
</tr>
<tr>
<td></td>
<td>White</td>
<td>Not measured</td>
<td>Skipped during the measurement</td>
</tr>
<tr>
<td>$\Delta f/f_o$ [ppm]</td>
<td>Red</td>
<td>30 – 40</td>
<td>Out of specification</td>
</tr>
<tr>
<td></td>
<td>Yellow</td>
<td>10 – 30</td>
<td>Out of specification</td>
</tr>
<tr>
<td></td>
<td>Green</td>
<td>1–10</td>
<td>Meets the specification</td>
</tr>
<tr>
<td></td>
<td>White</td>
<td>Not measured</td>
<td>Skipped during the measurement</td>
</tr>
</tbody>
</table>
6.7 Conclusions

The back-grinding and dicing tests do not have any detrimental effect on the resonators performance in terms of the electrical functionality of the resonators. The dog bone resistance increases significantly during back grinding to 250 µm and it fluctuates along the quartered wafer. This could be due to stress build up in the bulk silicon because of grinding forces. But this relaxes to a large extent after dicing and it levels off. The final value of dog bone resistance (i.e. after wafer dicing) lies within the specification [6, 8]. For the Intervia reinforcement, only wafer back grinding was performed. The dicing operation was skipped for this reinforcement as it was difficult to perform a full wafer measurement due to the shift in the position of the dies caused by dicing.

The frequency shift due to back-grinding is within 5 ppm. Wafer dicing, however, results in a 30 ppm shift. Perhaps, this is induced due to the mechanical force exerted by the diamond sawing blade on the silicon wafer. There is a wafer warpage of about 1.9 mm, which, is an issue for industrialization [7, 9]. This can be addressed by determining the impact of polyimide curing on wafer after removing the polyimide and measuring the wafer warpage. Based on this information a Design of Experiments (DoE) with the polyimide spin speed and curing temperature can be devised.
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References


Chapter 7

Impact of thermo-mechanical loading on electrical performance

The influence of thermo-mechanical loading during reinforcement processing on the quality factor is presented and discussed. Non-reinforced thin silicon-nitride capped-resonators on wafer are taken as a reference. Possible causes for the quality factor degradation are discussed and investigated, including the effect of temperature excursions and polyimide film stress.

7.1 Introduction

The impact of the reinforcement processing on the stability of the quality factor of the MEMS dog-bone resonator is discussed. The thin silicon nitride encapsulated MEMS resonators without any reinforcement layer are compared with the Intervia and Polyimide reinforced resonators. Throughout this chapter, the experiments and measurements were done at wafer level. The effect of thermo-mechanical loading on the quality factor is discussed using the available results. The effect of polyimide film stress can be large, showing up as alterations of the radius of curvature and the wafer bow in different processing steps (Table I). A negative curvature indicates a concave profile of the wafer after a layer is applied, as seen from the device side of the wafer. For Intervia, the numbers are not available as the coating stress and the curvature were not measured in a test experiment.

7.2 Aluminum plug stability

Possible effects of thermo-mechanical loading on the resonator are mentioned. A mismatch in the coefficient of thermal expansion (CTE) between materials of the capping can influence the stability of the cap. The aluminum plug on the thin silicon nitride can result in leaks, when subjected to a thermal excursion, due to much larger contraction of the plug. If a material with higher CTE as compared to the aluminum plug is employed (such as a polyimide thick film), this will help preserving the stability of the capping through the tensile stress exerted on the whole area of the thin silicon nitride cap. The CTE values are mentioned in Table II.
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Figure 1: Cross section of device, showing the aluminum plug which covers the opening in thin silicon nitride.

Table I: Measured radius of curvature, wafer bow and layer thickness at different steps of processing of the Polyimide reinforcement [1].

<table>
<thead>
<tr>
<th>Layer steps</th>
<th>Curvature [m]</th>
<th>Wafer bow [µm]</th>
<th>Layer thickness [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before / after Al deposition</td>
<td>-71 / 321</td>
<td>25.3 / -5.5</td>
<td>0 / 5</td>
</tr>
<tr>
<td>After Al deposition/Al etch</td>
<td>321 / -73</td>
<td>-5.5 / 24.8</td>
<td>5 / 0</td>
</tr>
<tr>
<td>After Polyimide /after cure</td>
<td>-91 / 35</td>
<td>20.7 / -52.2</td>
<td>31 / 20</td>
</tr>
</tbody>
</table>

In Fig. 1 the geometry of the silicon nitride and the aluminum plug are shown, leaving out the blanket cover of 20 µm of polyimide reinforcement. The stack of polyimide – aluminum plug – thin silicon nitride represents a structure involving very different material constants and CTEs. Polyimide has the highest CTE, followed by aluminum and silicon nitride. This configuration plays a role in preserving the integrity of the aluminum plug in the thin silicon-nitride cap. As seen in Table II, the effect of differential contraction is rather large. In addition to this, the overall wafer bowing due to CTE mismatch can result in the center-to-edge variation on the wafer.

As the CTE of polyimide is 40x that of thin silicon nitride and 2.4x that of the aluminum plug, polyimide experiences a contraction when cooling down from the curing temperature of 350 °C to room temperature. The aluminum plug contracts during the temperature excursion (from 350 °C to 25 °C). For polyimide, the contraction below its glass transition temperature (approx. 200 °C for polyimide) is 2.4 times more than the aluminum plug, causing additional stress build up. This is responded by the aluminum plug with an elongation at the interface, owing to the CTE difference and mismatch [2].

For a high-temperature excursion, the drop in the quality factor is higher (polyimide curing) than a comparatively lower thermal excursion (Intervia curing) [5, 12]. This is related to the outgassing of the underlying thin silicon nitride during the curing of the polymer reinforcement. In addition to this, the thermo-mechanical loading (stress) of the reinforcement layer (both polyimide and Intervia) due to CTE mismatch can add to the decrease in the quality factor from the resulting bow in the wafer. For the thin silicon nitride capping without reinforcement, the bow effect is a factor of 2x smaller and has a different sign.
Table II: Coefficient of thermal expansion (CTE) for the different capping materials [4, 5]

<table>
<thead>
<tr>
<th>Function: material</th>
<th>CTE [ppm/K]</th>
<th>CTE ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capping: thin SiN</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>Plug: aluminum (Al)</td>
<td>21</td>
<td>Al / SiN</td>
</tr>
<tr>
<td>Reinforcement: polyimide</td>
<td>50</td>
<td>polyimide/Al</td>
</tr>
</tbody>
</table>

7.3 Measurement strategy

When processing the polymer reinforcement layer, the wafer experiences both a temperature excursion for the curing and a mechanical stress load due to adding the extra layer. Both can have a detrimental influence on the electrical performance of the resonators by affecting the underlying thin silicon nitride. To obtain insight in the separate influence of these effects, we have set up a series of experiments to distinguish their contribution.

A MEMS resonator wafer encapsulated with thin silicon nitride (standard process flow) without any further reinforcement was subjected to a temperature excursion of 350 °C for 60 minutes. Since no pre-plug anneal was applied (as part of the test experiments, a pre-plug anneal was performed on some wafers with the objective to outgas the thin silicon nitride before sealing it with aluminum) before the polymer processing, the highest temperature that the resonators and the thin film silicon nitride capping along with the aluminum plug experience was 350°C, the curing temperature for Polyimide. This was done as a baseline experiment to distinguish between (a) the influence of only the temperature excursion and (b) the combined effect of adding a polyimide layer with its associated residual stresses that includes this same temperature excursion for curing. The results are presented in section 7.4.

Next, we apply the regular process steps for adding a thick polymer reinforcement-layer. Before the polymer processing in these experiments and the aluminum plug sealing, the thin silicon nitride was annealed for one hour at 250°C. The polymer was spin coated at room temperature and then cured. For Intervia the curing temperature was 190°C for one hour; for Polyimide it was 350°C for one hour. Apart from the extra temperature excursion to 250°C for annealing the plug, the temperature excursion is similar to the baseline experiment. The results are presented in section 7.5.

Finally, to investigate the role of stress in the polymer layer on the degradation of the quality factor independently from the role of the thermal excursion by curing, we relieve the stress by chemical removal of the polymer layer from part of the wafer. The results are presented in section 7.6.

7.4 Thermal treatment-induced degradation without reinforcement layer

In Fig. 2 we show the results of measurements of the quality factor before and after the temperature excursion from room temperature to 350 °C and back again. The devices are sorted by the magnitude of Q before the temperature excursion. Each device number thus represents a single device and shows the degradation for this specific device. For the resonators with a quality factor, Q > 20,000 the decrease ΔQ/Q is on the order of 25%. Resonators with lower quality values show a lower relative decrease or even no decrease at all for Q < 10,000. These resonators with low Q
could be due to the outgassing of the thin silicon nitride at 350 °C since no pre-plug anneal was done.

Figure 2: Quality factor of thin silicon nitride capped resonators on wafer, without a reinforcement layer: (1) before and (2) after one-hour temperature excursion from 25 °C to 350°C and back again.

We have also investigated if we observe an on-wafer spatial dependency of the value of the quality factor. Again this can serve as a reference for the reinforced wafers with their extra stress levels. In this case the wafer bow is very small and the radius of curvature is very large (> 300 m, see Table I), effectively resulting in a very flat and stress-free wafer. In Fig. 3 we show the results, plotted as the edge-to-center-to-edge variation along the principal wafer axes through its center. Along the horizontal axis (right hand panel) we do not see a variation that can be readily correlated to the location in a structured way. Along the vertical axis (left hand panel) we observe a structured behavior, however, that does not change with the temperature excursion.

Figure 3: Edge-to-center-to-edge variation of the quality factor in a baseline experiment with non-reinforced resonators: (1) before and (2) after a 1 hour temperature excursion at 350 °C. Wafer coordinates x (1 to 16), right panel and y (1 to 8), left panel [11] without reinforcement.

No cracks were observed on this wafer. We conclude that temperature-induced stress on thin silicon nitride alone does not result in an edge-to-center-to-edge variation of the quality factor.
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7.5 Polymer reinforcement-induced degradation

The polymer reinforcement layers Intervia and Polyimide are processed at an elevated temperature. The high temperature excursion is a requirement to cure the polymers to enable cross-linking. The maximum temperature is thus different for both reinforcement layers (section 7.3).

The quality factor does not drop after Intervia reinforcement processing on a wafer without curing. We observe a decrease in the quality factor after the final curing step at 190 °C for 60 minutes of the reinforcement processing, on the order of 11,000 [12]. The graph for this is not available as only a few measurements were performed on wafer to check this effect.

