

Replicated Optical Microstructures in Hybrid Polymers: Process Technology and Applications

Dissertation

submitted to the Faculty of Science of the University of Neuchâtel,
in fulfillment of the requirements for the degree of
Doctor of Science

by

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CH - 2007 Neuchâtel
Switzerland

2006

IMPRIMATUR POUR LA THESE

Replicated Optical Microstructures in Hybrid Polymers: Process Technology and Applications

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Neuchâtel, le 9 juin 2006

Le doyen :



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Abstract

This thesis reports the design, fabrication and testing of new microstructures made in inorganic-organic hybrid polymers. Sol-Gel materials of the ORMOCER[®] brand are such hybrid polymers that combine the properties of ceramics and organic polymers. These materials have a high temperature stability, very good chemical resistance and excellent optical properties, but can be processed by simple UV-casting methods. Low-cost replication technologies like injection molding or hot embossing are known for their high precision in the reproduction of very small features. This property is particularly useful for the manufacturing of micro-optical devices, where accuracies in the nanometer range are needed.

In this study, UV-replication processes have been combined with micro-fabrication techniques, such as photolithography and thin-film evaporation, to build microsystems in hybrid polymers. With very few process steps, complex microstructures like cantilever beams incorporating refractive microlenses have been made. High aspect ratios (20 to 1) in structures with feature sizes of 5 μm have been achieved with ORMOCER[®] contact photolithography.

One application of this microfabrication technology with inorganic-organic hybrid polymers is the assembly of microsystems with clipping structures. Two designs of microscopic clips have been developed and tested. Both types of clipping devices consist of two complementary (male and female) parts with a footprint of less than 1 by 1 mm. The clipping structures are capable of generating 100 mN of holding force per square millimeter. This assembly method is reversible; it has been demonstrated that the clips can be separated and engaged again without loss of retaining force.

The assembly of microsystems by clipping is a promising approach: Clipping is fast and cost-effective, because no temperature cycles are required. Pieces attached by clipping can be removed from the microsystem if needed, for example to replace broken or contaminated parts or to increase the yield in a production process. Arrays of clipping structures are expected to multiply the holding forces and to improve the precision. Potential applications of this technology include modules for optical communication devices, illumination systems, miniaturized cameras and sensors, and biomedical microsystems.

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Chapter 1

Introduction

1.1 Scope of research

This thesis, entitled “Replicated Optical Microstructures in Hybrid Polymers: Process Technology and Applications”, describes the investigation of new fabrication technologies, the analysis of new materials and the development of new applications in the field of optical microsystems. Hybrid polymer materials with excellent optical properties (ORMOCER[®]s) have been used to create microstructures by replication methods. Various applications, and in particular the assembly of microsystems with clipping structures have been investigated.

The goal of this thesis was to develop cost effective fabrication methods and microsystems. Miniaturized devices made by replication technologies in low-cost base materials like polymers are well suited for potentially very high volume productions. Besides reduced production costs, the miniaturization of mechanisms (as mathematically described by the scaling laws) offers several other advantages such as lower inertia, better heat transfer or increased adhesion. These properties can be used to create new devices at the micro-scale. Additional functions (for example optical or bio-chemical effects) can also be added to microsystems by using polymers.

The scope of this study extends into different technological fields, all related to micro-engineering. Here, a quick overview of the technological fields and the terms used in this work are given.

Within the area of micro-engineering, different technological branches can be distinguished:

- Precision Engineering
- Microfabrication Technology
- Nanotechnology

The intersections of these fields offer the most interesting opportunities for research and future product development. The work presented in this thesis consists of such research, but also overlaps with other fields of engineering such as optics and replication technologies.

Precision engineering is the branch of mechanical engineering where miniaturized mechanical devices are created. The best known example is the mechanical watch, especially in Switzerland. But precision mechanics is used in all kinds of industries like: Bio-Medical Engineering, Metrology, Microscopy and Aerospace Engineering. The combination of precision engineering with electronics and information technology leads to *robotics* or *mechatronics*. Examples are industrial robots or hard disk drives.

Microfabrication Technology (or micromachining, or micro system technology), is the technological field of MEMS (Micro-Electro-Mechanical Systems). Historically, MEMS technology is a spin-off from the highly successful IC (integrated circuit) technology, and still largely benefits from the advances made in that field, and uses similar production methods and facilities. MEMS devices are made either into (bulk micromachining) or on top of (surface micromachining) planar substrates.

The most common applications of MEMS devices include:

- Accelerometers
- Pressure sensors
- Inkjet printer nozzles
- Displays
- Optical data communications

Nanotechnology is a relatively new term covering several independent technological domains: The fabrication of feature sizes in the nanometer range by microfabrication technology and the manipulation of single molecules or even atoms to create new materials such as carbon nanotubes. The ultimate goal of future nanotechnology is to build machines no larger than a few molecules. But such developments still belong to the realm of fiction [1.1].

As stated in the title of this thesis, hybrid polymers (of the ORMOCER[®] brand) have been used for the development of new fabrication processes and applications. These hybrid polymers are the result of years of research in molecular chemistry [1.2]. Molecular chemistry plays an important role in the development of nanotechnology. During the thesis work, these hybrid polymers (ORMOCER[®]s) have also been used to fabricate structures with feature sizes in the nanometer range. However, most of the research presented here is best described as a new development in microsystem technology. New production methods to create MEMS

devices hybrid polymer with by replication technologies have been investigated.

Finally, one application of this new microsystem technology with hybrid polymers that has been explored further in the scope of this thesis, namely the assembly of microsystems with clipping structures in hybrid polymers, belongs to the field of precision engineering (Chapter 4).

1.2 Scaling laws

In all the branches of Micro-Engineering (Microfabrication Technology, Nanotechnology and Precision Engineering), the goal is to reduce the size of devices, machines and products. Such miniaturization generally offers several benefits, such as lower power consumption, reduced fabrication costs and lower waste production.

To mathematically describe the effects of miniaturization, scaling laws can be established [1.2]. For example, by reducing the size of a device with length l to l' , the surface of the device will shrink roughly with a factor of $\left(\frac{l'}{l}\right)^2$ and the volume will shrink roughly with a factor of $\left(\frac{l'}{l}\right)^3$. The fact that volumes shrink at a cubic rate and surfaces only at a square rate leads to the following generalization: All characteristics related to volume (mass, inertia, etc) become much less relevant, and characteristics related to surfaces gain importance (heat transfer, adhesion, electrostatic forces). Of course, the opposite is also true, small mechanical devices with extremely low masses can operate at high speeds and sustain large accelerations.

