Scale Effects in Freestanding Thin Metal Films for RF MEMS Applications

Student: Zlata Jelacic
Supervisors:
Prof. dr. ir. Marc Geers (TU/e)
Prof. dr. ir. Jaap den Toonder (Philips Research, TU/e)
dr. ir. Marcel Brekelmans (TU/e)
Abstract

The basic structure of a Micro Electro-Mechanical System for Radio Frequency applications (RF-MEMS), such as switches or tuneable capacitors, consists of a thin freestanding metal film that is actuated by an electrostatic force.

The mechanical properties of the thin film materials used in RF MEMS are crucial for their proper functioning. Previous research also showed that in the case of micro scales, the thickness has a great influence on the mechanical properties. The dependence of material mechanical properties on the size of the structure, which is often termed material length scales or size effects, is of great importance in many current engineering science applications. These effects are seen experimentally when the characteristic dimension of the physical phenomenon involved is in the order of the structural scale of interest. Therefore, the representative length scale $l$ of the deformation field sets the qualitative and quantitative behaviour of size effects.

In order to see whether or not this is the case in the thin metal films used in RF MEMS applications, special experimental techniques are used. The so-called microbeam bending experiments are performed on the dedicated mechanical test structures. The measurement results are then compared to the numerical model, based on the continuum theory, which does not account for scale effects. However, the results show that the experimental and the numerical part need to be optimized in order to make any conclusions concerning the scale effects. That is why this work is mainly an explorative investigation of the possibility of using microbeam bending experiments to assess length scale properties of polycrystalline metal thin films.
Acknowledgements

I would like to thank the following people, because without their help I would not be able to carry out this project.

First of all, many thanks to my supervisors Marcel Brekelmans, Marc Geers and Jaap den Toonder for their theoretical, experimental and numerical support during this graduation project. Furthermore Auke van Dijken for his contribution in the experimental part and Mathieu Ulenaers for making the samples. I would also like to thank Cees van der Marel for the XPS measurements. My special thanks go however to Monja Keiser for her patience and support with the FIB analysis. Last but not least, I would like to thank Vincent Burg for his help with the numerical part.
# Table of Contents

1  Introduction 6

2  Description of the Experiments 9

2.1 General 9

2.2 Test Structure Processing 9

2.2.1 PASSI Manufacturing System 12

2.2.2 Test Structures 13

2.2.2.1 Cross-Section Study of Al-grains 14

2.2.2.2 Cross-Section Study of the Beam Support 16

2.2.3 Thinning Down of the Films 16

2.3 Description of the Experiments 27

2.3.1 Stress Measurements 27

2.3.2 Microbeam Bending Experiments 31

3  Experimental Results 36

3.1 Introduction 36

3.2 Stress Measurement Results 36

3.3 Microbeam Bending Experiments 39

3.3.1 Thickness = 5 micron, length = 50 micron 39

3.3.2 Thickness = 5 micron, length = 75 micron 40

3.3.3 Thickness = 5 micron, length = 100 micron 42

3.3.4 Thickness = 4 micron, length = 50 micron 44

3.3.5 Thickness = 3 micron, length = 50 micron 46

2  Experimental Overview 45

3.4 Introduction 47

3.5 Numerical Model 47

3.5.1 Meshing 47

3.5.2 Nonlinear Analysis 48

3.5.3 Loading Strategy 49
1 Introduction

RF-MEMS are Micro-Electronic Mechanical Systems that will be used in the Radio Frequency field, e.g. in mobile phones. MEMS in general are small structures (order 1-500 micron) that are electro-statically driven to produce a mechanical movement. This movement provides in RF-MEMS an electric function, e.g. a switch or a tuneable capacitor. The benefits of the use of MEMS are a decreasing size and a better performance of RF systems.

Based on past research, it was chosen to make the MEMS structures out of aluminium. Aluminium is low cost material and combines low resistivity with good processing properties, such as good adhesion to dielectric materials and good corrosion resistance. The top aluminium layer is several microns thick and partly freestanding. It can move by applying a potential difference between the top and the bottom aluminium layer. In commercial products it should switch up to \(10^{11}\) times. Hence, reliability is a big issue. Not only during its lifetime, but also during processing stresses are introduced in the material due to temperature changes and etching steps. Therefore good mechanical properties like a high yield stress or a low creep are of big importance.

Further research [1] showed however that the basic pure aluminium as the freestanding metal layer was not sufficiently strong. Most of the structures were deformed after processing and annealing them made it even worse. Such a device is shown in Figure 1.2.

![Figure 1.1: MEMS capacitor](image1.jpg)

![Figure 1.2: Pure aluminium MEMS capacitor which is plastically deformed during processing](image2.jpg)
Big irreversible deformations are detrimental for RF-MEMS, because actuating voltages are changed unpredictably or the structures will not move at all. Improving the mechanical properties can prevent this. In the bulk industries the mechanical properties of aluminium can be improved by adding alloying elements. However, thin film properties deviate from bulk properties. This was already shown by results on aluminium films published in 1989 by Nix [2] (see Fig. 1.3). Data showed that the yield strength depends on the thin film thickness and on the nature of the boundary conditions (for freestanding films versus fixed films).

The difference in mechanical properties between the thin film and bulk material in the case of aluminium will be further deplored in this work. This analysis is build out of the experimental part, which is performed on the thin films and its comparison with the numerical model, based on the continuum (bulk) theory. The conventional continuum theories are however successful in macro-scale material structures, but they fail to predict the material behaviour observed at the micro-scale such as the depth dependent indentation hardness. Beginning at the molecular level (the level at which the fundamental properties of materials and systems are established), new chemical and physical properties emerge as cooperative interactions begin to dominate the behaviour of micro-molecular complexes (i.e. at the continuum level). The comparison should therefore lead to the investigation whether or not length scales have influenced the experiments.

This study has been performed in a research environment. Therefore the focus is on the experimental approach and setting up and carrying out experiments on freestanding test structures. This is done in order to get more insight into the separate influence of microstructure and film thickness on the mechanical properties of thin freestanding metal films. Microstructure is kept constant while film thickness varies. The measurements consist of loading the microscopic freestanding beams with a point load. The output of the micro-bending experiments is compared to the output of the numerical analysis using a set of material properties. For the analysis the standard continuum finite element model is used. The aim is to determine whether the effective properties such as elastic modulus and especially yield strength are influenced by the film thickness, in other words to determine whether there is a scaling effect, and if so in which ‘direction’. The following figure illustrates the analysis strategy.
In the next chapter the attention will be given to the processing of the test structures and the description of the experiments. Because of its importance in this work, first the experimental part is elaborated in detail. This is done in Chapter 3, which presents the results of the stress measurements and the microbeam bending experiments. Chapter 4 is build around the numerical model and gives an overview of the numerical results. Finally, in Chapter 5 the results of both the experimental and the numerical approach will be compared. Based on this comparison, conclusions will be drawn and the recommendations for future research will be given.

**Figure 1.5: Analysis strategy**

In the next chapter the attention will be given to the processing of the test structures and the description of the experiments. Because of its importance in this work, first the experimental part is elaborated in detail. This is done in Chapter 3, which presents the results of the stress measurements and the microbeam bending experiments. Chapter 4 is build around the numerical model and gives an overview of the numerical results. Finally, in Chapter 5 the results of both the experimental and the numerical approach will be compared. Based on this comparison, conclusions will be drawn and the recommendations for future research will be given.
2 Description of the Experiments

2.1 General

This chapter will give an overview of the processing and the kind of test structures used. Also the thinning methods in order to achieve the structures with the same microstructure and different thickness will be elaborated. At the end of the chapter, the build-up of the stress measurement and the microbeam bending experiments will be described. This chapter describes all the issues that play a role and influence the experimental results, which will be described in the next chapter.

2.2 Test Structure Processing

2.2.1 PASSI Manufacturing System

Within Philips an industrial process exists, called PASSI, which is suitable to introduce RF MEMS on a ‘passive IC’. This technology integrates passive components (e.g. capacitors) on dedicated high-ohmic silicon substrates. The integration of RF MEMS with the PASSI process has three big advantages:

- The high-ohmic silicon provides a good isolation, which is necessary for making RF MEMS.
- It is favourable for various applications like the VCO (Voltage Controlled Oscillator) tank circuit.
- The manufacturing costs are quite low and also the time-to-market is short, because the RF MEMS integration is based on an existing process, which is already relatively cheap due to a low mask count in comparison with mainstream CMOS (Complementary Metal Oxide Semiconductor).

The PASSI process, which is used for manufacturing MEMS, is a three-metal thin-film process on high-ohmic silicon substrates, which is shown in Figure 2.1.
To create RF MEMS with the PASSI process it is extended with surface micro machining. It consists of removing the silicon oxide layer, the second aluminium layer and/or the silicon nitride layer to create an air gap between 0.4 and 3 micron, depending on the kind of PASSI process.

In this case, the ‘active’ layer (the layer that partly floats) consists of pure Al with a thickness of 5 micron. Two batches of wafers with structures are made: batch 1047, processed with PASSITM-I, and batch 1048, processed with PASSITM-II. It needs to be mentioned that the wafers from the same batch are made with the same process conditions. The mechanical test structures of a selection of those wafers are measured. The main difference between the two manufacturing processes is the sacrificial layer. Another difference is the gap between the two metal electrodes, which is 3 micron and 1.4 micron in the case of PASSITM-I and PASSITM-II, respectively. The manufacturing of both processes will be illustrated below.