In Fig. 4, the change in the quality factor before and after reinforcement processing for polyimide is shown. The device number along the horizontal axis corresponds to consecutive locations along the x-axis of the wafer. The numbers along the horizontal axis represent an index for the devices measured, without a correlation to the wafer coordinates. As seen in Fig. 4, the 140 devices with a quality factor $Q > 30,000$ all show a decrease in $Q$ of typically 25%. For the five devices with an initially already rather unsatisfactory quality factor $Q < 20,000$ or less, the effect of the temperature excursion is much lower on a relative scale. This can be understood rather easily: a high quality factor is readily killed off by, e.g., out-gassing or leakage, while an already poorly functioning device does not suffer from some extra damping [4].

![Figure 4: Quality factor for resonator, for the P1522 NE resonator type [4]: (1) before and (2) after processing and curing for Polyimide. The horizontal axis denotes the index number of resonators measured on wafer.](image)

Wafers with Polyimide and Intervia reinforced resonators show a pronounced bow effect in both $x$ and $y$ directions, with a resulting edge-to-center-to-edge variation of the quality factor. For the polyimide reinforced and thermally cured [3] resonators the data on the spatial dependency of $Q$ are given in Fig. 5. The graphs concern resonators at the same location, but on three different wafers. A single index thus indicates data of different resonators. As a reference, we use data taken for resonators with only a thin silicon nitride encapsulation, without any reinforcement. Here, after the
temperature excursion (section 7.4), the spatial dependence in the quality factor is not evident as the values are sorted in descending order with the index along the x-axis.

![Graph showing spatial dependency of the quality factor values for three different wafers: (1) thin silicon nitride only after a pre-plug anneal and before curing; (2) Intervia cure (190 °C, 60 min); (3) Polyimide cure (350 °C, 60 min). Case (2) and (3) show a pronounced centre-to-edge variation. The discontinuities in the plots are due to skipped devices during the measurement.](image)

For the Polyimide and Intervia reinforced resonators, after curing the wafer, we see a pronounced spatial dependency of the quality factor (for the solely thin silicon nitride case, the spatial dependency is discussed in section 7.4). The edge-center-edge variation is on the order of 30%. Before the curing step, there is no such effect noticed [12]. We also see that the polyimide reinforced devices – cured at 350 °C – show a much larger decrease in quality factor than the Intervia reinforced ones – cured at 190 °C.

### 7.6 Polyimide removal-induced improvement?

To investigate the role of stress on the electrical parameters independently from the role of the thermal excursion by curing, we can relieve the stress by chemical removal of the Polyimide layer. The polyimide thick-film reinforcement was removed on a quarter part of a wafer with MEMS resonators by applying fuming 100 % nitric acid at 70°C for approximately 10 minutes [8].

![Optical microscope images showing thin silicon-nitride capping along with the aluminum plug is intact after removal of the polyimide](image)

The thin silicon-nitride capping along with the aluminum plug is intact after removal of the polyimide, as investigated by using an optical microscope (Fig. 6). Dark-field illumination is used to look for possible cracks in the capping. In the blown-up images (right panel), the grain boundaries of the sputtered sacrificial layer are prominently seen on the capping. The structure is the remainder of grain boundaries after etching away the aluminum layer. These are not cracks. It has to be noted that, during the measurement, the probes landed very close to one of the walls of the capping, as seen in the optical microscope pictures. But, no damage of the caps is observed.
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Figure 6: Optical microscope image (dark field) of the thin silicon-nitride capping and the aluminum plug at location \((x, y) = (-5, -1)\), with a blow-up of the small 60x60 micrometer bond pad in the middle in the right-hand panel.

In Fig. 7, the quality factor and the shift in resonance frequency are shown, before and after polyimide removal, respectively. We observe an increase in the quality factor of about 10% after the polyimide removal. This is typically only one third of the loss in the quality factor incurred on a virgin thin-silicon nitride capped device by only a temperature excursion or adding the thick-film polyimide capping to a virgin thin-silicon nitride capped device. The measurement accuracy is within 1% [9].

Figure 7: Left panel: Quality factor \(Q\) before and \(A\) after the removal of the thick-film polyimide reinforcement, showing an increase of 10%. Right panel: frequency shift \(\Delta f/f\) after polyimide removal.

7.7 Conclusion

It is evident that the curing of the polymers and the thermal treatment of the thin silicon nitride cap results in degradation of the quality factor. Thermal treatment can result in outgassing of silicon nitride capping layer and also cause a displacement of the aluminum plug on the silicon nitride hole due to CTE mismatch. In addition to this the quality factor varies from centre of the wafer to the edges.

The temperature treatment of the resonators on wafer is the major driver (factor 2/3) of the degradation of the quality factor and not the mechanical stress by itself (factor 1/3). The shift in resonance frequency by the removal of the polyimide is on the order of -10 ppm. This also suggests that the large wafer bow and wafer warpage due to polyimide- indicating high stress- does not have
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an impact on the quality factor of the resonators. This is important to know, because there is a stringent specification requirement for the operating frequency of the MEMS resonator [10].

References


Chapter 8
Stress tests on packaged resonators

Thin-film plastic-packaged resonators are tested after molding (zero hour) and the typical electrical performance parameters are reported. This is done to check whether the resonators survive the assembling steps and a molding pressure of 80 bar. Three important accelerated stress tests are performed on packaged resonators to assess the quality of the chosen packaging route, based on the analysis of the main electrical parameters namely the quality factor, the dog-bone resistance and the resonance frequency.

8.1 Motivation

The resonator is the core element of NXP’s final product, the MEMS oscillator. It is a major challenge in terms of design, processing, assembly and packaging to achieve oscillator samples for product-level functionality demonstration. Therefore, monitoring the electrical functionality of packaged resonators as time elapses and under accelerated-stress conditions (well known by the term reliability) helps us to understand the possible failure mechanisms. The packaged resonator is basically a simple model that has been used to study reliability aspects. This will give us the confidence to proceed towards the more complex system in package, the oscillator, its packaging and electrical testing. So, as a first step, packaged resonators are electrically tested both at zero hour (virgin packaged samples) and are then monitored at specific cycles during the accelerated tests such as TMCL, UHAST and HTOL.

8.2 Zero-hour test

The resonators-on-wafer are assembled as product after wafer-thinning, dicing, wire-bonding and finally, molding at 80 bar resulting in a plastic package, as illustrated in Fig. 1. As the name implies, a zero hour test is done just after the first products-in-package are available, after the molding. Table I lists the yield, before and after assembling and molding for Intervia and Polyimide reinforced resonators [1]. We obtain a yield of about 95 % (40 out of 42 packaged resonators) for Polyimide reinforced resonators, 95 % (43 out of 45 packaged resonators) for the Intervia reinforced resonators and 90 % for the thick silicon nitride in package. The main electrical parameters - the quality factor and the dog bone resistance - do not degrade after molding. These are the parameters of interest for all
the accelerated tests: the quality factor is indicative of the micro-cavity pressure, the dog-bone resistance and the resonator frequency are sensitive to the mechanical loading, and the stress transmitted by the thin-film capping. The thick silicon nitride reinforced MEMS (deposited by PECVD at 250 °C) resonators are compared with the Polyimide and Intervia reinforced resonators in package [2].

Figure 1: Sequence of steps from wafer-level capping up to packaging.

The quality factor serves as a measure to verify the robustness of the reinforcement layers used for the capped resonators, as mentioned in Chapter 3. The degradation in the quality factor for the Intervia reinforced resonators in package may have resulted due to the difference in thickness between polyimide and Intervia reinforcement layers and thick silicon nitride: a larger deformation of the capping stack, for the Intervia reinforced resonators due to a 6 µm lesser thickness than required for the deformation of Polyimide or thick silicon nitride when subjected to a molding pressure of 80 bar (Table III in Chapter 3).

8.3 Reproducibility of resonator-package measurements

To check the consistency of our packaged samples measurements, electrical measurements were performed (1) on a day-to-day basis on a reference sample and (2) with a delay of two months on ten packaged samples that were subjected to an accelerated life-time test. The purpose is to determine the consistency of the measurement setup with reference measurements, and, distinguish between repeatability and accelerated effects on packaged resonators subjected to lifetime tests. This packaged sample consisted of polyimide reinforcement on a wafer-level thin-silicon-nitride-capped dog-bone resonator. This was assembled and molded in a HVSON10 thin-film plastic package as shown in Fig. 2.
Table I: Average value of change in quality factor and yield of packaged resonators after dicing, die bonding, wire bonding, molding and post-mold cure

<table>
<thead>
<tr>
<th>Reinforcement</th>
<th>Thickness [$\mu$m]</th>
<th>Quality factor before molding</th>
<th>Quality factor after molding</th>
<th>Quality factor change (degradation) after molding at 80 bar</th>
<th>Yield [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thick silicon nitride</td>
<td>6</td>
<td>29000</td>
<td>26200</td>
<td>-3000</td>
<td>90</td>
</tr>
<tr>
<td>Intervia</td>
<td>15</td>
<td>32000</td>
<td>23000</td>
<td>-9000</td>
<td>95</td>
</tr>
<tr>
<td>Polyimide</td>
<td>21</td>
<td>31000</td>
<td>31000</td>
<td>0</td>
<td>95</td>
</tr>
</tbody>
</table>

All electrical measurements were done on a socket that was intended for package-level measurements. Nominal biasing conditions: drain current $I_d = 2.5$ mA and gate voltage $V_g = -5.75$ V are used during the measurements. The packaged resonator was pressed on to the socket and the socket’s lid is closed. By this action the packaged sample’s lead frame made contact with the pins in the socket. Cables were connected to the socket from the measurement setup. In Fig. 3, the measurement setup is illustrated. The electrical measurements were done in the following sequence:

- Connecting the cables to the network analyzer (via bias tees) and to the test socket;
- Placing the packaged resonator inside the socket and close the lid;
- Measuring the resonator using the routine/program developed in LABVIEW.

Figure 2: Wire bonding diagram for the resonators in HVSON10 package. Only one out of four resonators is measured.
Figure 3: Block diagram of the measurement setup used for the HVSON10-packaged resonator measurements.