Scaling laws can also be observed in nature: Small animals tend to be extremely agile and have fragile-looking body parts, but suffer from heat loss, whereas large animals need thick bones and cannot lift much more than their own body weight. [1.3]

In the work presented here, scaling laws play an important role. Some applications, such as electrostatic actuators are only viable in microscopic devices (Chapter 3.7.2). In Chapter 4, one part of the research has been to scale down a well-known clipping mechanism (a LEGO[®] brick) to a size of 1 by 1 mm. Because of the increased adhesion forces and the greatly reduced inertia, such mechanisms are very effective when miniaturized.

1.3 Economic benefits of miniaturization

From an economic viewpoint, the advantages of miniaturization are manifold. Arrays of nearly identical parts can be used to make devices working in parallel (ICs, digital mirror devices (DMD), sensors), or that have a built-in redundancy in case of the failure of one part. Unique products can be created by integrating many different functions into one small device. Different technologies can be combined to make for example MOEMS (micro-opto-electro-mechanical systems) or biomedical microsystems. In this thesis, several fabrication methods are proposed to create complex microsystems that integrate optical, mechanical and / or electronic functions (Chapter 2).

Small devices are very well suited for mass production. In mass production, there is a big benefit from the *economies of scale* because fabrication costs for a single device can be very low even with high initial investments in R&D (research and development) and production facilities. A very well known example of economically successful miniaturization is the reduction in size of the transistor in integrated circuits [1.4]. However, there are certain limits that have to be taken into account:

- In the future, base costs of a microfabrication production will become increasingly important as upcoming state-of-the-art manufacturing facilities will require a bigger and bigger investment [1.5].
- A product made by microfabrication technologies can only be successful if there is a market for literally millions of such devices.

For a small series of devices, there is often a limit where precision-mechanic or electronic (solid state) solutions are more cost-effective than MEMS devices. For example, based on MEMS technology, several types of high bandwidth full-optical switches for optical telecommunications have been developed. However, worldwide, there are currently only a few nodes in the optical transmission networks where such products can be used. In this case, the equipment for conversion to electric signals and electronic switching is still more cost effective than producing a small series of full optical MEMS switches. In the future, when all-optical networks may become more widespread there may be a need and a market for mass-produced MEMS devices.

Very large series of MEMS devices also have limits, if the fabrication becomes too complex (too many mask processes, for example) the final

product will still be extremely costly. Modern ICs (integrated circuits) are limited by the same problem. Only if the market is ready to buy millions of high-priced chips (Pentiums[®], graphic engines, or digital light processors (DLPs[®]) cost hundreds of dollars) these products can be sold. So there is always a need to reduce costs, even in high volume series.

The cost of a silicon microsystem is calculated by the cost of silicon wafer surface. In order to decrease production costs further, one approach is to replace silicon as base material and use manufacturing methods that are known to be well suited for mass production of very small feature sizes: replication technologies. Furthermore, new functionalities can be added to miniaturized devices with the polymers used in replication methods.

1.4 Polymers in microfabrication

UV-casting, hot embossing and injection molding are production methods that belong to the group of replication technologies. The replication fabrication approach uses one master (also called a *mold* or a *template*), to create many identical copies of a certain pattern. Replication technologies are used in the mass production of everyday devices (injection molding, especially), but are also very effective at the micro scale. Some of the best known examples for the high volume fabrication of devices with a very high precision are CDs and DVDs (hot embossing), and security holograms (roll-to-roll embossing). With some notable exceptions (ceramic or metal injection molding CIM, MIM), most products produced by replication technologies are based on polymers. The work presented in this thesis is focused on the efforts to use replication technologies with hybrid polymer materials (ORMOCER[®]s) for the fabrication of microsystems.

Examples of low cost, high volume miniaturized products on the market are microfluidic devices [1.6] or embossed lenses (instead of lenses etched into glass). In fact, the use of polymers in the fabrication of microsystems already has a certain tradition. Photoresists like SU-8 are used in many MEMS devices [1.7]. Replication processes for microsystems were developed (LIGA). Current research aims to replace UV-Photolithography with nanoimprint lithography (NIL) for the production of circuitry with nanometer-scale feature sizes [1.8].

Silicon manufacturing includes many process steps that produce pollutants, despite being sometimes promoted as a “clean” technology compared to traditional heavy industries. To fabricate state-of-the-art 30”

diameter monocrystals, huge chemical processes are needed and large amounts of waste is produced. The same is true for the silicon etching processes in MEMS fabrication. These processes are time consuming and expensive (dry etching) or produce a lot of waste (wet etch). The production of polymer materials can be far cheaper and the manufacturing processes applying polymers are generally less pollutant. For future markets, a clear goal is to produce cheap, disposable polymer micro-devices.

Polymer materials open new possibilities for applications of microsystems that are not possible with silicon. The different material properties can be used to realize devices with completely new functions, such as sensors with selectively adsorbing films.

The materials used during the work for this thesis are hybrid polymers, synthesized by the Sol-Gel process. These materials are commercially available in the form of UV-curable resins by the trade name ORMOCER[®]s. Based on the Sol-Gel process that has been developed a long time ago, these hybrid polymers have interesting properties that make them suitable for a large number of applications [1.9]:

- UV curability: suitable for low-cost UV-casting processes
- Temperature resistance (compatible with lead-free soldering) for integration into existing process chains
- Optical properties for optical applications
- Biocompatibility for biomedical applications

1.5 Integration of assembly and packaging

If the base material cost of the device can be lowered by using polymer materials, the other costs in the manufacturing will play a more significant role. This is especially true for assembly and packaging of the devices. As the devices become also more various in the design, (MEMS, MOEMS, etc) with the integration of different materials, a more modular technology for the assembly steps is needed. As described above, polymers are expected to lower to cost of fabrication to the point where disposable devices can be mass-produced. However, complex microsystems may be composed of disposable and non-disposable (expensive) parts [1.10]. Here a reversible assembly technology has a huge advantage.

Clipping as an assembly technology has several advantages:

- Combination of different materials
- Speed of assembly, no thermal treatment needed
- Reversibility for disposable parts or to increase yield in production chains

To make clipping a viable approach, the necessary clipping structures have to be integrated into the device with as few process steps as possible. Here again, the use of versatile polymers for the manufacturing is a promising approach. One goal of this thesis was to demonstrate the feasibility of such a clipping method by using hybrid polymers for the fabrication of clipping structures.