**PASSITM-I**

In this case silicon-nitride has been used as the dielectric layer between the two metal electrodes (the green coloured layer in Figure 2.2). One of the advantages of this process is that it is close to the original (proven) PASSITM material system. Another advantage is the use of wet processing (wet etching), which is quite cheap.

One of the disadvantages of such a process is the limited dynamic range (pull-in effect). Another problem is to control the dielectric layer thickness.

In the next picture the processing of the mechanical test structures is illustrated. This is also an example of the selective etching method where different materials are removed during different etching steps.
PASSITM-II

In this case no dielectric layer between the metal electrodes is being used: there is an aluminium-to-aluminium contact. One of the advantages of this process is ‘infinite’ dynamic range (pull-in effect can be avoided) and the fact that DC actuation electrodes can be decoupled from the actuation path.

One of the disadvantages is the reliability of the aluminium-to-aluminium contact.
2.2.2 Test Structures

In order to perform dedicated experiments, special mechanical test structures have been designed. Using the previously described processing methods, these structures are fabricated on silicon test wafers. Test structures consist of cantilevers, double-clamped beams and ring-beam structures, whose function will be described in the section 2.3.1. In the next figure an overview of the test structures is given.

In order to achieve the freestanding test structures, several etching steps needed to be performed. In the next part the influence of these etching steps will be investigated through the grain structure study and the cross-section analysis. Both factors are of great importance for the mesh build-up of the numerical model.

The analysis is performed with the FIB (Focused Ion Beam) technique. The module of which the Al-layer was studied is the so-called double clamped beam structure with a length of 50 \( \mu \text{m} \).

Using the FIB it is possible to mill a hole with a steep edge through the region of interest and a stair-case-like construction on the opposite side. By tilting the sample 45° it is possible to study the cross-section made through the region of interest.

Figure 2.5: Mechanical test structures
Prior to preparation a Pt protection-layer of 1\(\mu m\) thickness was deposited on the region of interest. This is mainly done to protect the cross-section surface. For imaging ions are used to scan the surface and the generated secondary electrons are detected. Note that for the images taken with the sample tilted over 45°, a correction factor of \(\sqrt{2}\) must be used for all vertical dimensions (like layer-thickness) measured. All the values of the layer thickness mentioned in this report are already corrected for the 45° tilt.

2.2.2.1 Cross-Section Study of Al-grains

The aluminium layer is sputtered with a thickness of 5 micron on the silicon substrate. The thickness of the sputtered layer is directly proportional to the sputter time needed, which influences the grain size. Longer sputter time means longer exposure to the high sputter temperature, which then stimulates the grain growth. It is also known that the grains in this case have a columnar growth over the thickness. The only information remaining is to find out if the grain columns are homogeneous over the beam thickness. This part has a direct influence on the modelling and the interpretation of the results.

![Figure 2.6: FIB images of the cross-section of a freestanding test structure (double clamped beam)](image)
In the previous figure, different images display the cross-section at different magnifications (with the sample tilted 45°). Images C and D were taken at the same magnification with the only difference that image D was taken at a higher ion beam voltage to enhance the contrast in (between) the grains. In image D the solid arrows mark grain boundaries whereas the dashed arrows indicate two twin boundaries within grains. Based on these images, following can be concluded:

- Independent on the diameter of the Al-grains, the thickness of the grains is equal to the layer thickness.
- The layer thickness is 5.2 µm.

On top of the oxide and the bottom of the Al layer re-deposited material is present.

2.2.2.2 Cross-Section Study of the Beam Support

The type of the boundary condition influences strongly the mechanical behaviour. This means that small changes in the boundary conditions will affect the outcome and thus play an important role in the interpretation of the results. Therefore it has been decided to examine the beam support in detail before doing any experiments. Because the anchor points are the only fixed points of the beam, the thickness of the beam is measured over its length in order to see whether there are any discrepancies between the fixed and the freestanding part.

![Figure 2.7: Overview FIB image displaying the middle part of the module in cross-section (sample is tilted 45°). The floating part of the module is visible. The grains inside the Al-layer can clearly be discerned.](image-url)
In the top image the positions are indicated at which thickness measurements of the Al were performed (see also Table 2.1).
In Fig. 2.9 it is clearly visible that the bottom Al-layer stops 2 µm besides the edge of the top Al-layer. The silicon-nitride layer continues at the point where the bottom Al-layer stops. The Pt-protection layer is (re-) deposited on top of the bottom Al-layer and at the bottom side of the floating part of the Al-layer. In the table below the thickness of the Al-layer measured at different positions as indicated in Fig. 2.8 are presented.

<table>
<thead>
<tr>
<th>Section of structure</th>
<th>Al-layer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>floating</td>
</tr>
<tr>
<td>Left (clamp)</td>
<td>5.0</td>
</tr>
<tr>
<td>Middle (floating part)</td>
<td>5.0-5.1</td>
</tr>
<tr>
<td>Right (clamp)</td>
<td>5.2</td>
</tr>
</tbody>
</table>

*Table 2.1: Thickness of the Al-layer in µm. The thickness presented here is not measured at grain boundaries.*

The following conclusions could be drawn from this analysis:

- The Al layer thickness is constant over the whole floating part of the layer.
- The Al-layer thickness in the clamped part decreases towards the region where the Al floats (indicated by the arrow labelled with ‘edge’ in Fig. 2.8). This causes the huge range in thickness for the clamped parts.
- At the grain boundaries the Al-thickness decreases by 0.1-0.2 µm.
- Below the Al-layer a crystalline layer, the Al bottom electrode is present. This layer is present in both the clamped parts and underneath the floating part. The thickness of this layer is 0.5 µm.
- In between the substrate and the crystalline layer a thinner, silicon-nitride layer is present. The thickness of this layer is 0.1 µm.

2.2.3 Thinning Down of the Films

With the usual deposition techniques, the film thickness and grain size cannot be varied independently. By adjusting the thickness of the Al-layer during deposition also its microstructure is changed. As a result the influence of a different Al-layer thickness cannot be investigated.
In the previous pictures, the microstructure of an AlCuMgMn alloy is presented as an illustration of the dependence between grain size and sputtered film thickness. The thicker the sputtered layer, the bigger the grains because in the case of thicker films, the material is longer exposed to the higher sputtering temperature, which stimulates the grain growth.

In our case, the processed test structures have the same thickness of 5 micron and thus, the same microstructure. In order to reduce the film thickness and keeping the microstructure unchanged, several thinning techniques have been investigated. First the FIB-modification (Focussed Ion Beam) is tested on its feasibility to modify the thickness of the floating part of a MEMS-structure. In this case the material is sputtered with the Ga+ ions. In the first attempt the ion beam is perpendicular and in the second attempt the sample has been tilted. The module of which the Al-layer was thinned is the so-called double-clamped-beam structure.

**Figure 2.12: SEM photo of 5 micron thick AlCuMgMn module**

**Figure 2.13: Overview of the modified test structure.**
The previous image displays an overview of the modified 150µm MEMS structure (together with MEMS structures of other lengths) and the test structure in the bond pad. The grainy structure of the Al can still be seen after modification. This can be seen best in the test structure.

Figure 2.14: Images displaying the 150 µm MEMS module (together with modules of other lengths) after removal of a) 600 nm, b) 750 nm and c) 1230 nm.
Note that the indicated depths are merely indications of the removed material since no calibration was performed yet. Only from the floating part of the module material was removed. The floating part was recognised by bright lines at each end of the line. In the bottom image, these bright lines (indicated by the green arrows) are best visible in the 50µm module. Re-deposition of the material removed is already seen after 600 nm Al-removal. However, in the bottom image the re-deposited material is visible best. The sidewalls of the floating module modified look rough after modification. This can be explained by the grainy structure of the Al. Sputtering along grain boundaries will be faster than through the grain itself.

Using a white-light interferometer the real depth of the material removed was measured on both locations modified. It appeared that 1.7µm in thickness was removed from the 150µm MEMS structure compared to 3µm in thickness from the test location in the bond pad. Although this difference in depth is unexpectedly high, this difference can be explained. Milling in the bond pad is at a certain point the same as milling in a hole: ions that would miss a free-standing structure due to the fact that they have a higher opening angle, are now scattered at the sidewalls of the hole and hence contribute to the sputter process (Fig. 2.15).

Furthermore a high surface roughness of the milled areas was seen. This surface roughness is caused by:

1) the fact that material is removed faster by sputtering along grain boundaries than through grains and

2) the dependence on crystal orientation: ions are highly susceptible to channelling. If crystal planes are oriented parallel to the ion beam, the probability of the interference of an ion with an atom is rather small and hence removal of material is relatively slow. If a crystal is oriented randomly with respect to the ion beam, material will be removed relatively fast.

**Figure 2.15: Schematical drawings of the ion beam path in case of a) milling a freestanding structure, b) milling in a hole**
Since the FIB is not calibrated for Al, a standard material inputfile was used. In a previous analysis it was seen that more material was removed than asked for (1.7\(\mu\)m instead of 1.5\(\mu\)m). Thus an adjusted depth was chosen to compensate for the higher sputter rate.

The desired area was milled in four steps. Each time the sample was rotated over an angle of 45°. This is done in order to avoid the differences in height between the grains of the same beam caused by different orientation.