An Agilent E5071C network analyzer has been used to measure scattering parameters $S$ at and near the resonance frequency of the resonators under study. The DC biasing of the resonators was provided by Keithley 2400 source measurement units. Bias tees of Pico second were used to separate the RF and DC signals. These bias tees have a DC resistance of approximately $1k\Omega$. In order to measure the voltages on the resonator more accurately, the transmission lines behind the bias tees was tapped with a $10k\Omega$ resistor and fed into the ‘sense’ input of the Keithley 2400. The electrical parameters - quality factor $Q$, frequency shift $\Delta f/f_0$ calculated with respect to zero hour (0h, after molding) and the $\Delta R/R_0$, calculated with respect to the dog bone resistance $R_0$ at zero hour - are taken for comparison and data analysis. The value of $Q_0$ was measured six months earlier from the time this measurement was carried out, on August 7, 2010. We see that, during a single day and between two consecutive days, the measurement of the $Q$ factor of a given sample is dominated by random errors. We do not observe systematic errors like a rapid drift in time on a single day or a statistically significant difference in the values measured two days apart. The mean value and the variance are given in Table II [3]. This provides us information about the systematic and random variations in the electrical parameters of interest. The systematic error (over a time of six months) is not measurement-induced as the measurement equipment is calibrated on a regular basis. The change in dog bone resistance is not significant, but for quality factor it is a considerable (real) change of the electrical characteristic of the sample. The frequency shift determination strongly depends on the ambient temperature in the laboratory.
8.4 Possible failure modes during the accelerated tests

The purpose is to ensure proper functioning over the lifetime of the device, and the proper way to do this is to identify failure mechanisms and acceleration factors. Only based on this knowledge, proper tests can be identified that accelerate the failure mechanisms. Accelerated stress tests are applied because the occurrence of failure mechanisms can be observed in a limited time, by not waiting for years. But, for emerging technologies involving new materials and/or constructions, identifying certain unknown failure mechanisms is really challenging. The predictability of failure rate of the semiconductor devices is inherently low [4]. Due to this reason, the semiconductor industry uses a technique called acceleration based testing to predict device performance over life time. In our case, this procedure is applied as well. Elevated stresses such as temperature, pressure etc. are used to induce the same failure mechanisms as would be observed under normal use conditions, but in a shorter time period. Based on the failure modes specific for a test, acceleration factors are employed by manufacturers to estimate failure rate and life time. Table III lists the possible potential failure modes for the tests used in our case.

The following three tests were performed on packaged resonators at zero hour (virgin samples): (1) unbiased highly accelerated stress test (UHAST) to study effect of moisture penetration into the micro cavity [14]; (2) life test or high temperature operating life time test (HTOL) to study the effect of electrical and thermal stress on the resonator [15]; (3) temperature cycling test (TMCL) to study the effect of thin film capping integrity and resonator functionality [16].

8.5 UHAST

The three electrical parameters, Q, $\Delta f/f_0$ and $R_d$ are measured for the polyimide and Intervia reinforced resonators. They are analyzed and compared with the results for the thick silicon nitride reinforced resonators. The latter material for reinforcement – silicon nitride - was the choice of preference of NXP at the start of the project on polymer reinforcements in the summer of 2008. For this reason it is essential to apply the same accelerated life time tests on these devices, to show in retrospect if it was a wise decision to invest in alternative materials and approaches to develop reliable and commercially viable processes for reinforcing the thin silicon nitride covered MEMS resonators.

**Thick silicon nitride**

In Fig. 3 (top panel) the quality factor versus UHAST stress time is shown for the thick silicon nitride reinforced resonators. The measurements have been carried out on wafer at four positions. At the time of this investigation, the packaged resonators with thick silicon nitride reinforcement were not functional at the preconditioning and the first 96 hours of UHAST stress. Measurement results at package level are not available because the resonators showed charging due to the presence of water [2].

<table>
<thead>
<tr>
<th>Error type</th>
<th>Repeatability</th>
<th>$Q/Q_0$ [%]</th>
<th>$\Delta f/f_0$ [ppm]</th>
<th>$\Delta R/R_0$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systematic</td>
<td>Six month change</td>
<td>+3 %</td>
<td>-90 ppm</td>
<td>-0.6 %</td>
</tr>
<tr>
<td></td>
<td>Two day change</td>
<td>0.2 %</td>
<td>25 ppm</td>
<td>0.15 %</td>
</tr>
<tr>
<td>Random</td>
<td>Variance</td>
<td>0.2%</td>
<td>4 ppm</td>
<td>0.03 %</td>
</tr>
</tbody>
</table>
We observe a severe degradation of the quality factor (on the order of 32%) after 96 hours. The degradation does not stop, but continues at the same rate in the time step between 96 and 192 hours. At 192 hour we already have an unacceptable low value of $Q = 10000$. The four devices given in Fig 4 all show the same behavior: an excellent reproducibility of this poor performance! We conclude that the resonators reinforced with thick silicon nitride are very sensitive to the UHAST test. The reason for the degradation is attributed to the penetration of water vapour during the test.

The behaviour of the dog-bone resistance and the frequency shift is slightly different. As the middle and lower panels of Fig. 4 show, the largest effect is observed after the second time lapse between 96 and 192 hours. The increase in the resistance is most pronounced, with a typical value of 9%. This can be explained by the penetration of moisture and depositing on the dog-bone springs and the mass. Water accumulation can retard the applied electric field (under actuation), rapidly reducing the stored energy (represented by the quality factor). The observed frequency shift is about 80 ppm. It could be due to water loading. This 80 ppm shift is very large when compared to the required frequency specification for the resonator (1 ppm for frequency shift based on ageing).

The resonance frequency shift is reported only up to 192 hours. For the next stress time (288 hours) the resonators failed to resonate due to the too low value of the quality factor, as can be expected from approximately linear decay in time shown in the top panel of Fig. 4. This is most likely due to water vapour penetration into the micro-cap and charging thereafter. This is discussed in reference [2].

We have to conclude that it was a wise choice to start the project on alternative materials for the reinforcement at an early stage in July 2009. In the current configuration, the thick silicon-nitride capping does not result in an adequate protection of the resonator structure during reliability testing.
Figure 4: Quality factor $Q$ (top), dog-bone resistance $R_d$ (middle) and frequency shift (lower panel) for the four thick silicon-nitride reinforced resonators (measured on wafer) during the UHAST test, up to 192 hours of testing. All coordinates are from one quarter of the wafer.
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Intervia

In Table IV we present the results of UHAST testing for four packaged samples reinforced with Intervia. Only the results for the quality factor and the dog bone resistance are given. The data on the frequency shift have not been taken during these tests. We present the results of four samples.

We observe a huge drop (29 %) in the quality factor after 96 hours of testing. After this, the degradation at every stage is less (2 %). Somehow, the package is very sensitive to the first 96 hours of test compared to the rest of the stress hours. The mechanical stress conditions (2.1 bar pressure, 130 °C temperature) perhaps have made the capping unstable and leaky directly in the first stage of the test. The change in $R_d$ is within 1%, compared to the 9% change for the thick silicon nitride reinforced resonators. This small change in $R_d$ can be due to mechanical loading (strain experienced by the dog bone).

The drop in quality factor is too large to meet the specifications for a commercial application [10]. This fact stops our investigation on Intervia reinforced and packaged samples. Given the time left in the project (summer 2011), we will not retrace our steps and try to further understand the reason for this loss in quality factor by packaging. Polyimide is our only option that is still left open. Intervia is found to absorb moisture and release it into the micro cavity. Another reason is the 5µm lesser thickness of the polymer compared to Polyimide (21 µm final thickness) that makes it mechanically less robust to withstand the 80 bar molding pressure.

Table IV: Relative change of the quality factor and dog bone resistance of four packaged samples with an Intervia reinforcement during the UHAST test up to a time $t = 288$ hours, together with the mean value and the variance (in the last digit given).

<table>
<thead>
<tr>
<th>Wafer coordinates</th>
<th>$\Delta Q/Q(0)$ [%] with $\Delta Q = Q(t) - Q(0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>t (hours)</td>
<td>96</td>
</tr>
<tr>
<td>(-5, -4)</td>
<td>-28.2</td>
</tr>
<tr>
<td>(-4, -4)</td>
<td>-29.7</td>
</tr>
<tr>
<td>(-4, -5)</td>
<td>-28.9</td>
</tr>
<tr>
<td>(-3,-4)</td>
<td>-30.37</td>
</tr>
<tr>
<td>mean (var)</td>
<td>29.3 (9)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wafer coordinates</th>
<th>$\Delta R/R(0)$ [%] with $\Delta R = R(T) - R(0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>t (hours)</td>
<td>96</td>
</tr>
<tr>
<td>(-5, -4)</td>
<td>-1.41</td>
</tr>
<tr>
<td>(-4, -4)</td>
<td>-1.41</td>
</tr>
<tr>
<td>(-4, -5)</td>
<td>-1.40</td>
</tr>
<tr>
<td>(-3,-4)</td>
<td>-1.39</td>
</tr>
<tr>
<td>mean (var)</td>
<td>-1.41(1)</td>
</tr>
</tbody>
</table>
Polyimide

We have investigated five resonators assembled in a HVSON10 package. The samples come from different areas of the same wafer (selection based on known good die), as can be seen from the wafer coordinates that are mentioned in Fig. 5.

Quality factor

The data on the evolution of the quality factor during the UHAST test are given in the top panel of Fig. 8.4. For three devices Q remains stable within a margin of ΔQ/Q = 4 %; the other two devices show an increase of 6 %. The reason for this improved quality factor is not exactly known at the moment. However, the moisture uptake in polyimide can change the state of stress in the thin film capping stack i.e., relieve the pressure on the capping. The sample size is much too small to draw conclusions on this specific behavior. We conclude that the quality factor remains more or less stable within a range of 0 to +6%.

Dog bone resistance

In the middle panel of Fig. 5 we show the results on the behaviour of the dog-bone resistance $R_d$ during the UHAST test. We observe that its value does not change more than 0.5% for stress times up to 768 hours. This is not a significant change and does not have an impact on the dog bone resistance specifications. We conclude that $R_d$ does not change due to UHAST.

Frequency shift

In the lower panel of Fig. 5 the shift in resonance frequency is shown for the polyimide-reinforced resonator samples in package. At the end of 768 hours, a shift in the order of 200 ppm is seen. The observed resonance frequency shift for all samples is huge, considering the requirements for the resonance frequency specification [11]. We see that all samples show the same trend in the resonance frequency shift. Sample (-7,-6) is an outlier.

Such a huge shift in the resonance frequency could have been due to the day-to-day drift in the resonance frequency of -28 ppm/°C due to the temperature fluctuations of 1 or 2°C in the measurement laboratory. In addition to this, the self-heating of the piezoresistive dog-bone resonator due to the applied read-out current ($I_d$, 2.5 mA) could have contributed to the temperature rise in the dog bone, causing a shift in its resonance.
Figure 5: Quality factor $Q$ (top), dog-bone resistance $R_d$ (middle) and frequency shift (lower panel) for the polyimide reinforced resonators in HVSON10 package, during the UHAST test, up to 768 hours of testing. The numbers in the brackets indicate the wafer coordinates.
8.6 Thermal cycling and Bias stress tests

The two other accelerated tests, namely the thermal cycling (TMCL) and the bias stress, or, high-temperature operating life (HTOL) are carried out to accelerate failure modes such as interface and delamination in the polymer-silicon nitride interface in the capping, cracking of the mold compound and also to check the endurance of the packaged samples [11, 12]. Table V illustrates the recorded values of the relevant electrical parameters for the two tests.