1.6 Further perspectives

In the future, the integration of various technologies into miniaturized devices will become even more important: Optics, material sciences, biomedical engineering and other fields will create completely new areas of micro-engineering. Besides the perpetual demand to lower fabrication costs for economic reasons, the curiosity of the research scientist is the driving force behind the continuing miniaturization. The goal is to find out if it is possible to get a device to work at a scale that was previously unthinkable. Polymer materials of various forms are going to play an even larger role. Specially tailored materials with unprecedented functionalities are already emerging: piezopolymers, electrically conductive polymers, (semiconductor) light emitting polymers, or even completely organic circuits are going to spawn new microsystems that are cheaper to produce and offer even more varying applications. Such applications will find specialized market niches where they are useful or they may open completely new markets.

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Chapter 2

ORMOCER® process technology

2.1 Introduction

In this chapter, an introduction to ORMOCER® Sol-Gel materials is given. Basic properties and main applications are explained. Details of the manufacturing processes and the fabrication steps developed in this work are elaborated. Combinations of the different process techniques for special microstructures are presented.

ORMOCER is an acronym that stands for ORGanically MODified CERamics, referring to the hybrid composition of ORMOCER® materials. ORMOCER® inorganic-organic hybrid polymer materials of different types are used for a vast range of applications in different technological fields.

Application areas include:

- Electronics (ORMOCER® has excellent dielectric proprieties) [2.1]
- Medicine, especially dental medicine and ophthalmology [2.2]
- Optics and telecommunication [2.3]

One branch of ORMOCER® materials has been developed specially for integrated optics and optoelectronic devices at the ISC Fraunhofer Institut für Silikatforschung, Würzburg, Germany (Figure 2.1). This type of material offers very interesting possibilities in the development and fabrication of micro-optical devices: ORMOCER® materials can be used in relatively simple low-cost UV-casting processes. A vast range of micro-optical devices can be manufactured in ORMOCER®: (refractive) microlenses, diffractive gratings and beam shapers, waveguides, opto-mechanical submounts and so on. Integration of ORMOCER® microstructures directly into optoelectronic devices is another application area. The manufacturing needs only few process steps and can be used on large substrates.

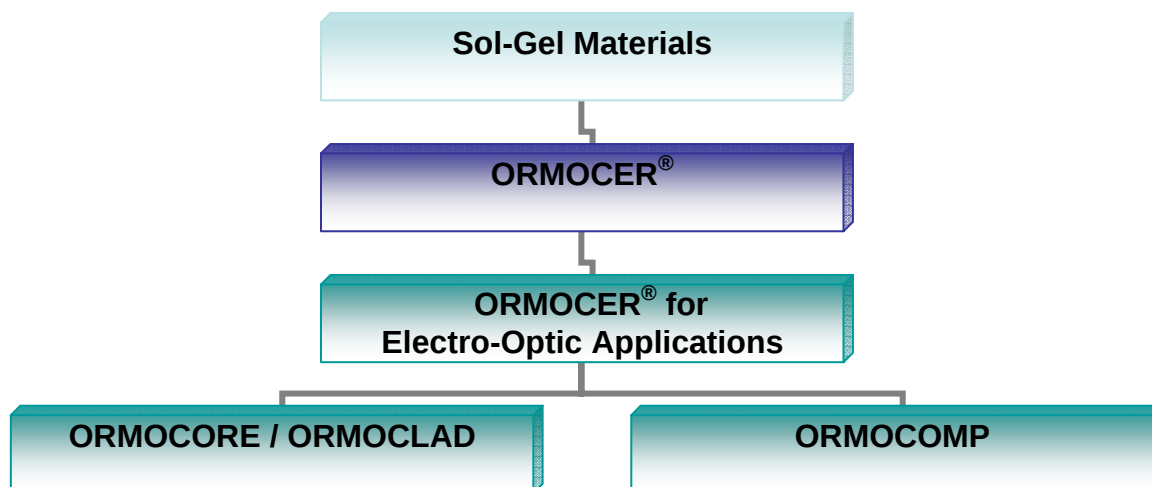


Figure 2.1: ORMOCER[®] family tree. In this thesis, the ORMOCORE / ORMOCCLAD and ORMOCOMP material types have been used. They belong to the branch of ORMOCER[®] materials for electro-optic applications, developed at ISC Fraunhofer Institut für Silikatforschung, Würzburg, Germany. ORMOCER[®] materials in general form a much larger group that is part of the family of Sol-Gel materials. (See chapter 2.2.1)

The aim of this thesis was to expand the applications of this material in micro-optics and into fields closely related to micro-optics and to improve the manufacturing techniques for these applications by using ORMOCER[®] material. In this work, mainly commercially available ORMOCER[®] materials have been used:

- ORMOCER[®] type 1, also known as b59, trade name: ORMOCORE. ORMOCORE was designed for the use as *waveguide core* material.
- ORMOCER[®] type 2, also known as b66, trade name: ORMOCCLAD. ORMOCCLAD was designed for the use as *waveguide cladding* material (with a lower refractive index as ORMOCORE).
- ORMOCER[®] type 4, also known as US-S4, trade name: ORMOCOMP. ORMOCOMP was designed for the use as material for various *optical components*.

These materials are sold as highly viscous resins that can be cured by UV radiation (Table 2.1). The commercial supplier of ORMOCER[®] material is Micro Resist Technology GmbH, Berlin, Germany.

Table 2.1: Viscosity values of different ORMOCER[®] resins at room temperature.

Product name:	ORMOCORE	ORMOCCLAD	ORMOCOMP
Viscosity:	5 - 8 Pa·s	10 - 12 Pa·s	2 - 6 Pa·s

2.2 ORMOCER® and Sol-Gel materials

2.2.1 Classification and material composition

ORMOCER® materials belong to the family of Sol-Gel materials because they are synthesized by the Sol-Gel process. This classification can be misleading because of the high organic content in ORMOCER® (See precursor materials in Table 2.2). Unlike ORMOCER®, common Sol-Gel materials are prepared from nano-particle precursors containing metal oxides like SiO_2 , ZrO , MgO , Al_2O_3 , TiO_2 or Ta_2O_5 (alkaloxides) [2.4].