*Before milling*

![Images taken with the sample untilted (A,B) and 45° tilted (C) displaying the 150 \(\mu\)m structure before thinning of the Al-layer.](image)

*Figure 2.16: Images taken with the sample untilted (A,B) and 45° tilted (C) displaying the 150 \(\mu\)m structure before thinning of the Al-layer.*
During and after milling the first step

Figure 2.17: Images taken during and after the first milling step.

In the picture A) it is seen that after removal of 30 nm in thickness the grains are better visible. Probably a thin oxide layer was removed which enhanced the view on the grains. In this case the sample is tilted over 45°. Pictures B) and D) are taken after removal of 250 nm in thickness. Also here the sample is tilted over 45°. Picture C) is taken after removal of 250 nm in thickness when the sample is not tilted.
During and after milling the second step

In this figure the same structures are presented as in the Fig. 2.17, but after a second material removal. Picture A) shows the structure morphology after removal of 310 nm in thickness, B) and D) after removal of 500 nm. It should be clear that in pictures A), B) and D) the sample is tilted over 45°. Picture C) represents the same as B) and D), but without the sample tilt.

Figure 2.18: Images taken during and after the second milling step.
After milling the third step

Figure 2.19: Images during and after third milling step. A), C) after removal of 750 nm in thickness. The sample is tilted 45°. B) after removal of 500 nm in thickness. The sample is not tilted.
During and after milling the fourth step

Figure 2.20: Images during and after fourth milling step. A) after removal of 860 nm in thickness. The sample is tilted 45°. B) after removal of 1000 nm in thickness. The sample is not tilted. C) after removal of 1000 nm in thickness. The sample is tilted 45°.

Based on the previous pictures, taken during different etching steps, it seems that the morphology of the Al layer is not modified. Several crystals can be followed during all (and after) the thinning steps.

Although precautions were taken (i.e. sample rotation) to avoid too large height differences in the thinned Al-layer, in all images taken with the sample tilted, surface roughness can be seen. The question is now whether this roughness is less severe compared to the modified test module in previous analysis. To determine the realized thickness removal by etching and its effect on the surface roughness, the structures have
been analysed by the white-light interferometer. In the following pictures (taken with the Zygo), the interferometry measurements are presented. The figures show the morphology of the aluminium layer before and after the etching.

**Figure 2.21:** Interferometry picture of the etched structure with respect of the anchor point.

**Figure 2.22:** Height difference between the grains of a
In Fig. 2.21 it can be seen that in this case the desired $1.5\mu m$ of the material was removed. This height difference is measured between the unchanged anchor point and the highest grains of the beam. In Fig. 2.22 the height difference between the grains of the same beam, which can be as big as $1.5\mu m$ in worst case, is shown. This means that in some cases instead of $1.5\mu m$ almost $3\mu m$ were removed. It is clear that this extreme surface roughness makes it impossible to perform any kind of representative measurements on these structures. In order to account for this problem in the future, it is recommended to modify the samples with a Ga$^+$-ion beam incidence angle of $0^\circ$ instead of the $45^\circ$ incidence angle in this case.

The second technique is the sputtering with the Ar$^+$ ions using the XPS apparatus. X-ray Photoelectron Spectroscopy known as XPS or ESCA (Electron Spectroscopy for Chemical Analysis) is mainly used for surface analysis, but the spectroscopy measurement was not the main reason for the use of this equipment. Instead, only the sputtering part of the XPS equipment is used for the material thinning. In order to do this, the structures are exposed to the Ar$^+$ ion beam (instead the Ga$^+$ ions in the case of FIB), which shoots the material particles away and by doing this etches the material away. To achieve a homogeneous material removal, the sputtering was rotational. This is different to the case of the sputtering with the FIB technique where the sample is fixed.

In Figs. 2.23 & 2.24, the surface roughness are presented respectively before and after the etching with the XPS apparatus. When both pictures are compared, it is clear that in case of the XPS etching the surface roughness is almost not influenced. The samples modified in this manner are therefore more suitable for the experiments. The amount of the removed material is also much better controlled in this case than in the case of FIB thinning.

![Surface Profile](image)

**Figure 2.23:** Surface roughness before the XPS etching.
The third technique tested in order to see whether it can be used for material thinning, is the chemical back-etching method. In fact, the same etching technique that was used to make the freestanding test structures out of the uniform layer is now used to thin down the samples. The only difference is that in this case no masks are needed. Because the etching is assumed to be isotropic it is possible to calculate how long the structures should be exposed to the etching fluid in order to be thinned. In order to thin down the structure for a micron, the structure should be etched for about 10 minutes, as etching speed is 100 nm/min. This technique works however well for the uniform layers, but it is not recommended in the case of freestanding structures as the fluid than acts on both the bottom and the topside of the metal film. This effect not only speeds up the etching process, but also completely changes the geometry of the structure (e.g. anchor point, width of the beam). This method can however be used for the sacrificial layer etching (Fig 2.3).

Previous analysis of the thinning methods shows that the second method gives the best results. That is, the thinning using the XPS apparatus is the most reliable and hence chosen for the thinning of the tested samples.

2.3 Description of the Experiments

2.3.1 Stress Measurements

During sputtering and structure processing (e.g. etching) the wafers undergo several temperature steps. These temperature changes however have a great influence on the thin fixed metal layer that is partly made freestanding. The freestanding test structures are no longer withheld by the thick substrate and are free to deform. As these are the structures
that will later be used in the applications, their stress state is measured. In order to differentiate the stresses, special test structures have been developed. Using the white light interferometry the deformation of these structures is measured and afterwards used to calculate the stresses present in the metal layer. In the following, the principle of the mechanical test structures will be elaborated.

*Cantilever beams* can be used to indicate a stress gradient over the thickness of a metal film. Defining a positive algebraic sign for tensile stress and a negative sign for compressive stress, a cantilever will bend upwards if a positive stress gradient is present (tensile stress on the bottom side of the cantilever) and downwards if the stress gradient is negative (compressive stress on the bottom side of the cantilever). Next figure depicts a SEM image of cantilever beams deformed by a stress gradient over the thickness.

![Figure 2.25: Cantilever beams (deformed by stress gradient)](image)

The stress gradient $\Delta \sigma$ over the thickness in a cantilever beam is related to the deflection of the free end $\delta$ of the beam with the length $l$ and thickness $t$ according to:

$$\frac{\sigma}{t} = \frac{E}{1-\nu} \cdot \frac{2}{l^2} \cdot \delta$$

(2.1)

In the previous relation $E$ is the material’s Young’s modulus and $\nu$ its Poisson’s ratio.

If compressive stress is present in the wafer layer it will be indicated by a deformation of the double-clamped beams, as they will buckle upwards or downwards if their length exceeds a critical length. For the determination of a compressive stress *double-clamped beams* (see Figure 2.26) are used.
According to the Euler-criterion for buckling of a beam that is clamped at both ends and has rectangular cross-section, the critical length $l_c$ for buckling at a certain (compressive) stress $\sigma$ can be calculated with the following equation:

$$l_c = \sqrt{\frac{E}{3 \cdot \sigma \cdot t}},$$

respectively

$$\sigma = \frac{E \cdot \pi^2 \cdot t^2}{3 \cdot l_c^2},$$

where the critical length can be estimated by an array of double-clamped beams with different lengths.

To achieve a deformation by tensile stress that can also be detected by VSI (Vertical Scanning Interferometry), the tensile stress has to be converted into compressive stress. This is done by ring-beam structures, which are shown in Figure 2.27 (see also Figure 2.28). The ring structures contain a thin metal ring, which is attached to the wafer at two opposing points to pick up the tensile stress. The ring structure then converts the tensile load into a compressive load for a double clamped beam inside the ring. This beam is fixed to the ring perpendicularly to an axis that is defined by the opposing attachment points of the ring. Similar to the double-clamped beams this beam will buckle up- or downward at a certain stress, if their lengths exceed a critical value.
The calculation of tensile stress using ring-beam structures will only briefly be outlined because of its rather large complexity. The complete background has been presented by Guckel et al. [3].

As mentioned above the ring-beam converts a tensile stress into a compressive stress that affects an inner beam. The efficiency of conversion is described by a ratio $\frac{R_i}{R}$ that depends on the specific dimensions of the ring-beam structure. Just as the simple double-clamped beams show a critical length for buckling, it is possible to find a critical inner radius $R_{icr}$ for buckling of the inner beam. If the width $b_b$ of the beam exceeds its thickness $t$, the beam will buckle upwards (or downwards), which is called ‘out-of-plane’-buckling by Guckel.

For the related tensile strain $\varepsilon_0$ between the attachment points of the ring, the following equation was found:

$$\varepsilon_0 = \frac{(kR)^2 \cdot \left(\frac{t}{R_{icr}}\right)^2}{12 \cdot g(R_i)}. \quad (2.4)$$

In this equation $R$ represents the averaged radius of the ring, $R_i$ its inner radius and $t$ the thickness of the material. The factor $kR$ has to be calculated from the specific dimensions of the complete structure.

According to Hooke’s law the tensile stress then is:

$$\sigma = \varepsilon_0 \cdot E, \quad (2.5)$$

where $E$ is the Young’s modulus of the material.
To be able to detect whether there is an anisotropy of the stress gradients or the stresses inside the wafer layer, all structures exist in twofold in orthonormal arrangement (x- and y-direction), where the direction perpendicular on the wafer’s flat end serves as a reference (y-direction).