TMCL

A 10 % drop in quality factor is seen for the silicon-nitride reinforced resonators-in-package. It is interesting to look at the quality factor drop at level-3 preconditioning and then at different thermal cycling stages. There is a steep drop at level-3 preconditioning and then not as steeper as this, except for one sample, implying that the samples recover after an initial drop in the quality factor. There is no correlation to the dog bone resistance. For the polyimide-reinforced resonators, there is no change in Q and $R_d$. The values are within the specification.

HTOL

There is a one-time-increase (after which it remains stable) in quality factor for the polyimide-reinforced resonators where as it first decreases at the first stress cycle for the thick silicon nitride reinforced resonators. The dog-bone resistance shows a 0.5 % change. The parameter $\Delta f/f_0$ shows a shift of -100 ppm for the polyimide reinforced resonators. This due to an uncertainty in measuring this parameter, explained in section 8.3. This value is not within the resonator specification.
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Table V: HTOL and TMCL results for polyimide- and thick-silicon nitride reinforced MEMS (in HVSON10)

<table>
<thead>
<tr>
<th>HTOL</th>
<th>Electrical parameter</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress (h)</td>
<td>$\Delta Q/Q^a$ [%]</td>
<td>$\Delta R_d/R_d^b$ [%]</td>
<td>$\Delta f/f_0^c$ [ppm]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>168</td>
<td>504</td>
<td>1008</td>
<td>0</td>
<td>168</td>
</tr>
<tr>
<td>Polyimide</td>
<td>0</td>
<td>+7</td>
<td>+7</td>
<td>+7</td>
<td>0</td>
</tr>
<tr>
<td>Thick silicon nitride</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>+1</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TMCL</th>
<th>Electrical parameter</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress (cycles)</td>
<td>$\Delta Q/Q^a$ [%]</td>
<td>$\Delta R_d/R_d^b$ [%]</td>
<td>$\Delta f/f_0^c$ [ppm]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-precon</td>
<td>0-200 cycles</td>
<td>0-500 cycles</td>
<td>0-precon</td>
<td>0-200 cycles</td>
<td>0-500 cycles</td>
</tr>
<tr>
<td>Polyimide</td>
<td>+1 to +2</td>
<td>&lt;+1</td>
<td>+0.5 to +1</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Thick silicon nitride</td>
<td>-10</td>
<td>3 to 4</td>
<td>3 to 4</td>
<td>0</td>
<td>-0.5</td>
</tr>
</tbody>
</table>

a. Relative change $\Delta Q/Q$ [%] with $\Delta Q = Q(T) - Q(0)$.
b. Relative change $\Delta R/R$ [%] with $\Delta R = R(T) - R(0)$.
c. Relative change $\Delta f/f_0$ [%] with $\Delta f = f(T) - f(0)$

8.7 Conclusions

UHAST testing is highly decisive for the choices to be made. For the thick silicon nitride reinforced resonators, it is the end of the story. Moisture penetration and the resulting resonator charging at 192 hours of UHAST cause failure of packaged resonators, resulting in 0% yield.

For Intervia-reinforced resonators the same story holds. The drop in quality factor is too large to meet the specifications for a commercial application [10]. This fact stops our investigation on Intervia-reinforced and packaged samples. For Polyimide-reinforced and packaged resonators, the results are rather favourable. The electrical parameters do not degrade during UHAST test. The polyimide thick film shields the underlying topography and the resonator from the influence of the 2.1 bar pressure mainly, accompanied by the relative humidity (RH) and temperature. A failure such as metal fatigue that could have caused the aluminium plug to fail is not seen. Also, moisture penetration into the capping is not evident.
For the two reliability tests TMCL and HTOL, the quality factor of polyimide reinforced resonators in package does not degrade at any stage of stressing. The suspected failure modes are not clearly observed based on our outcome. To our surprise, the quality factor increases by 7% for the bias stress test. There is more than one phenomenon which could have caused this effect. But, we believe that the stress-relaxation mechanism based on temperature and time inside the package could have helped relieving the thermo-mechanical stress in the package, leading to an increase in the quality factor.

The shift in resonance frequency is around 100 ppm. The temperature coefficient of the frequency shift of the resonator is 28 ppm/°K. The fluctuation in the lab temperature is 0.5 to 1 °C on a day-to-day basis. Also, because the frequency-dependence due to self-heating is not compensated in the resonator [3], the frequency cannot be measured with sufficient accuracy. Currently, a more accurate way to represent the frequency shift is available on selected samples and it has been shown that the frequency accuracy can be within 20 ppm on bias-stressed resonator-samples in package [13].

References

Chapter 9

Packaged MEMS oscillator

The functionality of the final product - the oscillator in a thin-film package - is demonstrated. The MEMS resonator that forms the core element of the oscillator has a polyimide-reinforced thin silicon-nitride capping. In its simplified form, the resonator with a feedback amplifier constitutes an oscillator - also called the MEMS timing device - generating a periodic electronic waveform. We prove that it is feasible to achieve a functional packaged oscillator, after doing all the BE operations and assembling the oscillator in a stacked-die configuration, where the MEMS resonator die is glued on top of the ASIC die (the amplifier) and wire-bonded to it. Also, the oscillators survive three harsh accelerated tests, exhibiting an acceptable performance and yield.

9.1 Introduction

The basis for the packaged-oscillator demonstrator is the success of the functionality of the packaged resonator, produced with the polyimide reinforcement route. The objective of this demonstrator is to first check whether the stacked-die assembly of the oscillator is feasible, including the molding at 80 bar, by verifying the electrical functionality of the oscillator. Subject to this, three accelerated tests, namely the unbiased accelerated stress (UHAST), thermal cycling (TMCL) and high temperature storage life (HTSL) are conducted on (zero hour) packaged-oscillator samples. The basis for carrying out these tests is to monitor the electrical performance of the oscillators and to assess the possible physical mechanisms that trigger failure. With this and the known functional specification for the oscillators, we estimate the yield percentage. It has to be noted that all tests have been done in parallel and not in series, i.e. the tests relate to different sets of devices.

9.2 Packaged oscillator in stacked-die configuration

The only reinforcement material that proved to be successful is polyimide. All data in this chapter thus refer to oscillators based on MEMS resonators with a polyimide-reinforced thin silicon-nitride capping. The MEMS dog-bone-shaped resonator is wire-bonded to the application-specific IC (ASIC) die that incorporates the charge pump, the phase-locked loop (PLL), the temperature-compensation circuitry and the gain amplifier as shown in Fig. 1. The oscillator is in the stacked-die configuration because the MEMS resonator die is glued on top of the ASIC die and then attached to the lead frame of the HVSON10 10-pin quad-flat-no-lead (QFN) package. In Table I, the thickness
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and the dimensions of the different components that comprise the oscillator in the stacked die are mentioned.

Figure 1: The 150 µm thick MEMS die is stacked on top of the 150 µm thick ASIC die (left: top view) by gluing on the lead frame. After this, wire-bonding is done. Finally, molding is done to have the HVSON10-packaged oscillator. Ball-stitch-on-ball (BSOB) is applied (right: cross-section of the stacked die) for bond pads #18, 20 and 24 in the stacked-die configuration.

Table I: Stacked-die dimensions for the packaged oscillator

<table>
<thead>
<tr>
<th>Component</th>
<th>Foot print/ size (mm x mm)</th>
<th>Number of pins</th>
<th>Thickness [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEMS resonator die</td>
<td>0.5 x 0.5</td>
<td>3</td>
<td>150</td>
</tr>
<tr>
<td>ASIC die</td>
<td>1.7 x 1.9</td>
<td>28</td>
<td>150</td>
</tr>
<tr>
<td>Lead-frame HVSON10 package size</td>
<td>2.7 x 2.0</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>Gold wire bond</td>
<td></td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>Die attach glue</td>
<td></td>
<td></td>
<td>35</td>
</tr>
</tbody>
</table>

9.3 Measurement setup

The measurement setup is used to test the oscillator output and to evaluate its performance. It is sketched in Fig. 2. A DC supply of 3.3 V is used to power the oscillator in the socket. The ‘Keithley 2000 I meter’ measures the current consumption and the ‘V meter’ measures the negative polarization (NEGPOL) voltage. The Agilent signal analyzer is used to determine the spectrum of the clock output frequency of the oscillator. The oscilloscope can be used to capture the periodic electronic wave pattern upon triggering the oscillator chip and also the MEMS analog output frequency (56 MHz) separately.
Figure 2: Setup used to measure the oscillator in package. This socket-level measurement setup captures the vital electrical parameters of the oscillator.

9.4 Monitored electrical parameters

The set of electrical parameters mentioned here have been taken from the overall context of the project. At this point in time, it was difficult to choose electrical parameters that would represent the effectiveness of the package functionality. However, digital clock-out frequency and negative polarization voltage are the most interesting parameters of interest. The following electrical parameters are monitored:

a. **Supply current (mA)** is the current the oscillator consumes, including the MEMS and all functional blocks in the ASIC.

b. **Amplitude of the digital signal (dBm)** represents the signal strength of the oscillator frequency peak (at 13 MHz). A negative or a positive value close to 0 dBm and above indicates a good signal and a negative value presents a noisy signal.

c. **Digital clock-out frequency (MHz)** is an important functional specification, indicating the target output frequency of the oscillator. The frequency of the generated periodic electronic waveform is 13MHz.

d. **Negative polarization voltage, Negpol (V)** is the voltage required for the charge pump to deliver to the pre-amplifier and the high gain amplifier and other functional blocks in the ASIC. The charge pump is expected to deliver -5.5 V, according to the design.

e. **Start-up time of the chip (ms)** indicates how rapidly the MEMS resonator responds to the ASIC’s impulse to generate the oscillation. The value usually is within 10 ms [1]. It must be noted that, in the electrical results, this parameter was not properly captured. We report on values in the order of 20-30 ms. This is typically the oscillator response immediately after resetting the chip that is required in the procedure to measure the oscillators.