The sol-gel process involves the transition of a material system from a liquid phase (more precisely: solid particles dispersed in a liquid phase; a colloidal “sol”) into a solid phase (more precisely: liquids dispersed in a solid phase; a colloidal “gel”). This means that the nanoparticles are dispersed in a (usually alcoholic) solution and after a series of hydrolysis and condensation reactions a “gel” is formed [2.5]. This gel is then dried and an inorganic structure remains. Depending on the application, ceramic fibers, coatings or bulk structures can be created this way (Figure 2.2).

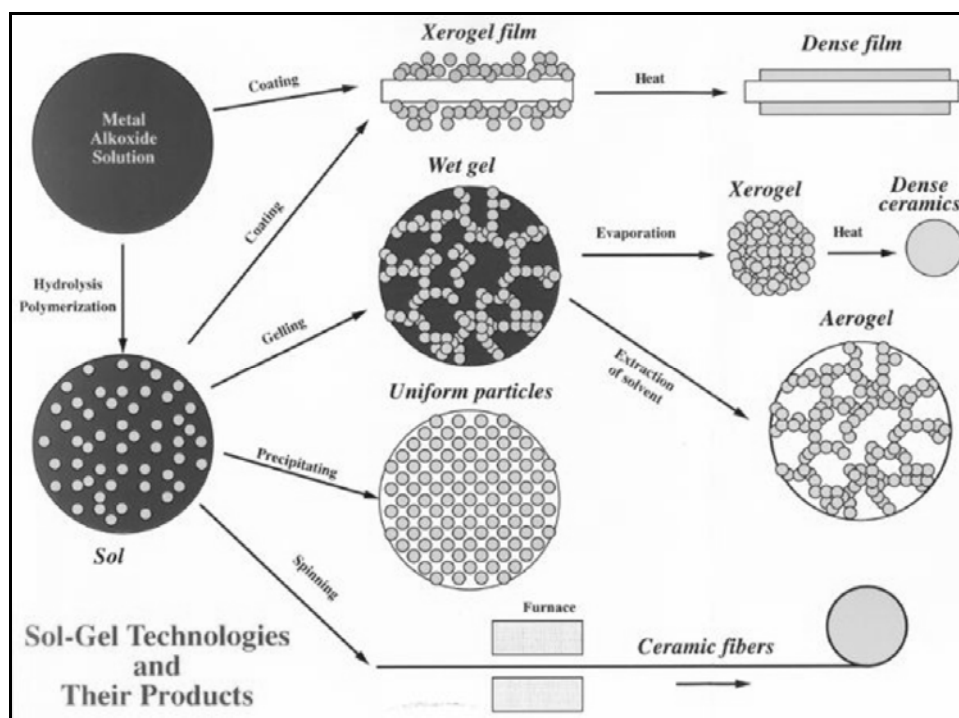


Figure 2.2: Overview of common Sol-Gel processing techniques. From metal alkoxides in alcoholic solution, different products can be obtained by applying different processes. (Figure courtesy of Chemat Technology, Inc. Northridge, Canada) [2.6].

By using the Sol-Gel process, “tailored” materials can be created by adding various substitutes to the base precursor material matrix. This well-known property is used for the synthesis of ORMOCER[®] materials (Figure 2.3). After the Sol-Gel processing of the ORMOCER[®] precursors, the resulting gel will not dry out but a UV-curable resin remains. Cured ORMOCER[®] materials have a higher elasticity and are less brittle than other Sol-Gel materials [2.7].

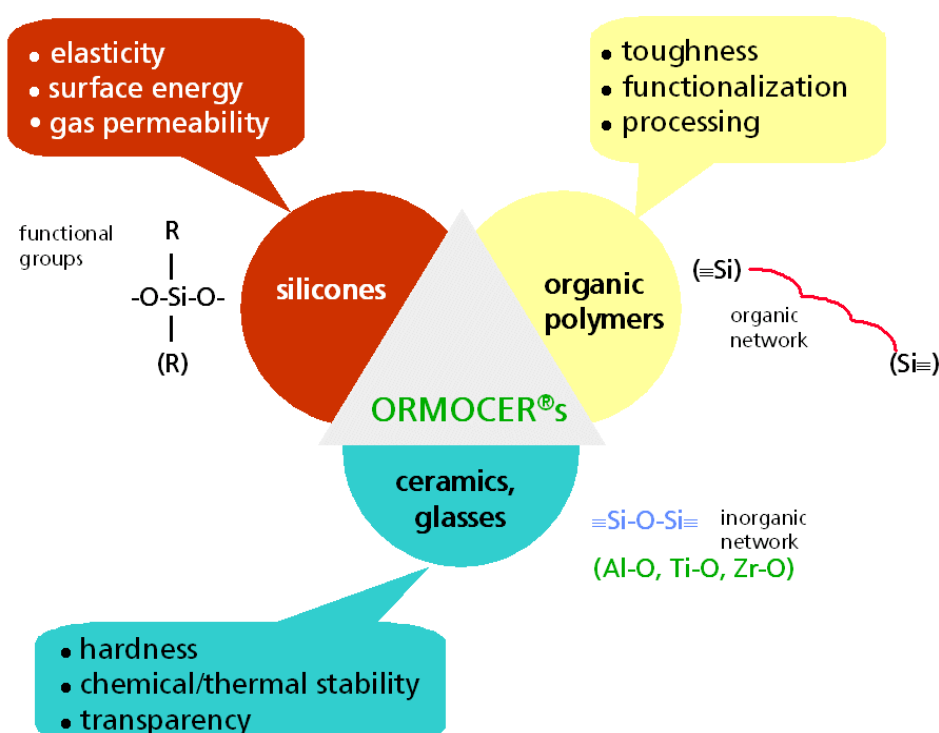


Figure 2.3: General properties of ORMOCER[®] materials. These materials combine the properties of silicones (elasticity), organic polymers (UV-curing) and ceramics (stability and optical properties). (Figure courtesy of ISC Fraunhofer Institut für Silikatforschung) [2.8].

Instead of simple alkoxides (SiO_2 , ZrO , TiO_2 , ...), the precursors for ORMOCER[®] materials are organosilane molecules that include 4 functional parts (Figure 2.4):

- A: -Si-O- groups to form the inorganic network
- B: Connecting groups (chains)
- C: Polymerizable units like acryl or methacryl groups
- D: Non-reactive groups to modify certain material properties: For example acryl groups to increase the refractive index or (fluorinated) alkyl groups to lower the refractive index.