2.3.2 Microbeam Bending Experiments

These experiments are performed using the continuous mode of the nanoindenter apparatus. The idea of using the indentation method arose from the realization that an indentation test is an excellent way to measure very small volumes of materials. In principle, if a very sharp tip is used, the contact area between the sample and the tip, and thus the volume of material that is tested, can be made arbitrarily small.

During this continuous indentation method, a preloaded stylus slides over the same beam surface three times. The used stylus has a radius of 20 µm and slides with the speed of 50 nm/s. In the next table an overview of the tested samples and the corresponding forces is given.

<table>
<thead>
<tr>
<th>Thickness [µm]</th>
<th>Beam Length [µm]</th>
<th>Applied Force [mN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>50</td>
<td>1.0, 2.0, 3.0</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>1.0, 2.0, 3.0</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>1.0, 1.25, 1.5, 2.0</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>0.5, 0.75, 1.0, 1.25, 1.50</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>0.5, 0.75, 1.0, 1.25, 1.50</td>
</tr>
</tbody>
</table>

Table 2.2: Experimental overview

First, the stylus makes a topography scan. This is the so-called surface-profiling step performed using a very low force (around 0.2 µN). The second scan is a sliding indentation. During this scan the stylus is loaded with a prescribed force (0.5 - 3 µN). During this step, the deformation of the beam occurs. At the end, another topography scan is made with a very low force. This scan is crucial in order to define whether or not there is plastic deformation. In the Fig. 2.29, an illustration of the measurement output is given.

Figure 2.29: Data chart of the nanoindenter test of the 50 micron long double clamped beam.
It can be seen that the second topography scan doesn’t fall together with the first topography scan. This indicates the presence of plastic deformation during the sliding indentation step.

In the next figure, the beam deformation is presented. The three graphs correspond to total, plastic and elastic deformation. In order to get these graphs, the data of the first topography scan have been subtracted form both the scratch and the second topography data. The corrected scratch data (S-T1) then represent the total deformation (both plastic and elastic) and the corrected topography data (T2-T1), the plastic deformation. The values of the elastic deformation are achieved by subtracting plastic deformation from the total deformation (S-T2). It needs to be mentioned that in this case the deformation at the tip still contributes to the total deformation.

It needs however to be mentioned that the deformation in the picture accounts for both the ‘global’ beam deformation under the applied load as for the local deformation at the indenter tip. In order to be able to compare these measurements to the model it is crucial to separate these four components of deformation – both kinds consist out of an elastic and plastic part- and arrive finally at the two tings that are of importance, namely the elastic and plastic bending deformation of the beam.

It is clear that over the length of the beam, both influences play the role. In the area of the anchor point however, there is no influence of the freestanding beam. It is therefore that the elastic and plastic deformation at the tip are calculated in this region and then subtracted from the total elastic and plastic deformation of the beam. This is done in a few steps.

![Graph](image.png)

**Figure 2.30: Corrected deformation data: total, plastic and elastic deformation.**
In the first step, the total deformation at the stylus tip is calculated through the hardness definition. If the yield stress is taken to be 100 MPa, which is acceptable in the case of aluminium, then the hardness is approximately (see Tabor [4]) equal to:

\[ H = 3Y = 300 \text{MPa}, \quad (2.6) \]

with \( Y \) the Yield stress.

If the area is considered to be circular, then the hardness definition yields:

\[ H = \frac{P}{A} = \frac{P}{(\pi a^2)}, \quad (2.7) \]

where \( P \) is the force applied on the tip.

From the previous expression, the area of the indenter tip can be calculated.

\[ A = \frac{P}{H} = \frac{10^{-3}}{300 \cdot 10^6} = 0.3 \cdot 10^{-11} = \pi a^2 \quad (2.8) \]

The rule of Pythagoras based on the Fig. 2.32 gives:

\[ a^2 + (R-h)^2 = R^2. \quad (2.9) \]

Combining the expressions (2.8) and (2.9) and neglecting the small values gives the next expression for the value \( h \). If the force is taken to be equal to 1mN and the radius of the stylus is 20 micron, it is possible to calculate the value of \( h \) in Fig. 2.32.
This value gives an idea about the value of the deformation at the tip and when compared to the total deformation in Fig. 2.31, it is clear that the deformation at the tip cannot be neglected. It wasn’t however possible to make any useful SEM pictures of the influence of the tip deformation because all the beams were destroyed after nanoindenter testing.

If the Hertzian pressure is used to estimate the deformation at the tip in the case of aluminium, the value is slightly lower but still not to be neglected. This calculation is presented in the next expression:

\[
h = \left( \frac{3}{4} \frac{P \cdot R^{-\frac{1}{2}}}{E_E} \right)^{\frac{2}{3}} = 17\text{nm.} \tag{2.11}\n\]

In the previous expression, \( P \) is the applied load, \( R \) the radius of the indenter tip and \( E \) the Young’s modulus for aluminium. Based on the previous research it is taken to be 70MPa.

As these values are only an indication of the deformation at the indenter tip, further analysis of the measurement data is needed in order to determine the elastic and the plastic deformation at the tip. If the total deformation is taken to be:

\[
h = h_{\text{tip,el}} + h_{\text{tip,pl}} + h_{\text{beam,el}} + h_{\text{beam,pl}}, \tag{2.12}\n\]

then the (total) beam deformation equals:

\[
h_{\text{beam}} = S - (h_{\text{tip,el}} + h_{\text{tip,pl}}), \tag{2.13}\n\]

where \( S \) represents the total deformation as presented in Fig. 2.30 and 2.31, without and with correction respectively.

The deformation at the tip is based on the date of the anchor point, as there is no beam bending present. For the estimation of the elastic and plastic deformation at the tip, next expressions are used:

\[
\left\langle h_{\text{tip,el}} \right\rangle = \left\langle S - T2 \right\rangle, \tag{2.14}\n\]

\[
\left\langle h_{\text{tip,pl}} \right\rangle = \left\langle T2 - T1 \right\rangle, \n\]

where \( S - T2 \) and \( T2 - T1 \) represent the corrected values of respectively the elastic and the plastic deformation as presented in Fig. 2.31.
These average values of the anchor area will then be subtracted from the data in the beam area to get the values of the elastic and the plastic deformation of the beam. This is done using the following expressions:

\[
\begin{align*}
h_{\text{beam,el}} &= (S - T2) - \left(h_{\text{tip,el}}\right) \\
h_{\text{beam,pl}} &= (T2 - T1) - \left(h_{\text{tip,pl}}\right),
\end{align*}
\]

(2.15)

where S-T2 and T2-T1 represent the corrected values of respectively the elastic and the plastic deformation as presented in Fig. 2.31.

In the following figure the calculated values of the elastic and the plastic deformation of the beam are presented. In this case there is hardly any plastic deformation of the beam present, so it can be supposed that all the plastic deformation is located at the tip.

Figure 2.32: Plastic and elastic beam deformation
3 Experimental Results

3.1 Introduction

In the previous chapter the performed experiments have been elaborated in detail, from the sample preparation to the measuring method. This chapter gives an overview of the experimental outcome. Besides the presentation of the results, the attention will also be given to the most striking effects by short description. The detailed analysis of those is for the next chapter together with the comparison to the theory (i.e. the numerical model).

3.2 Stress Measurement Results

For this kind of measurements, the processed wafers without thinning have been used. Therefore the thickness of the metal layer is in all the cases 5 micron. The outcome of these measurements should define the initial stress state of the metal layer as a result of the test structure processing. The stress values, as calculated from the deformation of the dedicated test structures, will be given.

PASSI-I Wafers

The INT material of these wafers is pure aluminium. In the Figure 3.1, the outcome of the interferometry measurements is presented. It can be seen that the double-clamped beams are not flat. Referring to the working principle of the mechanical test structures, this indicates that there should be compressive stress present in the INT layer. Because there are two sets of these structures on the same wafer, it is possible to distinguish the stress state in both the x- and the y-direction. In this case however all the beams are deformed. This makes it impossible to say anything more about the compressive stress value in the layer.

![Figure 3.1: Interferometry result of double-clamped beams](image1)

![Figure 3.2: SEM photo of ring-beam structures](image2)

Apart from the double clamped beams also another set of mechanical test structures, the ring beams, is examined. Figure 3.2 shows a SEM picture of these structures. The structures are broken because of the bad fitting of the masks during the lithography process. It is clear that based on the state of these structures, nothing about the value of the tensile stress in the metal layer of the PASSI-I wafers can be said.

Finally, the value of the stress gradient over the metal layer is examined. This is based on the deformation of the cantilever beams. As in the case of the double clamped
beams, also here the deformation takes place in both the x- and the y-direction. The average value of the stress gradient over the thickness of the beams is computed from this deformation and equals $\Delta \sigma = 28.36MPa$.

**PASSI-II Wafers**

When compared to the PASSI-I batch, the quality of the PASSI-II wafers is much better, meaning that there is no severe damage present of the mechanical test structures. Also in this case, the double-clamped beams are deformed in both the x- and the y-direction (see Fig. 3.3). As these structures are used to deduce the compressive stress, this indicates the presence of the compressive stress in the metal layer. Also in this case it is difficult to give an average value of the compressive stress since all the double clamped beams seem to be deformed.