In total, 100 oscillators have been assembled in the HVSON10 package. The resulting value of 76% yield at this stage of the project is rather satisfactory. In Table II, the overall yield is mentioned. We expect to gain considerably when we further optimize the process using a larger series.
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Table II: Yield of packaged virgin oscillators together with a break-up of the class of non-functional devices

<table>
<thead>
<tr>
<th>Quantity of interest</th>
<th>Sample size</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of samples</td>
<td>100</td>
<td>Molded (at 80 bar injection pressure) oscillators in stacked-die configuration.</td>
</tr>
<tr>
<td>Functional oscillators (yield)</td>
<td>76 (%)</td>
<td>Digital oscillator frequency and all relevant electrical parameters were good.</td>
</tr>
<tr>
<td>Functional MEMS component; non-functional oscillator</td>
<td>8</td>
<td>The analog output frequency of MEMS (56 MHz) was observed. But in the oscillator configuration, the samples were not functional.</td>
</tr>
<tr>
<td>Non-functional oscillators</td>
<td>16</td>
<td>These samples were not functional. The MEMS functionality was also not evident.</td>
</tr>
</tbody>
</table>

9.5. Repeatability at short time-scale

To check the measurement accuracy and repeatability, five consecutive measurements with a time interval of three minutes between each trial have been performed on a chosen (reference) sample. Taking the data takes typically two minutes, resulting in an elapsed time of 25 minutes for this investigation. Table III captures the drift over this period of time and the random fluctuation of the measurements. We see that, the frequency accuracy is very good over this time scale.

Table III: Repeatability of oscillator electrical parameters in five measurements in 25 min. The drift relates to the total change in this time interval.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Including drift with linear curve fit</th>
<th>No drift</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta f/f_0$ [ppm]</td>
<td>Total drift</td>
<td>Random noise*</td>
</tr>
<tr>
<td></td>
<td>-0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Amplitude [dBm]</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Negpol [V]</td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>

* rms value of deviation from curve fit

9.6 UHAST

UHAST stands for ‘Unbiased Highly Accelerated Stress Test’. It is used to determine the effect of moisture penetration through a functional layer. The test is performed by forcing 85% relative humidity (RH) at 130 °C, at a pressure of 2.1 bar. Measurements are done every 96 hours. This is the industrial reliability-test standard for consumer electronics and automotive applications [2]. It is one of the most severe stress-tests that must be passed to qualify products for production. This test has been performed on 20 packaged oscillators. In all our measurements, the start-up time is not
properly represented as we could not capture it with the oscilloscope properly. It is typically 2-3 ms for a properly functional oscillator.

Supply current

In Fig. 3, the supply current is plotted for read points up to 192 hours, starting from zero hour, on twenty functional molded samples. The supply current remains unchanged during 96 and 192 hours of UHAST, except for one sample. On most of the samples at zero hour, the supply current seems to be a little high, as compared to the expected value of 30 mA. These measurements were done at zero hour manually by triggering the oscillator and noting down the reading in the different instruments, due to downtime of the automated program. The Keithley current meter, used to capture the current consumption was not properly identified and initialized during the manual measurements at zero hour. The high value of the supply current at zero hour could have resulted from this omission.

The automated program in LABVIEW identifies the instruments and initializes (the span for the frequency spectrum) the oscilloscope and the signal analyzer. This avoids the errors made at zero hour in this test. Also, the data is read and stored by the routine automatically during the measurement. The two read points, at 96 and 192 hours were measured using the automated program. For sample (-13, 0) whose supply current drops sharply around 15 mA, there is no correlation whatsoever.

![Figure 3: Supply current plotted for 20 packaged oscillators starting at zero hour up to the second read point (at 192 hours) during UHAST. It is seen that the supply current is stable at 96 and 192 hours except for sample (-13, 0).](image)

Negative polarization voltage

This is representative of the supply voltage that the charge pump delivers to the PLL and the other parts in the ASIC during oscillation. To establish a proper oscillation, this should be very stable (5.6 V). The voltage reader instrument (Keithley 2000) used to capture the negative polarization voltage induced an additional one volt to the original value. This is due to the low impedance of the Keithley...
current meter instrument, which exaggerates the value by 1V magnitude. In our plots, 6.5V corresponds to 5.5 V, i.e., 1V has to be subtracted from the value reported by Keithley 2000. We observe a stable value on all the samples at 192 hours of UHAST, as plotted in Fig. 4. At the end of 192 hours of UHAST, the measured values lie in the acceptable range, for the given specification (5.5V) [1]. Variations that are seen, on the order of 25 mV at different read points (up to 264 h) are not significant enough to induce any changes in the oscillator performance. On all the zero hour packaged samples, the value is a little high.

**Frequency shift**

The output frequency of the oscillator is the most important parameter of interest. The shift in its value is a measure of how accurate this parameter is, for typical timing-reference applications. The oscillator specification puts a stringent requirement for this parameter [2]. In Fig. 5, the frequency shift is plotted up to 192 hours of UHAST. The samples are categorized as *good* (|Δf/f₀| < 25 ppm) and ‘second in grade’ (|Δf/f₀| > 25 ppm) based on frequency shifts that were observed on the samples. On both types, we see a positive as well as a negative shift in frequency. Moreover, there is sample-to-sample variation that could have come from the processing. The package-level stress (assembly, wire-bonding and molding) can also be different for all devices in this handful of samples. It has to be noted that samples (-13, 0) and (-12, -1) show similar frequency shifts at 96 and 192 hours, although the supply current for sample (-12,-1) remains stable at these read points.

![Figure 4: Negative polarization voltage plotted at different read points during UHAST, up to 192 hours. At the end of 192 hours of UHAST, the negative polarization voltage values are low and lie in the acceptable range. On all samples the (manually obtained) read values at zero hour are a little high.](image)

The effect of resonator self-heating due to a temperature increase (equal to 30 ppm/K) should result in a frequency shift in the positive direction. The temperature compensation and PLL in the ASIC should be able to correct for it [3]. But, if there is any uncertainty in determining the exact temperature of the MEMS by the temperature sensor, part of the frequency shift will still remain. With all these uncertainties, on three samples (-11,-1), (-10,-1) and (-14,-1), UHAST-induced
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changes are seen. We obtain a 55% yield based on the samples that have frequency shift < 25 ppm (good). The remaining 45% yield concerns ‘second grade’ oscillators with a frequency shift > 25 ppm for applications with a less stringent demand on frequency shift. The device with the run-away supply current also falls in this second class.

The sample-to-sample variation on wafer that is process-induced, could account for the positive and negative frequency shifts as seen in Fig. 5 for both good and second in grade samples. Moreover, package induced stresses play a crucial role in addition to the accelerated stress applied on the packaged oscillators. The increasing trend seen for the good samples (device (-10,-1) in Fig. 5) cannot be explained considering the frequency accuracy 25 ppm between two consecutive weeks.

![Diagram of oscillator frequency shift](image)

Figure 5: Shift in the oscillator frequency plotted for second in grade ($\Delta f/f_0 > 25$ ppm, upper graph) samples and good ($\Delta f/f_0 < 25$ ppm, lower graph). There is also randomness in the frequency shift.

9.7 TMCL

The purpose of carrying out the temperature cycling test is to accelerate the effects of thermal-expansion mismatch among different components of the package and device. It is used to determine package resistance during high and low temperature cycling, reflecting temperature changes during
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transportation and use [4]. This test has been performed for 20 packaged oscillators taken from different locations on the wafer.

The test consists of the following steps:

- **Preconditioning-level 3**: done at 30°C and 60% relative humidity for 192 hours; Preconditioning is a simulation of the surface mount process (board-level assembling of the packaged oscillator to the mother board). The surface-mount process may seem simple, but many problems can arise. For instance, moisture absorbed by the plastic packages can induce cracking. Such cracking is caused by extreme internal pressure created by moisture vaporizing under the hot temperature of solder-reflow conditions that is typically done at the PCB assembly houses.

- **Lead (Pb)-free, reflow for three times in hot convection oven at 245/260 °C for 1 hour to simulate the solder reflow process;**

- **The above step is followed by temperature cycling between –55 and +125°C at read points 200, 500 and 1000 cycles.**

The electrical parameters namely, the supply current, amplitude, negative polarization voltage and the digital clock output frequency shift are measured and monitored to study the impact of TMCL test on the HVSON10-packaged oscillator samples in stacked-die configuration. In Table IV, the electrical parameters are monitored up to 500 cycles of TMCL.

Table IV: Mean values of the important electrical parameters as measured at different stages of the TMCL. The standard deviation is given in parentheses [10]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>0 h</th>
<th>Preconditioning</th>
<th>200 cycles</th>
<th>500 cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>∆f/f₀ [ppm]</td>
<td>0</td>
<td>-12 (51)</td>
<td>-9 (47)</td>
<td>-14 (69)</td>
</tr>
<tr>
<td>Amplitude [dBm]</td>
<td>-6(17)</td>
<td>13(6)</td>
<td>13 (10)</td>
<td>8 (11)</td>
</tr>
<tr>
<td>Negpol [V]</td>
<td>-6.46 (0.07)</td>
<td>-6.54 (0.08)</td>
<td>-6.56 (0.09)</td>
<td>-6.54 (0.09)</td>
</tr>
<tr>
<td>Supply current [mA]</td>
<td>30(4)</td>
<td>30 (3)</td>
<td>31(15)</td>
<td>30(16)</td>
</tr>
</tbody>
</table>

_Frequency shift_

Out of the batch of 20 samples that have been stressed, a nice fraction of 13 samples show a frequency shift between -15 to +20 ppm (named **good**). Six samples show a shift between -100 to +100 ppm (named **second in grade**). For the frequency shift there is no clear trend in the ageing behavior. First, an increasing trend, going from zero hour to preconditioning is observed on majority of the good samples. Also, the frequency shift drops from 200 cycles to 500 cycles. One sample failed during preconditioning. Possible failure mechanisms could be mechanical failure such as crack in the capping, delamination of the die stack and broken wire bonds [6]. Considering the absence of serious problems with the other electrical parameters, the yield of ‘good’ oscillators after the TMCL test is 65% based on this parameter.
Amplitude

The amplitude of all samples at zero hour has been measured manually due to down-time of the programmed LabView measurement-routine. Three samples at zero hour showed very low amplitudes. But they showed good clock-frequency output upon three repeated trials (shift 13 MHz) and were confirmed to be functional based on other relevant parameters of interest. At the end of 500 cycles, the amplitude remains considerably good on almost all samples. One sample (-7, 3) failed at 200 cycles and did not revive at 500 cycles. Plots for all samples are mentioned in [5].