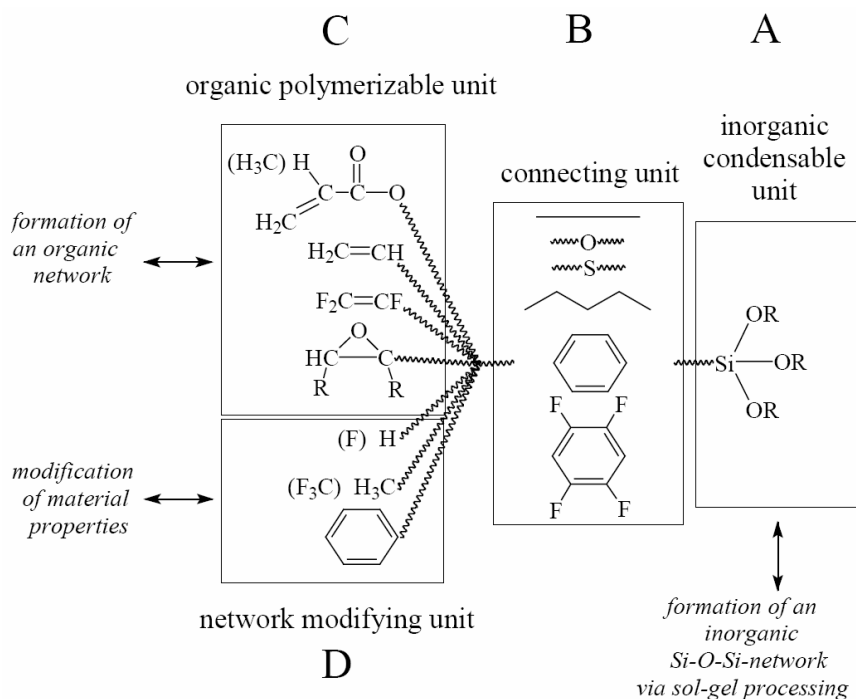


Figure 2.4: General formula of alkoxy silane precursors for ORMOCER® synthesis. The different molecule groups have distinct functions in the formation of the oligomers and in material curing and the material properties [2.9].

The precursors are then linked by inorganic -Si-O-Si- bonds to form nano-scale oligomers of typically 2 - 5 nm in size [2.1]. The polycondensation reaction that occurs during the sol-gel process is creating these links (Figure 2.5). Multiple alternating condensation and hydrolysis steps take place to create more and more -Si-O-Si- bonds. The sol-gel transition occurs: colloid liquid sol is transformed into the colloidal gel.

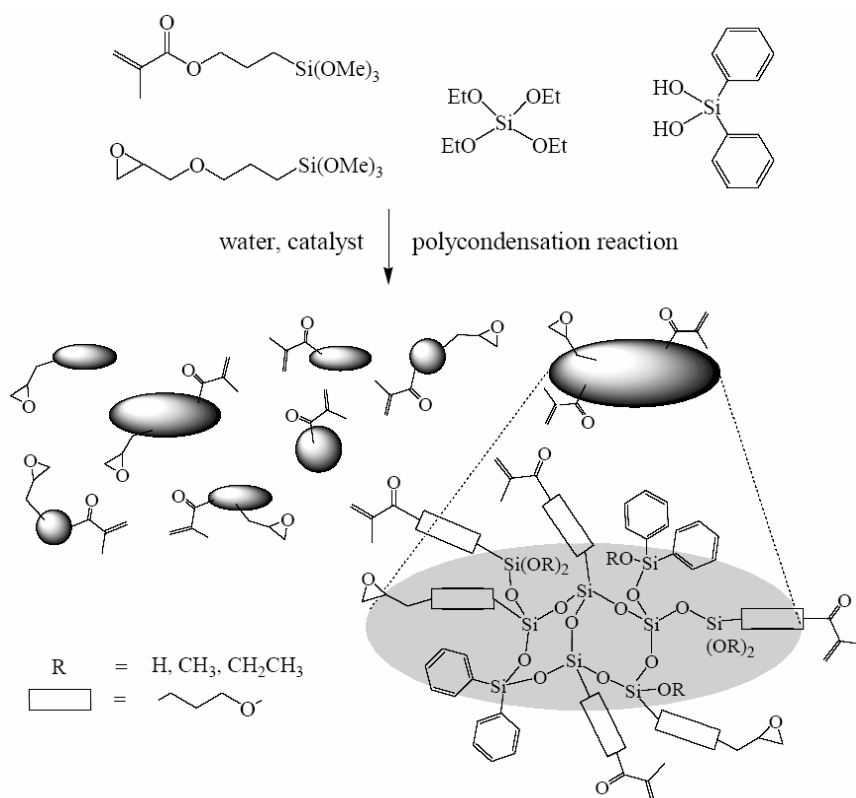
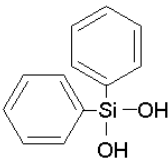
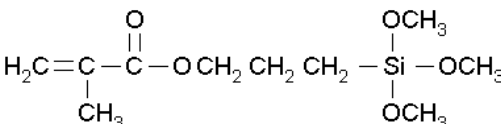
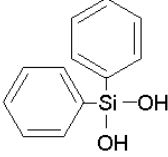
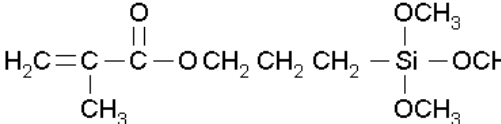
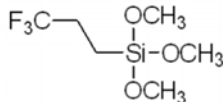
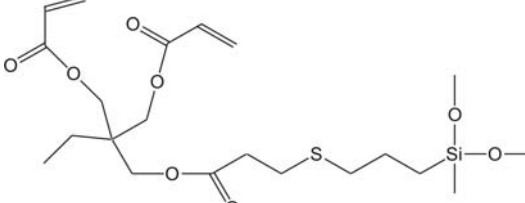


Figure 2.5: Formation of ORMOCER[®] oligomers from alkoxysilane precursors. In this example, molecules containing methacryl, epoxy, ethoxy and phenyl groups are linked by Si-O-Si bonds. (Figure courtesy of Micro Resist Technology GmbH, Berlin, Germany) [2.10].

The Sol-Gel processing is carried out by the commercial producer of the ORMOCER[®] material. After these steps, a photoinitiator is added to the resulting resin and then the material is ready for application and can be purchased like any photoresist used in the semiconductor industry. Commonly used photoinitiators for ORMOCER[®] resins are BASF Lucirin[®] TPO and Ciba[®] IRGACURE[®] 369 [2.11].