![Figure 3.3: Double-clamped beams](image)

The ring-beam structures of the PASSI-II batch are presented in the Figures 3.4. It can be seen that also these structures present deformation in both the x- and the y-direction. As they also deform apart from the middle beam, their interpretation in terms of the tensile stress measurement should be done with great care.

![Figure 3.4: Ring-beam structures (PASSI-II wafers)](image)

Figure 3.5 depicts the measured maximum displacement of the structures as a function of their radius.
The analysis presented in Fig. 3.5 should indicate from which radius onwards the ring beams deform. As each ring beam radius is related to another value of the tensile stress, this should indicate the present tensile stress in the metal layer. In this case however, all the ring beams seem to show a certain amount of deformation. This indicates the presence of a tensile stress. This is quite unexpected as in the same layer already compressive stress was measured. Obviously, it is not possible to have both tensile and compressive stress at the same time.

To determine the stress gradient over the thickness, the deformation of the cantilever beams is examined. In this case, the cantilever beams are deformed upward. The average stress gradient over the thickness of the beams equals $\Delta \sigma = 25.63 \text{MPa}$. It needs to be mentioned that the ring-beam structures are also sensitive to stress gradients, and this may interfere largely with the tensile stress measurements with these structures.
3.3 Microbeam Bending Experiments

In this part all the results of the bending experiments will be presented and described qualitatively. An overview of these experiments has already been given in Table 2.2. During the analysis it will be clear that not all the measurements are to be trusted. However, a possible explanation will be given for the ‘strange’ effects. The conclusion, which is given in Chapter 5, is only based on what are considered to be reliable results.

3.3.1 Thickness = 5 micron, length = 50 micron

Figure 3.7: Plastic and elastic deformation of the 50 micron long beam with the load of 1, 2 and 3 mN, respectively.
In Fig. 3.7 the elastic and the plastic deformation of the beam are presented. From the picture it is clear that in the case of a 1 mN load, there is hardly any plastic deformation of the beam present. As already explained in the previous chapter, the explanation for this effect could be the fact that all the plastic deformation is located at the indenter tip. The next effect is the roughness in the measurements, which is probably caused by the surface itself. It cannot be linked to the thinning methods, as it is also present in the case of the unchanged 5-micron thick samples.

When the applied load is increased to the value of 3 mN, some interesting things can be seen. In this case it seems like there is only plastic deformation of the beam present, which has increased with the increasing load. When elastic deformation plot is examined, a strange dimple near the anchor point is seen. In order to try to find an explanation for this effect, the raw measurement data are examined. These are presented in Fig. 3.8.

![Figure 3.8: Raw experimental data of the 50 micron long beam (P = 3 mN)](image)

From this figure it is clear that with the applied load, the maximum deflection of the beam (which is in this case the 1.4 micron gap) or the touch-down has been reached. But this still doesn’t explain the strange effect near the anchor point. As the beam deformation in Fig. 3.7 seems to go in the positive direction, it is possible that the beam has come loose from the anchor. This could be caused by the indenter tip, which pushes the beam when crossing from the lower anchor to the higher beam (see also Fig. 2.8).

3.3.2 Thickness = 5 micron, length = 75 micron

In the case of the 75 micron long beam, similar evolution of the plastic and elastic deformation can be seen. The main difference is that in the case of the longer beam plastic deformation occurs earlier, i.e. under the lower applied load.
Figure 3.9: Plastic and elastic deformation of the 75 micron long beam with the load of 1, 2 and 3 mN, respectively.
As the same strange ‘dimple’ effect is present as in the case of the 50 micron long beams, the same explanation can be used. As an illustration of this effect, the raw measurement data are presented in Fig. 3.10.

![Graph showing raw experimental data of the 75 micron long beam (P = 3 mN)](image)

**Figure 3.10: Raw experimental data of the 75 micron long beam (P = 3 mN)**

3.3.3 Thickness = 5 micron, length = 100 micron

In the case of the 100 micron long beams, the same effects can be seen as in the case of 50 and 75 micron long beams. The only difference is that in this case, as the beams are longer and therefore less rigid, the dimple effect and the maximal deformation are achieved with a lower load. In Fig. 3.11, an overview of the results is given.
Figure 3.11: Plastic and elastic deformation of the 100 micron long beam under different loads.
3.3.4 Thickness = 4 micron, length = 50 micron

Figure 3.12: Plastic and elastic deformation of the 100 micron long beam under different loads.
In the last picture of Fig. 3.12, the dimple effect can be seen. It is interesting to mention that this is the load where 100 micron long and 5 micron thick beam starts to show the same effect. Fig. 3.13 shows the raw data for this case.

Figure 3.13: Raw measurement results in the case of the 50 micron long beam (P = 1.25 mN)
3.3.5 Thickness = 3 micron, length = 50 micron

In Fig. 3.14 an overview of the experimental results for the 3 micron thick films is given. It needs to be mentioned that only the situation till the first dimple appearance is presented, because afterwards the deformation state stays the same.

Figure 3.14: Plastic and elastic deformation of the 100 micron long beam under different loads.
4 Numerical Analysis

4.1 Introduction

As already discussed in the introduction part, the main aim of this study is to analyse whether or not there are scaling effects present in the tested aluminium thin films. The experimental set-up and measurement results have respectively been described in Chapters 3 & 4. In order to analyse the presence of the scale effects, the experimental output is then compared to the theoretical model. For this purpose the conventional finite element method (FEM) software Ansys is used. The analytical model would be too simplistic, especially when considering the complex geometry (e.g. the anchor shape). More advanced models, like the atomic ones, are too complicated for the first analysis.

In the following parts the numerical model build-up and the necessary assumptions will be described. At the end of the chapter an overview of the numerical data will be given.

4.2 Numerical Model

In order to be able to make a serious comparison between the measurements and the theory great care is given to the meshing part. In the following the meshing, the used elements and the loading strategy will be elaborated in detail.

4.2.1 Meshing

The geometry build-up in this case is based on the FIB cross sectional analysis described in Chapter 2 (see Fig. 2.7). This detailed FIB examination of the test structures showed that the etching steps during the processing had a relevant influence on the suspension of the tested beams.

The modelled sample part consists out of the aluminium beam and the silicon substrate. To account for it, the mesh is three dimensional and composed out of different building blocks (volumes). This approach greatly simplifies the mesh building.

In the next picture the geometry of the numerical model is depicted. It can be seen that a part of the beam anchor is freestanding as in Fig. 2.7.

Figure 4.1: Illustration of the used mesh geometry.
4.2.2 Nonlinear Analysis

Most engineering problems contain nonlinear effects. In the same way that users must select material before setting a solver to run, nonlinear analysis calls for selecting a material model. This consists of a series of algorithms that describe how the material behaves under stress and temperature. For nonlinear analysis, the table presents a few material models and description of where they work best.

<table>
<thead>
<tr>
<th>MATERIAL CLASSIFICATION</th>
<th>MODEL</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastoplastic</td>
<td>von Mises or Tresca</td>
<td>These models work for most metals and plastics that will be loaded beyond their elastic range. For metals that undergo work hardening, select the isotropic or kinematic hardening condition in the software.</td>
</tr>
<tr>
<td></td>
<td>Drucker-Prager</td>
<td>This model works for soils and granular materials.</td>
</tr>
<tr>
<td>Hyperelastic</td>
<td>Mooney-Rivlin and Ogden</td>
<td>Use these to model incompressible elastomers such as rubber.</td>
</tr>
<tr>
<td></td>
<td>Blatz-Ko</td>
<td>This model works for compressible polyurethane foam rubbers.</td>
</tr>
<tr>
<td>Viscoelastic</td>
<td>Generalized Maxwell</td>
<td>This model works for hard rubber or glass.</td>
</tr>
</tbody>
</table>

Table 4.1: Material models

In our model the bilinear kinematic hardening has been implemented. This is an elastoplastic material model where the plastic deformation is described using the von Mises/Tresca criterion.

![Bilinear kinematic hardening](image)

Figure 4.2: Bilinear kinematic hardening

In the previous picture, slope m represents the hardening. In order to fit the experimental results, the model parameters (e.g. yield stress, Young’s modulus) have been varied. The optimized values are then used to perform the simulations.
4.2.2 Loading Strategy

As already explained in Chapter 2, the step in which the prescribed load is applied on the beam is the so-called sliding indentation. This step is modelled in Ansys. To describe the continuous movement of the indenter tip, a load moving in discrete steps is used. This load as applied in Ansys is illustrated in Fig. 4.3.

![Figure 4.3: Applied load in ansys](image)

The main difference between the sliding indentation and the approximation by discretely applied loads is the unloading between the loads. It is therefore crucial to show that during this *unloading* no significant plastic deformation occurs.

Fig. 4.4 tests the reliability of the assumption. It shows the difference in plastic deformation between position 6 and position 7. It is also clear that the deformation is concentrated at the indenter tip, which was already indicated in the experiments. This means however that this assumption does not hold in this case.

![Figure 4.4: Difference in plastic deformation between the succeeding load positions.](image)

Another assumption is the approach of the indenter tip by a point load. The manner in which a force is applied can for example vary between a line force (line perpendicular to the length
direction) and a point force. In reality the stylus of the indenter has a certain radius, which determines in which way the force acts and the how the immediate neighbourhood deforms.