Negative polarization voltage

The negative polarization voltage remains stable on most of the samples. On a few samples, between zero hour and preconditioning, a 100 mV increase is observed. This shall be due to temperature and/or mild humidity levels that the samples experienced during preconditioning. At the end of 500 cycles, the values remain stable on all samples. The specified design value is around -5.5V. The Keithley 2000 voltage meter misrepresents this by adding -1V. Upon cross-checking this with a digital multi-meter, we see values in the -5.4 to -5.6V range. The trend is that preconditioning results in lower values by 50 to 100 mV. This can be due to the temperature and/or mild humidity levels that the samples have experienced during preconditioning. At 200 and 500 cycles no further decrease is observed for most devices.

At zero hour, the average value and variance are -6.45V and 0.05V, respectively. After 500 cycles the average value is lower by 100 mV at -6.55V. Except for sample (-2, 2) that shows a sudden decrease of 25 mV between 200 and 500 cycles, all 19 samples show stable values. These values are within the specification of the device, because a change in supply voltage only by 100mV does not influence the performance of the oscillator.

Supply current

On most of the samples there was a 1.2 mA step increase in supply current between the preconditioning and 200 cycles of TMCL. The exact cause of this increase is difficult to identify as the ASIC die comprises of many functional blocks, in addition to the separate MEMS die. One or more components in the ASIC die could have contributed to this small increase. The most likely cause is an increased current consumption of the associated circuitry in the ASIC. At 500 cycles, 19 samples are stable, with a mean value of 29.8 mA and a variance of 1.6 mA.

9.8 HTSL

The test is used to determine the effects of time and temperature, under storage conditions, for thermally-activated failure-mechanisms and time-to-failure distributions of solid-state electronic devices, including nonvolatile memory devices that suffer from data-retention failure mechanisms. During the test, accelerated stress temperatures are used without electrical conditions applied. This test may be destructive, depending on time, temperature and stress induced by packaging. The test is performed by storing the packaged oscillators at 150 °C without electrically biasing the MEMS resonator at 168, 504 and 1008 hours of storage read points. A batch of 16 packaged oscillator samples is used for this test. It has to be noted that the samples have been picked from different regions on the wafer. All of them were electrically functional at 1008 h. At zero hour, the measurements were carried out manually. Whereas for the rest of the read points (up to 1008 h), the measurements were done using the program/routine in LABVIEW.
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The monitored electrical parameters are the oscillator frequency shift, amplitude, negative polarization, current consumption (supply current) and off current. The results are mentioned in Table V. The variation of the different electrical parameters at all read points is given in [7].

Table V: Mean values of the important electrical as measured at different stages of the HTSL test up to 1008 hours. The standard deviation is given in parentheses [9]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>0 h</th>
<th>168 h</th>
<th>504 h</th>
<th>1008 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta f/f_0$ [ppm]</td>
<td>0</td>
<td>-3(31)</td>
<td>-22 (40)</td>
<td>-40 (31)</td>
</tr>
<tr>
<td>Amplitude [dBm]</td>
<td>-9 (14)</td>
<td>4(1)</td>
<td>14 (0)</td>
<td>14 (0)</td>
</tr>
<tr>
<td>NEGpol [V]</td>
<td>-6.46 (0.07)</td>
<td>-6.51 (0.08)</td>
<td>-6.58 (0.08)</td>
<td>-6.57 (0.08)</td>
</tr>
<tr>
<td>Supply current [mA]</td>
<td>27 (50)</td>
<td>31 (6)</td>
<td>30 (4)</td>
<td>30 (4)</td>
</tr>
</tbody>
</table>

**Frequency shift**

The shift in the digital clock-frequency of the oscillator samples shows an increasing trend, going from 168 to 1008 h of stressing. This is valid for two (from a total of 16) samples that show a shift $|\Delta f/f_0| <$25 ppm at the end of 1008 hours. For the remaining 14 samples ($25 < |\Delta f/f_0| < 60$ ppm), the ageing trend appears to be very different. With the added stress to these devices, different acceleration mechanisms can play a role in the frequency shift during the accelerated test. Overall yield of ‘good’ oscillators for HTSL is 12.5%, based on the frequency shift. The rest falls in the class ‘second grade oscillators’ for less demanding applications.

**Amplitude**

The amplitude and the supply current have a one-to-one correlation on three out of four samples that showed low amplitude between zero hour and 168 h. This is evident for samples (-9,-2), (-12, 2), (-12,-3) and (-1,-1), mentioned in [7]. This would mean that the amplitude of the clock-frequency signal could be weak due to a lower current consumption than usual. A possible explanation is that the 168 h high-temperature storage accelerated the formation of intermetallic, resulting in a good contact between the wire and the ball bond. The amplitude further improved significantly on all samples from 168 h to 504 h.

**Negative polarization voltage**

The negative polarization voltage is stable at all read points except at zero hour. It is within a 100 mV range and has an acceptable value. As stated in [5] and [8], it is misrepresented by the Keithley 2000 current meter. A value of 1V has to be added, to be in the -5.4 to -5.6V range. The high temperature storage does not induce any effect on this electrical parameter.

**Supply current**

For four samples, the supply current shoots up by 33% going from 0 to 168 hours as mentioned in [7]. Perhaps, the stressing accelerated the oxidation phenomenon in the wire bonding/bond pad areas leading to more than normal current consumption on four samples (-7,-2), (-12,-3), (-12,-2) and (-11,-3). The rest of the samples show a stable current consumption.
9.9 Concluding remarks

UHAST

The frequency shifts about 20 ppm per 96 hours of UHAST on three samples that show the trend in one direction. The stress levels in these samples induced by the thin film plastic packaging are different from sample to sample. The thermal path varies inside the package due to the influence of moisture exposure and it can alter actual temperature of the MEMS die.

TMCL

On seven good samples, stress-induced changes are evident up to 200 cycles [10]. This could be directly related to thermal cycling impact on the package. All other relevant electrical parameters do not show a major degradation. One oscillator was not functional after the preconditioning step.

HTSL

Two samples show a clear ageing trend that is caused by mechanisms introduced by the high temperature storage for prolonged hours. This might alter the thermal resistance inside package. In total 15 samples show a huge frequency shift ($25 < |\Delta f/f_0| < 80$ ppm) and do not exhibit a clear trend in ageing. Due to the impact of HTSL, the ageing mechanism on these samples is believed to be very different compared to the good samples owing to the processing induced device-to-device variations.

Yield

The yield of packaged virgin oscillators is 76%, before they are submitted to the three harsh tests that are essential for proving their value in a potentially commercial product. At the end of all read points in the tests, the overall yield is 55% for UHAST, 65% for TMCL, and 12.5% for HTSL for oscillators classified as ‘good’. This applies if 25 ppm frequency accuracy is targeted for crucial applications such as high-performance equipment that require very stable frequencies such as networking base stations, smart mobile phones and global positioning systems (GPS).

The ‘second in grade’ devices with $25 < |\Delta f/f_0| < 100$ ppm will fit into applications that require less stable clock output frequencies, such as storage systems, desktop computers and universal serial bus (USB) portable devices [11]. The yield for these devices after testing is 45% for UHAST, 30% for TCML, and 87.5% for HTSL.

A surprisingly small fraction of oscillators is non-functional after testing. This only holds for TMCL where one device totally fails, resulting in a non-functional yield 5%. This shows promise for upgrading the process of device fabrication to a pre-industrial scale with larger samples. A wise decision could be to choose first for a commercial application with less stringent demands on the frequency shift, to buy time in the production process for gradual improvements. The demonstrator is the end of the preliminary experiments described in this thesis on design.

References

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Chapter 9


Chapter 10
Concluding remarks

Based on the outcome of the chosen wafer-level reinforcement flows, employing polymer thick films Intervia and Polyimide, important conclusions are presented, both for the packaged resonators and oscillators. The goal of the project is to demonstrate functional thin film packaged MEMS oscillators at zero hour and during the three important reliability tests UHAST, TMCL and HTOL. Our final choice, the polymer reinforced MEMS resonators stacked on to the ASIC die making it a MEMS oscillator, has helped achieving it.

10.1 Conclusion

By polymer spin coating and final curing, it is possible to reinforce the MEMS resonators with the polymers, Polyimide and Intervia. The reinforced resonators survive all BE handling steps, including molding at 80 bar without showing major degradation in electrical performance. Keeping the product in mind, the final choice for polyimide reinforcement of resonators can be successfully implemented as a functional thin-film packaged oscillator in the stacked die approach. The polyimide reinforcement allows the use of Thin Film Capping as a wafer-scale packaging technology for MEMS resonators. This thin-film capping is almost unique – and it might open up interesting possibilities for the future.

10.2 Resonators

Process technology-related

Proper choice of material together with the process technology plays the key role in the success of a device, both at wafer-level and also at product level. The MEMS resonators developed at NXP Semiconductors have a thin-film silicon-nitride encapsulation and metal plug processed using the standard processing steps such as PECVD, sputtering etc, that have been proven to ensure a good encapsulation for the resonators at wafer-level. To address the BE handling issues (Chapter 1), a number of materials have been considered to act as a reinforcement layer (Chapter 2). Ease of processing, compatible technology as a front-end standard CMOS processing, thermal budget in terms of not triggering the outgassing of the thin silicon nitride, availability of material and
relevance to the current wafer-level thin-film capping have been the considerations in choosing and experimenting the Polyimide and Intervia thick polymer films.

We know that the quality factor, one of the important electrical parameters of interest that represent the functionality of the MEMS resonators is affected during the reinforcement polymers processing (Chapter 7). The resonators exhibited an acceptable quality factor as dictated by the specification; given the impact due to the polymer reinforcement- spins processing and final curing. The main reason accounting for the huge quality-factor drop was the thermally-induced out-gassing and the stress in the polyimide causing the center-to-edge variation in the quality factor in the wafer. Polyimide was subjected to a final curing at 350 ºC for 60 minutes, whereas Intervia was cured only at 190ºC. As noticed in the electrical results, the Polyimide-reinforced resonators suffered a quality factor drop of about 40% compared to the Intervia-reinforced resonators (20%). For the reference resonator reinforced with, the 5 µm thick silicon nitride reinforced resonators; the quality factor drop was close to 30 %. Centre-to-edge variation in the quality factor was not evident. The stability of the aluminum plug was largely impacted during the thermal excursion.

Radiation and convection ovens are employed for the polyimide and intervia curing. An alternative to the thermal curing is the variable frequency microwave (VFM) curing that is being employed for certain class of polymers, to reduce the thermal load on the device. It has been stated that the rapid VFM curing of certain grades of photosensitive polymers is feasible. Complete polymer cross-linking required to achieve the mechanical robustness has been possible. The most significant differences in properties between VFM and thermally-cured films were in the electrical properties due to the slow evolution of chemical products [1].

To have a stable aluminum plug sealing for a vacuum tight cap, proper adhesion layer in between aluminum and the thin silicon nitride and also at the sealing recess holes can improve the mechanical stability of the vacuum seal during thermal excursions (during reinforcement processing).