Table 2.2: Precursor molecules of commercially available ORMOCER® resins. ORMOCORE and ORMOCCLAD are both made from the same precursors. In ORMOCCLAD, 3-(Trimethoxysilyl)propyl methacrylate is partly replaced by Trimethoxy(3,3,3-trifluoropropyl)silane to lower the refractive index [2.12]. ORMOCOMP consists of a completely different material system.

Product name:	Precursors:	Molecules:
ORMOCORE	Diphenylsilanediol	
	3-(Trimethoxysilyl)propyl methacrylate (MEMO)	
ORMOCCLAD	Diphenylsilanediol	
	3-(Trimethoxysilyl)propyl methacrylate (MEMO)	
	Trimethoxy(3,3,3-trifluoropropyl)silane	
ORMOCOMP	(Monomer without systematical name)	

2.2.3 General properties of cured ORMOCER[®] material

Table 2.3: Physical properties of ORMOCER[®] materials.

	ORMOCORE	ORMOCLAD	ORMOCOMP
Coefficient of thermal expansion (CTE)	100-130·10 ⁻⁶ K ⁻¹	100-130·10 ⁻⁶ K ⁻¹	60·10 ⁻⁶ K ⁻¹
Young's modulus E	860 +/- 120 MPa		925 +/- 100 MPa
Density ρ			1180 kg·m ⁻³
Permittivity ε _r	3.2 (@ 10 kHz)		
Resistivity ρ	10 ¹⁶ Ω·cm		

Table 2.4: Optical properties of ORMOCER[®] materials.

	ORMOCORE	ORMOCLAD	ORMOCOMP
Refractive index:			
λ = 588 nm			1.520
λ = 635 nm	1.5527	1.5343	1.519
λ = 800 nm	1.543	1.532	1.518
λ = 1310 nm	1.539	1.524	
λ = 1550 nm	1.537	1.521	
Optical attenuation:			
λ = 633 nm	0.06 dB/cm	0.10 dB/cm	
λ = 1310 nm	0.23 dB/cm	0.26 dB/cm	
λ = 1550 nm	0.50 dB/cm	0.48 dB/cm	

As stated in Table 2.4, the refractive indices (n) of ORMOCER[®] materials are around 1.52 for ORMOCOMP and 1.55 and 1.53 for ORMOCORE and ORMOCCLAD, respectively. These values are higher than the indices of fused silica (n = 1.4585 @ 587.6 nm) or PMMA (n = 1.492 @ 589.3 nm), but lower than the n of polycarbonate (PC) (n = 1.590 @ 589.3 nm).

2.3 ORMOCER® processing

2.3.1 Introduction

ORMOCER® material can be used in different ways. The basic casting process is very simple by itself, but can be expanded to allow the creation of more complex microstructures. In this section, the fundamental process (wafer scale replication) is described first and then 3 variations thereof are explained:

Wafer scale replication (Chapter 2.3.2)

- ORMOCER® photolithography (Chapter 2.3.3)
- Contact lithography (Chapter 2.3.4)
- Contact lithography on sacrificial layers (Chapter 2.3.5)

All the fabrication methods presented here are essentially add-on processes of 3D structured layers of polymers onto various types of inorganic substrates. Layers with a thickness in the range of 5 to 500 µm can be achieved. The substrates used here were glass plates or semiconductor wafers. The substrates are coated by casting or by spin-coating. Bulk processing of ORMOCER® is not common, but feasible (Chapter 3.2.1).

The applied ORMOCER® remains in liquid form until it is cured by UV-radiation. Unlike conventional photoresists, ORMOCER® resins contain no solvents. This lack of solvents allows a low shrinkage casting process (next section). The UV light cures the material by bonding the organic groups of the polymers. The materials used in this work are linked by acryl- or methacryl-groups (ORMOCOMP and ORMOCORE / ORMOCCLAD, respectively). The polymerization is triggered by photostarters that have been mixed by the supplier of the material into the resin (0.1 - 1 % weight). Commercially available starters used here include BASF Lucirin® TPO and Ciba® IRGACURE® 369.

The quantity of photostarter used is the determining factor of the quantity of crosslinks achieved by the UV exposure [2.13]. To guarantee the maximum of crosslinks for a certain amount of photostarter, and to stabilize the material, a hard bake step is used at the end of the process. The final material properties of the cured material depend mostly on the precursor materials used. The chain length of the precursor molecules influences the Young's modulus and the thermal expansion coefficient of the final material [2.7].

2.3.2 Wafer scale replication

The following process steps are needed to create a replica from a negative template (also called *master*, *mold* or *preform*) in an ORMOCER[®] film on a wafer (Figure 2.6). The mold consists of a transparent plate with a microstructured surface that has to be prepared with a release layer beforehand. The release layer (or *anti-sticking layer*) on the mold is essential to the casting process. In casting processes, the cured polymer tends to stick to the mold due to physical, chemical or mechanical bonding [2.14].

The microstructures on the mold increase the contact surface to the replica and amplify the problem. If parts of the replicated material remain on the mold after the separation, the replica is damaged and the mold is contaminated. To avoid any bonding between the replica and the mold and to decrease the force needed to peel the replica off the mold, a release layer is used on the mold. As release layers, sputtered polytetrafluoro ethylene (PTFE, Teflon[®]-like) thin-films or fluorosilane monolayers are used [2.15].

If the mold is opaque (for example a nickel shim), a transparent wafer has to be used on the other side, to allow UV irradiation. In this case, the ORMOCER[®] material is exposed with UV light through the wafer.