The Hertzian contact pressure is a helpful tool to determine the contact area of the stylus. This number will give clearance whether the force acts in a point or over a line. The value of the contact depth however will play an important role when the influence of the (plastic) deformation of the tip is estimated (this in the comparison with the experimental results).

The formula of the contact pressure is as follows:

\[
P_H = \frac{4}{3} \sqrt{R E_r} h^{3/2},
\]

where \( P_H \) is the applied force, \( R \) is the radius of the stylus, \( E_r \) is the effective modulus of elasticity and \( h \) is the contact depth.

If a force of \( 1 \text{mN} \) is applied on an aluminium double clamped beam with a width of \( \text{26\mu m} \) and a Young’s modulus of \( 70\text{GPa} \), and it is known that the radius of the stylus is \( \text{25\mu m} \), the measured contact depth is:

\[
h = \left( \frac{3P_H}{4\sqrt{R E_r}} \right)^{2/3} = 17\text{nm}.
\]

In order to calculate the contact area of the stylus, the next steps should be performed. First the radius \( a \) of the contact area is determined using the rule of Pythagoras (see Fig. 2.31 and expression (2.9):

\[
a^2 = 2Rh.
\]

The next step is to calculate the contact area \( A \):

\[
A = \pi a^2 = 2.67\text{\mu m}^2.
\]

The value of the calculated contact area is in the range of several square microns and thus it is reasonable to assume that the applied force acts in a point.

4.3 Numerical Results

4.3.1 Beam bending

4.3.1.1 Parameter estimation

Before carrying out the experiment-based simulations, the parameters of the used material model have been estimated. After the comparison to the experimental reference, a set of material parameters, which will be used in the rest of the simulations, has been defined.

First the value of Young’s modulus is estimated. The tested values are 60, 70 and 80 GPa. As a reference the ‘elastic’ microbeam bending experiment has been chosen, i.e. the 5 micron thick 50 micron long beam with the applied load of 1 mN.
In the picture below the output of the reference microbeam bending experiment is given. The plastic deformation in this case is around zero, which means that the total beam deformation equals the elastic deformation in this case.

![Graph showing beam deflection vs position](image)

**Figure 4.5: Plastic and elastic deformation of the beam (experiment).**

In the following pictures the total beam deformation (plastic and elastic part) is presented in the case the yield stress equals 200 MPa and the Young’s modulus 60, 70 and 80 GPa, respectively. Like in the case of the experiment, the considered beam thickness is 5 micron and the length 50 micron.

![Graphs showing beam deflection vs position for different Young’s moduli](images)

**Figure 4.6: Estimation of the Young’s modulus.**
In Fig. 4.6 it can be seen that the total beam deformation decreases as the value of the Young’s modulus increases. In the figure below this trend is depicted together with the measured deflection and its ‘expected’ value of the Young’s modulus.

![Young's modulus vs deflection](image)

Figure 4.7: Young’s modulus vs maximal deflection (trend based on the numerical data).

The value of the modulus based on the trend and the deflection of the beam seems to be even higher than 80 GPa. This is however too high in the case of aluminium. An explanation could be found in the fact that in the model several assumptions have been made. The assumptions concerning the load application have been discussed earlier. Another assumption is concerning the initial stress present in the samples (as seen in the interferometry analysis). This stress has not been accounted for. Small differences in the beam dimensions (e.g. thickness) between the model and reality can also greatly influence the deflection values. Deflection is however a function of the third power of thickness.

It needs however to be mentioned that in this case the difference between the model and experiments is around 20 %, which is rather good for experiments. This is why in the rest of the simulations the same value of 70 GPa for the elastic modulus (as in the experiments), is used.

Secondly, the value of the yield stress is estimated. The tested values were 150, 200 and 250 MPa. The measurements used as a reference are the microbeam bending experiments on the 5-micron thick beams with the load of 2 mN.

![Plastic and elastic deformation of the beam](image)

Figure 4.8: Plastic and elastic deformation of the beam (experiment).
In Fig. 4.9 the results of the numerical parameter estimation of the yield stress are presented.

To compare the measurement results to the model, the sum of the plastic and elastic deformation should be used as the total beam deformation. In the following picture an overview of the measured data and the model is given.

![Yield stress vs deflection](image)

Figure 4.9: Estimation of the Yield stress.

To compare the measurement results to the model, the sum of the plastic and elastic deformation should be used as the total beam deformation. In the following picture an overview of the measured data and the model is given.

![Yield stress vs maximal (absolute) deflection](image)

Figure 4.10: Yield stress vs maximal (absolute) deflection (trend based on the numerical data).
The value of the yield stress that could describe the experimental value of deflection has been extrapolated based on the numerical data. In reality it was not possible to test this numerically because of the convergence problem that occurred when values of yield stress below 100 MPa were used. The reason behind the convergence problem was not found.

In the rest of the simulations, the value of 200 MPa for yield stress is used.

### 4.3.1.2 Comparison with Experiments

**Thickness = 4 micron, Load = 0.5 mN**

First the experiments on the 4-micron thick samples will be described. The experimental data is therefore directly compared to the numerical. In the following pictures the experimental and numerical data are shown.

**Figure 4.11: Plastic and elastic deformation of the beam.**

**Figure 4.12: Numerical data.**

When the maximal deflection of the experiment is compared to the model, it can be seen that the experimental value is higher (260 nm vs 60 nm!). It needs however to be mentioned that in the numerical analysis there is no plastic deformation present and thus the presented value account only for the elastic deformation (130 nm vs 60 nm). As the difference in the results is
rather high, it could be caused by the use of the estimated material model parameters, especially the chosen yield stress. The latter may explain the lack of plastic deformation in the numerical results, as in this case the value of the yield stress is higher.

**Thickness = 4 micron, Load = 0.75 mN**

In the figures below, the experimental and numerical data of the 4-micron thick beam are presented for the applied load of 0.75 mN. With the increasing load also the plastic deformation in the experimental data increases compared to the previous case where the applied load was 0.5 mN.

![Figure 4.13: Plastic and elastic deformation of the beam.](image)

As in the previous case, similar discrepancies can be found in the data comparison. The difference between this and the previous case is the fact that the model shows also plastic deformation.

![Figure 4.14: Numerical data.](image)
Thickness = 3 micron, Load = 0.5 mN

The following pictures show the deflection as a result of the 0.5 mN load in the case of the 3-micron long beam. This load causes the beam to deform both elastically as plastically.

Figure 4.15: Plastic and elastic deformation of the beam.

Figure 4.16: Numerical data.

When the maximum deflection of the experiments and the model are compared, the same effect as in the previous cases can be seen. This means that also in this case the deflection in the case of the experiments is higher than in the case of the numerical model. The possible explanation for this effect remains the same.
Thickness = 3 micron, Load = 0.75 mN

As expected, the increased load is responsible for the increase in plastic deformation. The difference in data is still present, i.e. the deflection in the case of the experiments is higher than the one in the model.

Figure 4.17: Plastic and elastic deformation of the beam.

Figure 4.18: Numerical data.
From the previous comparison it is clear that the difference in the beam deflection in experiments and the model is that high that it cannot be contributed to the measurement errors (which could be as high as 20%). This discrepancy in the output data could therefore be caused by the assumptions on which the numerical analysis is based (e.g. the point load and the residual stress input).

To see what the influence of the residual stress would be, a simulation with a compressive stress is performed. The compressive stress influences the beam deflection in a positive manner, which leads to the higher deflection values.

The parameter estimation on the other hand suggested the use of a lower value for the yield stress, around 50 MPa instead of the assumed 200 MPa (Fig. 4.10).

In the Fig. 4.19 a comparison between the different values of the yield stress and the influence of the compressive residual stress is presented.

From the last picture in Fig. 4.19 it is clear that the combination of the low yield stress and the compressive residual stress have a positive influence on the deflection value. The gap between the experiments and the numerical data is however still big. The model set-up makes it however impossible to assign these effects to the influence of the length scales.
5 Conclusions & Recommendations

This chapter will give an overview of all the conclusions and provide recommendations for future research. Before doing this some general remarks about the set-up of this work needs to be given. It needs to be mentioned that the microbeam bending experiments that were carried out on the polycrystalline freestanding metal films are quite unique in its kind, form the use of the indenter apparatus to carry out the experiments to the specially processed test structures. The build up of the experiment out of two topography scans with a low load and a sliding indentation with the prescribed load, gives the possibility to split the plastic and elastic deformation of the beam and follow the way they progress with increasing/decreasing load.

The thinning of the samples made it possible to separate the influence of the film thickness and the grain size. The microstructure of the tested samples is kept the same while the thickness varies between 3 and 5 micron. To keep the microstructure the same while the thickness of the samples changes, special thinning methods were investigated. The used techniques consisted of FIB- and XPS- ion sputtering and in much less amount the chemical back-etching. The latter technique works well for the uniform layers. In the case of the freestanding structures it can only give reliable results when used for the sacrificial layer etching with a dedicated set of masks.

In the case of the thinning using the FIB apparatus (sputtering with Ga+ ions), the measured height difference between the grains of the same beam was as big as $1.5 \mu m$. This means that when in average $5.1 \mu m$ of the material is removed by etching, in some cases almost $3 \mu m$ was removed. It is clear that this extreme surface roughness makes it impossible to perform any kind of representative measurements on these structures. In order to account for this problem in the future, it is recommended to modify the samples with a Ga+ ion beam incidence angle of 0° combined with the rotation of the sample. Another thinning technique was the sputtering with the Ar+ ions using the XPS apparatus. In this case the surface roughness almost remained unchanged. The samples modified in this manner are therefore more suitable for the experiments. The amount of the removed material is also much better controlled than in the case of FIB thinning.