**Capping design related**

The mechanical stability of the aluminum plug decides the quality of the vacuum tight sealing of the thin silicon nitride capping. According to the design, it spans for 10 µm [2] on top of the thin silicon nitride. To ensure a better interface to the underlying thin silicon nitride, extension of the plug can be helpful.

The aluminum bond pad that is used to sense the resonance in a piezoresistive way is located very close to the active resonator region, as stated in the design rule manual. During electrical testing, the RF probes that are used to contact the bond pad for forcing currents, have the probability to scratch the capping and damage it. It is therefore wise to extend the distance of the bond pad edge toward the dog bone within allowable limits to prevent the damage to the thin film capping. An alternative would be to look for probes that can do vertical probing, unlike the ground-signal-ground RF probes.

Sharp corners in the bond pad region have been one of the important sources of stress concentration, leading to crack formation and propagation in the thin film capping. Providing rounded corners in the mask design would help minimizing stress concentration and possible failures due to this. It has to be noted that the polymer reinforcement layers investigated in this work are devoid of sharp corners. For polyimide reinforcement, we see a natural corner rounding because of the stress in the layer. For Intervia reinforcement, an acute corner rounding is not evident, but there is some degree of rounding, as seen in the optical microscope inspection of the bond pads.
Chapter 10

10.3 Oscillators

In total, 100 oscillators have been assembled in the stacked-die configuration employing the core element, the 20 µm polyimide-reinforced MEMS resonator, wire bonded to the ASIC. This leads to the final product, the MEMS oscillator operating at 13 MHz. Proof of feasibility is given by the fact that the majority of the assembled oscillators are functional at zero hours. The observed yield is about 76%. When subjected to HTOL, TMCL and UHAST, the chief electrical parameters do not degrade and the digital clock-frequency shift is within 25 ppm for good samples and about 100 ppm for samples that are considered to be second best in performance (second in grade). Due to shortage of time, was not possible to analyze the possible failure mechanisms and the triggering modes, based on the reliability test results on packaged oscillators. The shift in the resonance frequency for the good and the second in grade packaged oscillators can be due to the following reasons:

a. The temperature sensor is incorporated in the ASIC die. The frequency shift is caused by the MEMS resonator [3]. In addition to the measurement related uncertainties, the variation in the thermal path between the MEMS resonator and the ASIC die needs to be taken into account.

b. The packaging-induced stress play a major role; the assembling steps leading to the stacked die, such as wafer thinning, dicing, lead frame assembling, wire bonding for the resonator and the ASIC dice and finally molding can induce mechanical strains in the dog-bone shaped resonator. This would alter its operating resonance frequency from the specifications.

c. Accelerated stress tests induce physical changes in the resonator and the ASIC dice. This can lead to a frequency shift of the oscillator.

d. Last but not the least, random variations, such as, contact resistance changes during the socket-level measurement, thermal conductivity changes inside the package, fluctuations in the laboratory room temperature not properly compensated or taken care by the temperature in the ASIC die can induce changes in the electrical parameters.

Design-related proposals for packaged oscillators at this stage are open, due to limited experience gained in understanding their behavior based on the stress test results. Overall, we understand that the important electrical parameters do not exhibit major degradation at zero hour and during the three reliability tests (Chapter 9).

Currently, a 10-pin QFN (HVSON10) package has been used to demonstrate the oscillator functionality. The wired connections to achieve the oscillator do not exploit the available pins offered by the package. To minimize noise and the parasitic effects induced by lengthy gold wire bonds and the cross talk due to many wired connections inside the package, a small outline package with a reduced pin count can be adopted. One resonator in a package does not require more than three connections: one drain, one gate and a ground (pin) to function as a resonator as an oscillator. The area permitted for the small aluminum bond pads is 65 µm². To enable easy access and to improve the contact resistance, larger bond pads would be helpful.

References

Chapter 11
Implementation hick-ups and outlook

Around the fall of 2010, NXP decided to prepare for production of the resonator. It was decided to outsource this production to a partner that is providing both research and foundry services. The partner that was selected by NXP to further develop and ramp up to volume production was IMEC, the Inter-University Microelectronics Center (IMEC) in Belgium. The processing at IMEC would cover all front-end processing steps, both the manufacturing of the resonator structure with typical MEMS processes as well as the processing steps to realize the thin-film capping structure (thin silicon nitride encapsulation, aluminum plug sealing and polyimide reinforcement-layer processing).

At the time this decision was taken, the polyimide reinforcement approach was certainly regarded to be a viable option for mass-scale fabrication of packaged MEMS. As usual for a technology project in this phase of development, some optimization steps were still required. In this case the optimization steps were targeted to achieve a smooth BE-handling according to the industrial specifications on wafer warpage after wafer-thinning step. These steps were: applying a slightly thinner polyimide layer (< 20 µm) and adopting a low-density version of our polyimide. Within NXP these steps were proven to be feasible [1], as to be expected.

Regrettably IMEC decided independently to abandon the route of polymer reinforcement because of problems that emerged during implementation of the polyimide processing: a) poor polyimide thickness control after polyimide spin processing, b) insufficient descum (required to remove contamination after polymer processing), and c) risk of cross-contamination by polyimide of the tools used. Although none of the problems identified can be regarded as a blocking issue to implement the polymer-reinforcement processing route, it can be understood that under the pressure to reduce the time-to-market a reinforcement process was selected that was already well developed and qualified within IMEC [6].

This fallback to an existing (non-polymer based) process flow was clearly driven by the desire to reduce risks and it does not mean that there is no outlook on implementation in the future. Polyimide is already being used as a wafer-coat material by many well established wafer foundries and semiconductor manufacturers all over the world and its technology is well established [3, 4, 5]. In addition, it has been adopted by many subcontractors as dielectric for redistribution layers in wafer-level packaging. With smart fine-tuning experiments, the minor technological problems can be
addressed and solved. Since the polyimide processing route clearly provides a cost advantage in mass manufacturing we believe that adoption of this technology will someday happen in the semiconductor industry.

References

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Summary

Polyimide reinforcement of capped MEMS devices: soft and simple

Micro-electromechanical systems (MEMS) devices are extremely sensitive to their environment, especially at the wafer level, until they are packaged in final form. The harsh back-end (BE) operations that the MEMS devices have to endure include dicing, pick-and-place, wire bonding, and molding. During these processing steps, the MEMS device is exposed to particles and contaminants, also to loads and stresses. Therefore, protection at an early stage is a fundamental requirement. A piezoresistive MEMS-resonator timing-device that finds application in the radio frequency (RF) front end, for example, in cell phones, is taken as a MEMS vehicle for our work. The final product is a MEMS-based oscillator. This project is part of the core business of NXP Semiconductors. It is an example of an extremely sensitive MEMS device, because the resonance frequency shifts significantly when additional mass is accidentally deposited on its surface and a reasonable good vacuum of ~ 1mbar is needed for its operation.

In this thesis, the need for a reinforcement to protect the MEMS resonator s is outlined and the polyimide reinforcement on thin silicon-nitride capping-route is demonstrated, first on MEMS resonators and then on the final product, the NXP MEMS oscillator. At the time of commencement of the project work, the thick silicon-nitride reinforcement deposited at low temperature was the only available option at NXP. It was not possible to take this route further for industrialization, as the MEMS resonators with this capping did not survive the harsh reliability stress-tests, mainly the unbiased highly accelerated stress-test (UHAST). It took around fourteen months to prove that it is possible to apply the polyimide-reinforcement route and achieve functional packaged oscillators that survive three important reliability tests.

In chapter 1, the problem is introduced and need for reinforcement is emphasized. Chapter 2 comes up with a wise choice of the three polymers: SU-8, Intervia and Polyimide, with the commonality that all are negative-tone polymers.

Mechanical-stress simulations have been carried out to determine the thickness of the polymers in combination with the thin silicon nitride employing possible boundary conditions. The thickness of the polymer is chosen based on safe margin and the capping geometry that is worst exposed to loading, namely the 80 bar molding pressure and excursion temperature of 175°C during packaging. This is elucidated in chapter 3. To show feasibility of the polymer-route compatibility, experiments were carried out on-wafer with processed resonator and the thin-film silicon-nitride capping. The results of this are presented in chapter 4. We conclude that polyimide and Intervia are the viable candidates, discarding SU8 due to its poor definition and pattern shift on the underlying thin silicon-nitride layer.

It is important to know whether the polymers, being hygroscopic materials, can effectively combat moisture and protect the resonator under the capping. Other possible risks are assessed and discussed in chapter 5. The pre-assembly steps and final packaging plays a crucial role in determining the value of the final product. Also it can contribute up to 60% of the product’s total cost. NXP’s oscillator is no exception. So it is vital to know the effect of all pre-assembly operations on the polyimide-reinforced resonators on-wafer. This is studied and the findings are discussed in chapter 6. The temperature is around 350°C during the processing of the wafer-level encapsulation and reinforcement layer. It is worthwhile knowing the impact of thermo-mechanical loading on the stability of the thin-film capping and in turn of the device survival. By means of test experiments the effect of thermal treatment is known. This is described in chapter 7.

The reliability tests conducted on plastic-packaged resonators (chapter 8) reveal that the devices reinforced with Intervia, lead to degradation over time. Polyimide reinforced, packaged resonators survive the reliability tests without any major problems. So, the polyimide reinforcement is our final
choice. The final product, the oscillator is made of polyimide-reinforced resonators bonded to the amplifier circuit (ASIC) in a ‘stacked-die’ configuration, realized in a QFN plastic package. In order to check the ‘heart beat’ and see whether the oscillator survived the pre-assembly operation or not, zero-hour tests are carried out.

Reliability tests are carried out to see whether the oscillator endures the tests, and also understand how the device responds to the accelerated stress-tests. Moreover, the intention was to see what shifts are witnessed in the typical electrical parameters. The scope of the electrical testing was to know whether the oscillator is ‘alive’ or not. A detailed oscillator characterization has not been performed, given the scope of the work. The results are presented and discussed in chapter 9, with some concluding remarks in chapter 10. Some immediate hick-ups and the likely future of the polyimide route are mentioned in chapter 11.