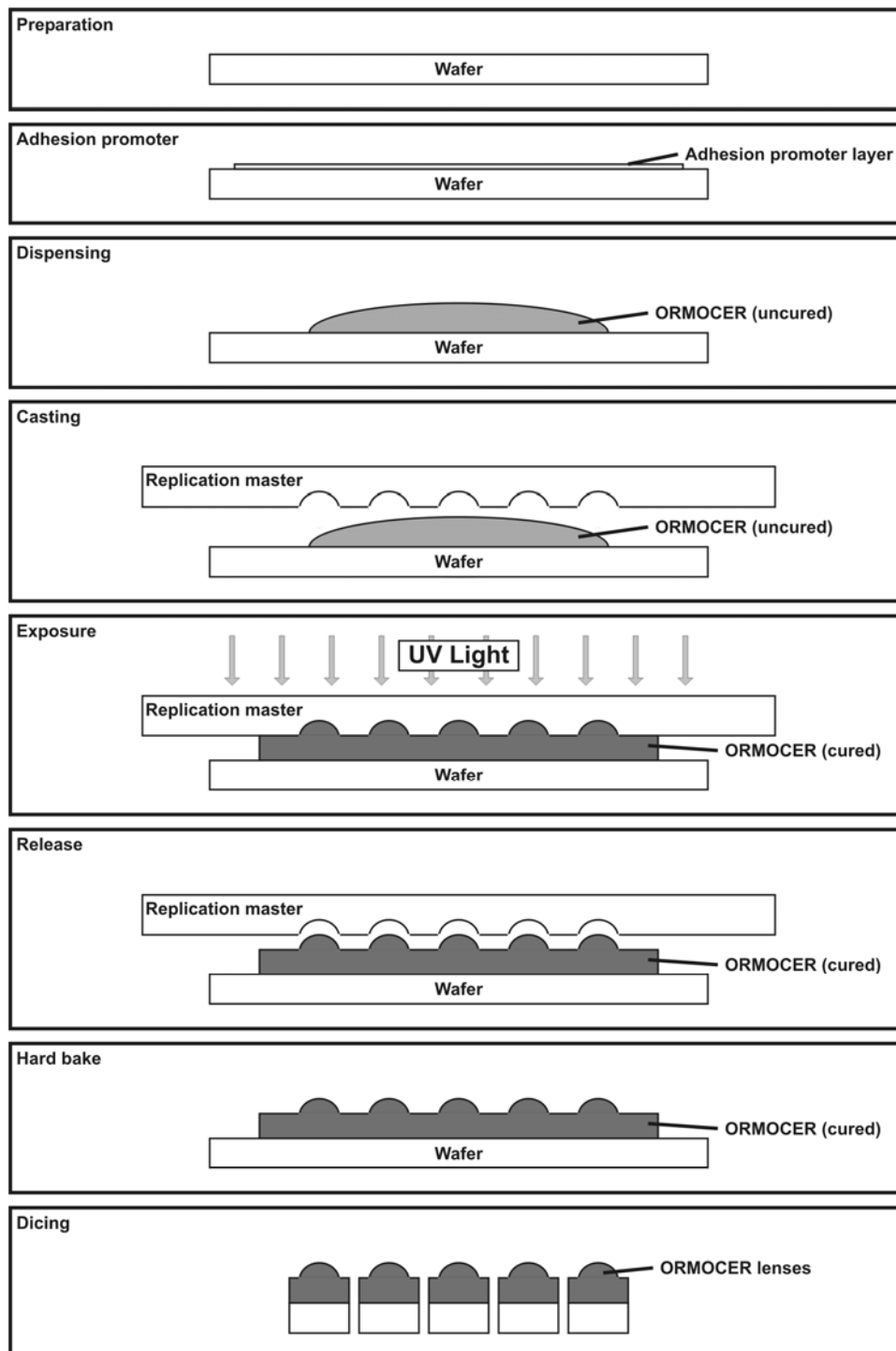


Figure 2.6: Wafer scale replication process. After the application of the adhesion promoter, the casting material is dispensed onto the wafer. Then the liquid material is pressed into the desired form by the replication master (mold) and exposed with UV-light. After removing the mold, the resulting microstructures are hard baked and the wafer is diced.

1. Preparation of the substrate

The wafer has to be cleaned and dried to eliminate surface contaminations. In this work, ORMOCER[®] layers have been applied on substrates made of floatglass, quartz, silicon and gallium arsenide.

2. Application of adhesion promoter

Good adhesion of the ORMOCER[®] layer on the wafers is crucial in all applications. To ensure excellent adhesion of the hybrid polymers on different substrates, a good bonding at the molecular level is needed. A silane adhesion promoter can be used for ORMOCER[®] layers: 3-(Trimethoxysilyl)propyl methacrylate (MEMO) [2.3]. MEMO is also a precursor molecule for the ORMOCER[®] resins ORMOCORE and ORMOCOMP. Using silane coupling agents to bond organic materials to an inorganic matrix is a very common technique. [2.16, 2.17]

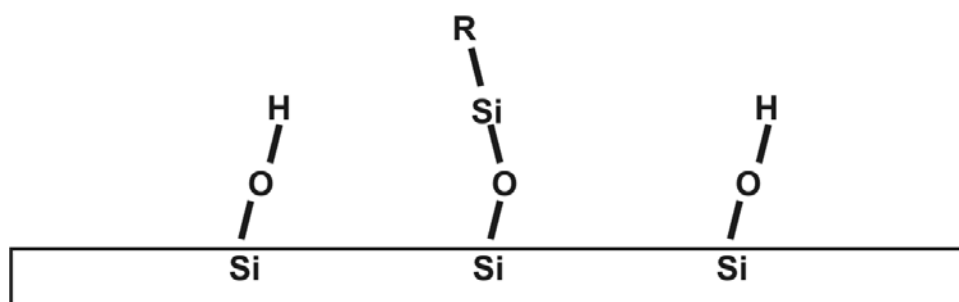


Figure 2.7: Substrate with Si-OH groups on the surface. The Adhesion promoter silane molecule bonds with a Si-O-Si to the substrate. R is the organic part of the molecule.

The silane adhesion promoter is applied to the mineral substrate in a slightly acidic aqueous solution. In this solution, the silanes do not condensate (they do not form cluster oligomers). The silanes form hydrogen bonds to the Si-OH groups on the wafers. Then, a polycondensation reaction will form stable Si-O-Si links in between the substrate and the coupling agent molecules. The following layer of ORMOCER[®] oligomers bonds to the methacryl groups of the silane monolayer during the exposure and hardbake steps.

3. Dispensing

The ORMOCER[®] resin is simply poured onto the wafer. This step is usually carried out in a mask aligner machine equipped with dispensing tools. The

highly viscous liquid ($\mu = 2 - 10 \text{ Pa}\cdot\text{s}$) forms a drop in the center of the wafer.

4. Casting

In the mask aligner, the mold is first mounted above and parallel to the wafer with a certain gap. After dispensing, the machine lowers the mold without wedge error until the liquid casting material is in contact with the mold. The ORMOCER® resin is compressed until the desired film thickness is reached. Due to the high viscosity of the resin, the thickness of the gap is normally reduced in several small steps with waiting times in between.