Before the experiments on the test structures were performed, the stress state of the metal layer was investigated. The interferometry analysis showed the presence of the compressive stress in the metal layer: the double clamped beams were deformed. This is however quite strange as the sputtered uniform films on Si substrates always have a tensile residual stress (conform previous research). So the explanation of the suggested compressive stress (material is jammed together) does not hold, since this effect is always overruled by the thermal expansion mismatch stresses that develop during the cooling down to room temperature from the sputtering temperature. It is still very remarkable that the DCB’s seem to indicate a compressive stress, considering the previous point. The deformation of the DCB’s is probably not so much caused by the stress during sputtering, but by deformation during the sacrificial layer etching: this happens at higher temperatures, which causes the beams to deform, and if the yield strength is exceeded, the beams will be permanently deform and will not return to their original shape. The deformed shape is therefore specific for the geometry of the beam. Another test structure used to measure stresses is the “rotating beam” and this test structure always indicates a tensile stress, even on wafer on which the DCB’s are also deformed. Obviously, it is not possible to have both tensile and compressive stress ate the same time. What is clear is that the deformation of one particular structure cannot be translated to a stress in another structure.
in the case when plastic deformation occurs during processing, since merely due to the
difference in geometry, the structures have seen different loading histories.
The ring-beam structures are also sensitive to stress gradients, and this may interfere largely
with the tensile stress measurements with these structures. The stress measurements are
therefore not consistent and nothing about the value of the residual stress could be concluded.

The microbeam bending experiments form the core of this work and they are directly
compared to the numerical data. When the plastic deformation increases, a strange ‘dimple’
effect near the anchor point could be seen. When the raw measurement data are analysed, it is
seen that this occurs in the case of the beam touch-down or really close to it. But this still
doesn’t explain the strange effect near the anchor point. As the beam deformation in this case
seems to go in the positive direction, it is possible that the beam has come loose from the
anchor. This could be caused by the indenter tip, which pushes the beam when crossing from
the lower anchor to the higher beam.
In order to extract the beam deformation from the total deformation of the experiment, the
influence of the indenter tip, which seemed to have an important role, has been subtracted.

The most relevant scan is the sliding indentation in which the prescribed load is applied on the
beam. This part of the experiment is modelled in Ansys by discretely applied loads. This
approximation however has an influence on the beam deformation, especially the plastic one
that seems to be concentrated at the load action point. This illustrates also in this case the
importance of the influence of the indenter tip. The strange ‘dimple’ effect from the
experiments could not be seen in the numerical results. It could be caused by another force
component (e.g. horizontal force). The modelled force is a point load with only one
component in the y-direction.
In order to fit the experimental data, the material model parameters were estimated. This fit
showed that the yield stress in reality lies much lower than first assumed. This however could
be expected in the case of pure aluminium. The parameter estimation suggested a lower value
for the yield stress, around 50 MPa instead of the assumed 200 MPa.

From the previous comparison it is clear that the difference in the beam deflection in
experiments and the model is that high that it cannot be contributed to the measurement errors
(which could be as high as 20%). This discrepancy in the output data could therefore be
caused by the assumptions on which the numerical analysis is based (e.g. the point load and
the residual stress input). The gap between the experiments and the numerical data is big. The
model set-up makes it however impossible to assign these effects to the influence of the
length scales. That is why this work is mainly an explorative investigation of the possibility of
using microbeam bending experiments to assess length scale properties of polycrystalline
metal thin films.

Based on the previous conclusions, some recommendations for the future research can be
given. First it is recommended to optimize the (etching) mask design in order to improve the
region around the anchor points. Right now, a part of the beam anchor is freestanding and
influences the beam deflection as a result of the applied load. It could be also interesting to
design new mechanical test structures, which will be less sensitive to other stress components,
like stress gradients and in that way give a more clear view of the stress state in the metal
layer.
The microbeam testing on the nanoindenter apparatus should and could be further explored in order to make more dedicated experiments. Apart from several strange effects, which might be only geometry dependent, it gives nice illustration of the beam behaviour under loading. The used material model in the numerical analysis gives a nice (first) impression. It could be even better if some pure numerical problems (e.g. load application) are solved. The use of more advanced models is only interesting when both the samples and the experiments are optimized. Therefore much attention should be given to the processing of the mechanical test structures and the implementation and the role of the processing (temperature) steps on the deformation process.
Appendix

Ansys

A.1 Input file

/filnam, double_clamped_beam
/prep7

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!*---------------------------------------------------------------------*
!*GEOMETRICAL PARAMETERS************
!*---------------------------------------------------------------------*

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

Adjustable parameters:
!units: microns and microN

load=-1e3 !total load (micronewton)
beam_l=50 !beam length
beam_w=26 !beam width
beam_t=5 !beam thickness
anchor_l=40 !anchor length
anchor_w=80 !anchor width
si_l=40 !silicon anchor length
si_w=80 !silicon anchor width
gap=5 !gap under beam
substr_t=20 !substrate thickness
mod_l=5 !modified anchor length
mod_t=1.4 !modified anchor height

!positie puntkracht
ndivis=10
xbkracht=-beam_l/2
xekracht=beam_l/2
xstep=(xekracht-xbkracht)/ndivis

zkracht=0
ykracht=substr_t+gap+beam_t

beam_free_l=beam_l-(si_l-anchor_l) !length of free part of beam
total_l=beam_free_l?*si_l !total length of structure

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

building the geometry

!nodes for load applications
*do,j,0,ndivis
n,,xbkracht+j*xstep,ykracht,zkracht
*enddo

!substrate
yb=0
xe=substr_t
xb=-total_l/2
xe=total_l/2
zb=-si_w/2
ze=si_w/2
block,xb,xe,yb,ye,zb,ze

!metal anchors I
xb=-total_l/2
xe=xb+(si_l-mod_l)
yb=substr_t
ye=yb+gap
zb=-si_w/2
ze=si_w/2
block,xb,xe,yb,ye,zb,ze

xb=total_l/2-(si_l-mod_l)
xe=xb+(si_l-mod_l)
yb=substr_t
ye=yb+gap
zb=-si_w/2
ze=si_w/2
block,xb,xe,yb,ye,zb,ze

!metal anchors II
xb=-(beam_l/2+anchor_l)
xe=xb+(anchor_l-mod_l)
yb=substr_t+gap
ye=yb+beam_t-mod_t
zb=-anchor_w/2
ze=anchor_w/2
block,xb,xe,yb,ye,zb,ze

xb=beam_l/2+mod_l
xe=xb+(anchor_l-mod_l)
yb=substr_t+gap
ye=yb+beam_t-mod_t
zb=-anchor_w/2
ze=anchor_w/2
block,xb,xe,yb,ye,zb,ze

!metal anchors III
xb=-(beam_l/2+mod_l)
xe=xb+mod_l
yb=substr_t+gap
ye=yb+beam_t
zb=-anchor_w/2
ze=anchor_w/2
block xb xe yb ye zb ze

xb=beam_l/2
xe=xb+mod_l
yb=substr_t+gap
ye=yb+beam_t
zb=-anchor_w/2
ze=anchor_w/2
block xb xe yb ye zb ze

!beam

xb=-beam_l/2
xe=beam_l/2
yb=substr_t+gap
ye=yb+beam_t
zb=-beam_w/2
ze=zkracht
block xb xe yb ye zb ze

xb=-beam_l/2
xe=beam_l/2
yb=substr_t+gap
ye=yb+beam_t
zb=zkracht
ze=beam_w/2
block xb xe yb ye zb ze

vglue all

!Define element
!See the Ansys element manual
!structural solid
et 1 solid95

!Meshing parameters:
allsel all
mshkey 0 !free meshing
!smrtsize 6
smrtsize 4
mshape 1 3D

!materials
/input materials inp

!substrate
mat,1
type,1
vsel,s,loc,y,0,substr_t
cm,substrate,volume
vmesh,all

!metal anchors
mat,4
type,1
vsel,s,loc,y,substr_t,substr_t+gap
cm,al_anchors,volume
vmesh,all

!aluminium beam
mat,4
type,1
vsel,s,loc,y,substr_t+gap,substr_t+gap+beam_t
cm,aluminium,volume
vmesh,all

allsel,all
nummrg,node

!loading

!******************************************************************************
!*****START OF LOADING************
!******************************************************************************

fini
/solu

nlgeom,on !nonlinear geometric effects (large deformations)
nsubst,10 !number of substeps in analysis
autots,on !automatic load incrementation
!neqit=25 !number of equil. iterations at each substep
!ncnv,... !controls program termination (e.g. at CPU limit)
pred,on !predictor
outres,all,all !control of output results (default only last subst)

!boudary conditions

nset,s,loc,y,0,0 !bottom plane fixed
d,all,ux,0
d,all,uy,0
d,all,uz,0
allsel
moving load