The main contribution of the work presented in this thesis is to enable the encapsulated resonator to be a functional component of the packaged oscillator, and to make the oscillator as a whole work without any major degradation in the important electrical parameters. The key to this is the polyimide reinforcement route to encapsulate the resonator that has made it happen!
Samenvatting

Mikro-elektromechanische systemen (MEMS) zijn - tot het moment van hun definitieve verpakking - zeer gevoelig voor beschadigingen, met name als zij nog op de wafer zitten. De ingrijpende ‘back-end’ behandelingen die zij moeten ondergaan zijn o.a. ‘dicing’, montage via ‘pick-and-place’, het aanbrengen van elektrische aansluitingen (‘wire bonding’) en het inpakken in een kunststof behuizing (‘molding’). Tijdens deze processtappen wordt de MEMS bloot gesteld aan microdeeltjes en verontreinigingen; verder wordt het system blootgesteld aan mechanische belastingen en spanningen. Het is daarom van wezenlijk belang dat de MEMS al op de wafer wordt beschermd tegen deze invloeden. Als proefstuk voor dit onderzoek is gekozen voor een piezo-resistieve MEMS resonantiekring die als klok kan dienen voor het RF ‘front-end’ van elektronische apparatuur zoals een mobiele telefoon. Het eindprodukt is een MEMS oscillator, een uiterst precieze digitale klok.

Het project is onderdeel van de kernactiviteiten van NXP Semiconductors. Door de grote gevoeligheid van de MEMS klok voor de (ongewenste) depostie van zelfs een monolaag van verontreiniging en verstoring door drukken van 1 mbar of hoger, is het gekozen proefstuk een gedurfde en relevante keuze om de kwaliteit van ons werk te onderzoeken.

Bij aanvang van dit proefschrift bespreken wij waarom het noodzakelijk was om de MEMS resonatoren te beschermen. Daarna laten wij zien dat een extra versterking van het dunne SiN kapje met een dikke polymeer overkapping succesvol kan worden geïmplementeerd. Hiervoor gebruiken wij eerst MEMS resonatoren en uiteindelijk de MEMS klok. Bij aanvang van het project was versterking door depositie bij lage temperatuur van een tweede – dikke – laag SiN de enige optie die door NXP was onderzocht. Deze procesgang was niet op te schalen naar een industriële aanpak: de prototypes waren van onvoldoende kwaliteit om de ingrijpende beproevingen op betrouwbaarheid te overleven, vooral wat betreft de zg. UHAST test (Unbiased Highly Accelerated Stress Test). Wij hebben binnen 14 maanden aangetoond dat versterking met een overkapping van zorgvuldig geselecteerde polymeren resulteert in goedfunctionerende oscillatoren, die de drie meest belangrijke betrouwbaarheidsonderzoeken overleven.

In hoofdstuk 1 wordt de noodzaak voor een nieuw proces voor de versterking van de MEMS behandeld. Hoofdstuk 2 is gewijd aan een optimale keuze voor de drie polymeren die wij hebben onderzocht: SU-8, Intervia en Polyimide. Alle drie zijn het ‘negative tone’ polymeren.

Om een goede keuze te kunnen maken voor de gewenste dikte van de polymeeroverkapping zijn numerieke simulaties uitgevoerd, rekening houdend de onderliggende dunne SiN lag. Omdat de mechanische bevestiging aan de randen niet eenduidig is bepaald, zijn deze simulaties uitgevoerd met verschillende randvoorwaarden zoals punt- en lijnbevestiging. De gewenste dikte is gekozen met een ruime veiligheidsmarge, rekening houdend met de meest extreme condities die optreden tijdens het productieproces: een druk van 80 bar druk en een temperatuurexcursie van 175 °C tijdens de verpakkingsfase (‘molding’). Deze simulaties worden beschreven in hoofdstuk 3.

In hoofdstuk 4 wordt aangetoond dat het gebruik van een polymeeroverkapping een haalbare kaart is. Hiervoor zijn ‘on-wafer’ experimenten uitgevoerd met MEMS resonatoren, die eerst met een dunne SiN overkapping waren uitgerust. Wij stellen vast dat Polyimide en Intervia overblijven als mogelijke kandidaten. Het onderzoek aan het polymer SU-8 is niet voortgezet, ingegeven door de slechte resultaten en de kruip van de polymeerlaag over het onderliggende SiN.

Polymeren zijn hygroscopische materialen. Het is dus van wezenlijk belang om vast te stellen of de overkapping voldoende weerstand biedt tegen luchtvochtigheid om de MEMS werking niet te verstoren. Dit risico - en ook andere risico’s - worden besproken en afgekaart in hoofdstuk 5. In hoofdstuk 6 wordt de invloed van alle ‘pre-assembly’ handelingen onderzocht. Dit is van groot belang omdat de kosten van deze montagehandelingen en de uiteindelijke verpakking uiteindelijk op kunnen lopen tot 60% van de totale vervaardigingskosten.
Bij de depositie van de overkapping hoort een temperatuurbehandeling rond 350 C. Deze temperatuurexcursie resulteert in een thermisch-geinduceerde mechanische spanning, waarvan moet worden onderzocht welke invloed dit heeft op de stabiliteit van de overkapping en hiermee op de overlevingskans van de MEMS resonator. Met behulp van goeddoordachte experimenten is de invloed van de thermische behandeling gemeten. Hiervan wordt verslag gedaan in hoofdstuk 7.

In hoofdstuk 8 bespreken wij de betrouwbaarheidstesten die uitgevoerd zijn op verpakte resonatoren. De met Intervia versterkte MEMS resonatoren vertonen als functie van de tijd een verlies aan functionaliteit. De met Polyimide versterkte MEMS resonatoren doorstaan de betrouwbaarheidstesten met glans. De keuze is nu duidelijk: een overkapping met Polyimide is de oplossing die verder onderzoek rechtvaardigt.

Het eindproduct, een met Polyimide versterkte MEMS resonator die in een ‘stacked-die’ configuratie is samengevoegd met een versterker chip (ASIC), is verpakt in een QFN plastic behuizing. Er is onderzocht of deze MEMS klokken (a) de behandeling hebben overleefd en (b) voldoen aan de elektrische specificaties. Voorafgaand op de duurtesten is als nul-meting het functioneren van de MEMS klokken onderzocht, direct na het productieproces.

In hoofdstuk 9 worden de MEMS klokken onderworpen aan de, voor de halfgeleiderindustrie gebruikelijke betrouwbaarheidstests. Het is van belang om te weten hoe de klokken zich gedragen tijdens deze versneld uitgevoerde tests, onder welbepaalde maar extreme omstandigheden qua vochtigheid, druk en temperatuur. Vooral het al dan niet optreden van drift en/of verschuiving van de essentiële elektrische parameters - zoals bv. de resonantiefrequentie - is van cruciaal belang. Wij hebben ons hierbij beperkt tot de hoofdlijnen van het functioneren van de MEMS klok, zonder in te gaan op verdere details zoals bv. faseruis.

Een samenvatting-in-vogelvlucht van de bereikte resultaten wordt gegeven in hoofdstuk 10. In hoofdstuk 11 wordt kort verslag gedaan van enkele voetangels en klemmen die het project is tegengekomen in de fase van pre-industriële implementatie van het Polyimide process. Dit is interessant om te rapporteren, maar valt buiten het bereik van dit proefschrift.
Acknowledgements

My first and foremost sincere thanks go to my promoter, Prof. Herman Beijerinck at TU/e. Ever since my start at the Technological Design (PDEng) DTI program, he has taught me in a very practical way, what it means carrying out a project in an Applied Physics-related topic in the industry, be it experimental work, technical writing, or giving a presentation. I appreciate all his invaluable contributions of time, ideas and efforts to make my ‘PhD on Design’ experience a very productive one.

I sincerely thank my project supervisor at NXP Semiconductors, Coen Tak for giving me an opportunity to carry out my project work on MEMS Timing Devices packaging, even during the difficult times with project funding. I thank him for allowing me to take the time to understand the project and organize my tasks, and for his worthy suggestions that made me come up with a good project plan. I very much appreciate his constant support and guidance throughout my project and thank him for all his suggestions and comments.

I would like to thank Prof. Paddy French at TU Delft for agreeing to be my second promoter. I take this opportunity to thank the PhD defense committee members: Prof. Lina Sarro, Prof. Richard van der Sanden and Prof. Bart Smolders. I thank Prof. Gerrit Kroesen for chairing my defense. Thanks go to Prof. Oliver Paul from IMTEK, Germany for agreeing to be part of the PhD committee.

I thank Micha in’t Zandt at NXP Research for helping me with the short loop and full experiments with the polymers that I investigated at MiPlaza clean room. Throughout my project, his cooperation is very much appreciated.

I thank Corné Rutjes at Philips Applied Technologies for helping with the polymers spin processing at the spin coater.

At NXP Research, I thank Martijn Goossens for introducing me to the MEMS resonator measurement setup. Also, I thank Cas van der Avoort and Kim Phan for helping me during the packaged MEMS oscillator testing.

I thank the entire MEMS Timing Devices project team, including the Reliability group at NXP Nijmegen for providing a very challenging and interesting work atmosphere, which served as a platform for my professional development.

I would like to thank a lot, my other NXP colleagues and friends at the High Tech campus, Eindhoven for their great support and encouragement. Memories of Grand Café coffee chats, De Markt lunch hours and other occasional, informal discussions with them are best cherished and well-remembered.

I thank my parents, brother, sister and their families, parents-in-law, sister-in-law and brother-in-law for their support.

Last, but not the least, I thank my wife Nithya for being there for me at all times. I am grateful to her for her kindness, impeccable love, care and affection.
Curriculum Vitae

Krishnan Seetharaman (1980) was born in Chennai, India. He graduated with a Bachelor of Engineering degree in Electronics and Instrumentation from the University of Madras in June 2001. From July 2001 to February 2002, he followed the Post Graduate Diploma in Embedded Systems at Telecommunications Consultants India Limited, after which he was project trainee and engineer at Signals and Systems India Private Limited. In September 2003, he started pursuing the Master of Science (Microelectronics and Microsystems) at the Hamburg University of Technology, which, he completed in March 2006. After carrying out a post-study internship at Robert Bosch, Gerlingen-Schillerhöhe, Germany, he enrolled for the Professional Doctorate in Engineering (PDEng) program at the Eindhoven University of Technology, in April 2007. He carried out his design project at NXP Semiconductors, Nijmegen in a topic related to wafer-level encapsulation and packaging of MEMS Devices. As part of the curriculum, he spent the last three months of the PDEng program carrying out an internship at Systems on Silicon Manufacturing Company (SSMC) in Singapore. After graduating with the PDEng degree in July 2009, he continued to work on MEMS oscillator packaging at NXP Research, Eindhoven, until December 2011. The results of this work are presented in this dissertation. From January to September 2012, he was employed as Technology Development Engineer at Telefunken Semiconductor GmbH (now Telefunken Semiconductor International Inc.). Since October 2012, he is employed as Product Quality Engineer at Dialog Semiconductor, Kirchheim-Teck, Germany.