!*do,j,0,ndivis
!nsel,s,loc,x,xbracht+j*step
!nsel,r,loc,z,zkracht
!nsel,r,loc,y,ykracht
f,all,fy,load
allsel
solve
fdele,all
*enddo

nsel,s,loc,x,xekracht
nsel,r,loc,z,zkracht
nsel,r,loc,y,ykracht
f,all,fy,load
allsel
solve
fdele,all

finish

A.2 Material file

*=================================================================
* ** MATERIAL PARAMETERS       ********
*=================================================================

substrate

MATERIAL NUMBER 1
!linearly elastic
!(E,nu,alpha)
!room temperature data
!Young’s modulus E=140e3 N/mm^2
!Poisson’s ratio nu=0.2
!thermal expansion coefficient: alpha=5E-6
!no temperature dependence

mp,ex,1,140e3
mp,prxy,1,0.2
mp,alpx,1,5E-6

resist
MATERIAL NUMBER 2
(linearly elastic)
(E,nu,alpha)
(room temperature data)
Young's modulus $E = 3 \times 10^3$ N/mm$^2$
Poisson's ratio $\nu = 0.3$
thermal expansion coefficient: $\alpha = 16 \times 10^{-6}$
(no temperature dependence)

\[
\begin{align*}
\text{mp,ex,2,} & \quad 4.3\times10^3 \\
\text{mp,prxy,2,} & \quad 0.3 \\
\text{mp,alpx,2,} & \quad 16\times10^{-6}
\end{align*}
\]

MATERIAL NUMBER 3
(linearly elastic)
(E,nu,alpha)
(room temperature data)
Young's modulus $E = 70 \times 10^3$ N/mm$^2$
Poisson's ratio $\nu = 0.3$
thermal expansion coefficient: $\alpha = 16 \times 10^{-6}$
(no temperature dependence)

\[
\begin{align*}
\text{mp,ex,3,} & \quad 70\times10^3 \\
\text{mp,prxy,3,} & \quad 0.3 \\
\text{mp,alpx,3,} & \quad 16\times10^{-6}
\end{align*}
\]

MATERIAL NUMBER 4
(aluminium, no temperature dependence)
elastic-plastic, bilinear kinematic hardening
(E,nu,alpha,Y,m)
(room temperature data): 
Young's modulus $E = 70 \times 10^3$ N/mm$^2$
Poisson's ratio $\nu = 0.3$
thermal expansion coefficient $\alpha = 16 \times 10^{-6}$ K$^{-1}$
yield stress $Y = 200$ N/mm$^2$
tangent modulus $m = 14 \times 10^3$ N/mm$^2$
temperature dependence: no
A.3 Other Ansys Plots

In this part some pictures of the numerical analysis will be presented. Some examples are the pictures of the deformed beam during loading and the evolution of the plastic deformation. They can help to learn more about the loading part of the model.

In the following pictures the stress state of the beam is illustrated. All the pictures are taken when the load acts in the middle of the beam.

Figure A.1: Deflection in the case of centrally applied load.
It can be seen that the highest stress values are situated around the connection between the anchor points and the freestanding beam.

Figure A.2: The stress in the x-, y- and z-direction, respectively.

Figure A.3: The equivalent elastic strain.
The elastic deformation takes place in the immediate neighbourhood of the indenter tip and in the contact area between the anchor and the beam. When looking at the plastic deformation (Fig. 4.4) and the general stress values (Fig. A.2) in the three directions, it can be concluded that the deformation is (mainly) concentrated at the load action point.

B Electrostatic Modelling

B.1 Introduction

Pull-in phenomenon is a discontinuity related to the interplay of the elastic and electrostatic forces. When a potential difference is applied between a conducting structure and a ground level the structure deforms due to electrostatic forces. The elastic forces grow about linearly with displacement whereas the electrostatic forces grow inversely proportional to the square of the distance. When the voltage is increased the displacement grows until at some point the growth rate of the electrostatic force exceeds that of the elastic force and the system cannot reach a force balance without a physical contact, thus pull-in occurs. The critical voltage is known as the pull-in voltage. The pull-in phenomenon is of great practical importance in the design of micro-electro-mechanical (MEMS) sensors and switches, for example.

The determination of the pull-in voltage and position requires the solution of a coupled electrostatic-elastic system. Traditionally the pull-in analysis is done using voltage iteration (VI), which is a method of brute force. In the method the potential difference is gradually increased and for each value the coupled problem is solved iteratively. If a solution is obtained then the voltage is below the pull-in voltage otherwise the opposite is true. This scheme has no physical limitations but it is computationally very expensive. Around the pull-in position the convergence of the coupled problem may be slow. The accuracy of the scheme is determined by the step-size of the scanning. Economical and reasonably accurate scanning strategies usually require some initial estimate of the pull-in voltage.

The most simple pull-in geometry is the one-dimensional resonator for which an analytical expression for the pull-in position may be found. The formula is limited to cases, which may be expressed by a lumped one-dimensional model. However, it turns out that it is possible to create a lumped model for the original distributed system. This lumped model can then be used to resolve the pull-in position and voltage on-the-fly. Even this strategy leads to an iteration scheme but in this case it converges accurately to the desired value. The method is not limited in generality and it may therefore be applied to cases of arbitrary geometries.

In the following the mathematical model for the general case is presented. Thereafter the measurement equipment will shortly be described and some results will be presented.

B.2 Mathematical Model for Electro-Mechanical Systems

For convenience the pull-in phenomenon is presented in an idealized setting where the equations of electrostatics and elasticity obtain their simplest forms. This is, however, not a necessary limitation of the computational schemes used for the pull-in extraction. A schematic setup for the corresponding electro-mechanical system is shown in Figure B.1. The electric and magnetic fields are described by the Maxwell's equations. Assuming linear isotropic medium with constant permittivity, $\varepsilon$, and no free charges they result to
an equation for the electric potential, $\phi$,

$$-\nabla \cdot \varepsilon \nabla \phi = 0 \text{ in } \Omega_e.$$  \hspace{1cm} (B.1)

The electric field then yields

$$E = -\nabla \phi.$$  \hspace{1cm} (B.2)

At the conducting boundaries the electric potential is set. For simplicity we assume that there are only two possible values, one for the ground level and the other for the structure,

$$\begin{cases} 
\phi = 0 \\
\phi = V
\end{cases} \text{ at } \Gamma_0 \text{ and } \Gamma_f \text{ respectively.}$$  \hspace{1cm} (B.3)

The electric force acting on the surface of the structure is

$$f_e = \tau \cdot n \text{ at } \Gamma_f,$$  \hspace{1cm} (B.4)

where Maxwell's stress tensor is

$$\tau = -\varepsilon E E + \frac{1}{2} \varepsilon E^2 I.$$  \hspace{1cm} (B.5)

The total energy of the electric field may be computed from the integral

$$\varepsilon' = \int_{\Omega_e} \frac{1}{2} \varepsilon E^2 d\Omega.$$  \hspace{1cm} (B.6)

From the energy also the capacitance of the system is obtained easily, $C = 2\varepsilon'/V^2$.

![Figure B.1: A schematic picture of the electro-mechanical system](image)

The electrostatic force causes the elastic structure to deform. Assuming linear elasticity and neglecting the body-forces the steady-state equation for elastic deformation may be written as
\[- \nabla \cdot \sigma = 0 \text{ in } \Omega_m, \quad (B.7)\]

where the stress tensor for isotropic and isothermal materials may be expressed as
\[
\sigma = 2 \mu \varepsilon + \lambda \nabla \cdot uI, \quad (B.8)
\]

where \(u\) is the displacement field. \(\mu\) and \(I\) are the first and second Lame parameters respectively, and \(\varepsilon\) is the strain tensor. Lame parameters in terms of Young’s modulus, \(E\), and Poisson ratio, \(\nu\), read
\[
\mu = \frac{EV}{(1-\nu)(1-2\nu)} \quad \text{and} \quad \lambda = \frac{E}{2(1+\nu)}.
\quad (B.9)
\]

In steady-state analysis the structure must be fixed on part of the boundary, which leads to Dirichlet conditions,
\[
u = 0 \text{ at } \Gamma_m. \quad (B.10)
\]

At the conducting boundaries of the structure the boundary condition for the stress tensor yields
\[
\sigma \cdot n = f_e \text{ at } \Gamma_f. \quad (B.11)
\]

This equation closes the system.

The determination of the pull-in voltage is equivalent with finding the largest value \(V\) for which the system has a solution. This is particularly difficult since a value exceeding the critical value easily leads to numerical divergence. Otherwise the solution must be approached from below, which further cripples the VI scheme.

Note that as the elastic body deforms also the shape of the electrostatic domain changes. Therefore if the electrostatic equation is solved with typical volume discretization methods also the electrostatic domain must be made compatible with the deformed elastic structure. Typically solving an additional deformation equation for the free space, now assuming that all the displacements on the boundaries are given may do this.

### B.3 Measurement Equipment

As a preparation to the electrostatic actuation, the test structures have first been packaged and then mounted on a printer circuit board. The whole has then been placed under the microscope of the WYKO interferometer. This equipment serves to capture the changes of the actuated test structures.
For the actuation of the test structures, the standard voltage actuation equipment has been used (Fig. B.3). The voltage was applied in steps of 10, between 0 and 100 V.

Figure B.2: Packaged test structures and mounting on the printer circuit board

Figure B.3: Voltage actuation equipment
C Reference List

[16] Beek, J. van; Grootel, M. van; Rijks, T.; Ulenaers, M., Processing of RF MEMS in Passi-3 Technology, Philips Research, Technical Note NLTN 2003/00052