5. Exposure

Exposure of the liquid ORMOCER® film with UV light immediately initiates curing. The linking of the polymer chains is triggered by the photostarters mixed into the resin. However, as the radical activation is blocked by oxygen, the sample has to be in a controlled, atmosphere (usually nitrogen) [2.11].

6. Release

As soon as the ORMOCER® film is UV-cured, the wafer can be separated from the mold. The ORMOCER® layer is peeled off from the mold by applying a gentle force on one of the plates. If the release layer is still intact the mold can be used again.

7. Hard bake

To finalize the curing process, a hard bake step is necessary. A thermal curing step of 150°C for 8 hours in an oven completes the cross-linking of the molecules and the hardening of the material [2.9].

8. Dicing and post processes

ORMOCER® layers will not be damaged by most dicing processes in conventional dicing saws. However, for thick films it is preferable to keep the dicing lines on the wafers free of ORMOCER® to avoid any peel-off of the material from the substrate due to dicing.

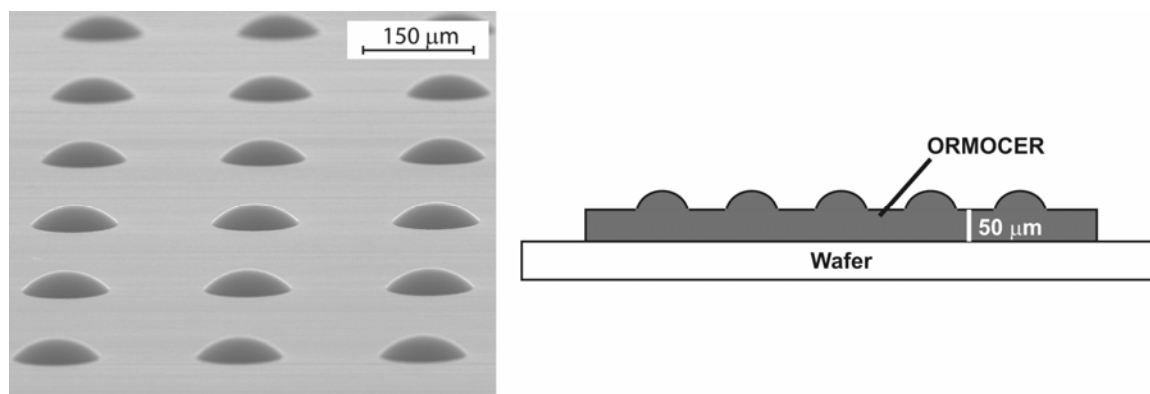


Figure 2.8: Array of microlenses in ORMOCORE fabricated with the wafer scale replication process. The lenses have been fabricated on a glass substrate. In between the lenses, the ORMOCER[®] film has a thickness of around 50 μm .

As stated above, the shrinkage of ORMOCER[®] material during curing is very low (2-8 % in volume) [2.7]. During the exposure and hard bake steps, the replicated microstructures are only slightly deformed, meaning that this process is very well suited for the fabrication of optical microstructures. The effect of the shrinkage on high precision microoptics has been studied in Chapter 3.5.

2.3.3 ORMOCER[®] photolithography

As shown in Figure 2.9, a basic form of ORMOCER[®] photolithography combines the wafer scale replication process with partial illumination through a chrome mask. To avoid contamination of the mask, the mask is usually not in contact with the ORMOCER[®] material. So no 3D microstructures are created; only the 2D pattern of the mask is reproduced in the spin-coated film. To overcome this limitation, a combination of molding and photolithography has been developed (next section).

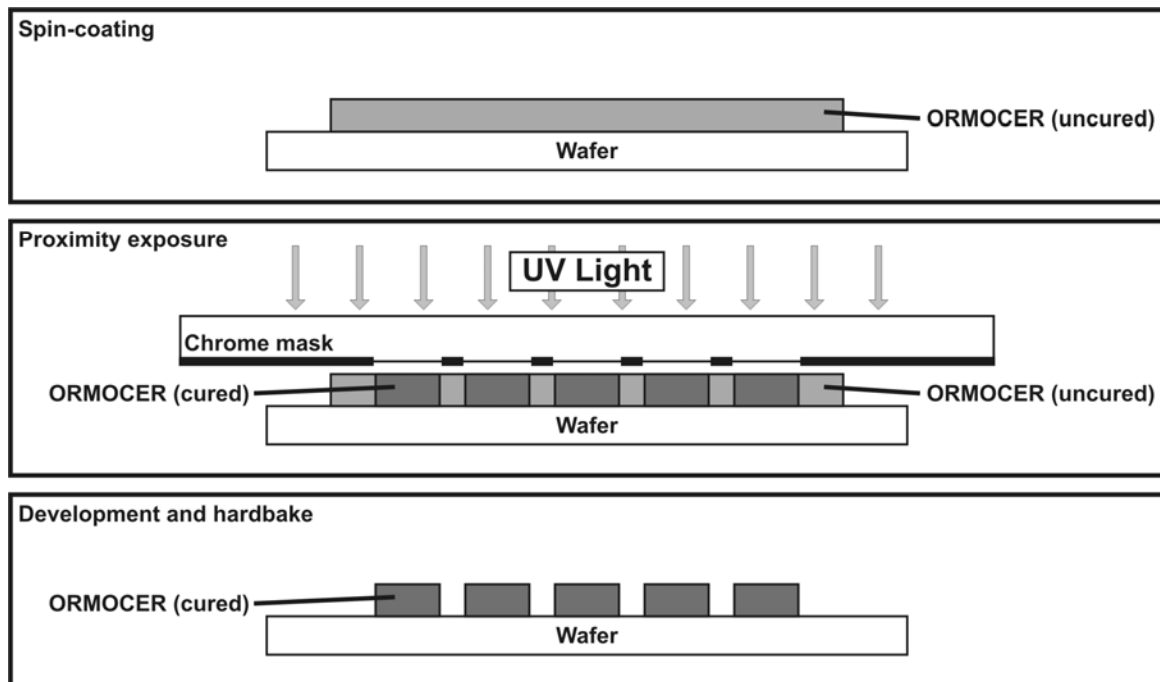


Figure 2.9: ORMOCER® photolithography process steps. A thin layer of ORMOCER® (1 - 100 μm) is spin-coated onto a wafer. Proximity exposure is used to avoid contamination of the mask with liquid resin. The unexposed material is removed from the wafer with developer solution.

Exposure of the ORMOCER® material through a mask will cure only selective parts of the cast material (Figure 2.9). In fact, ORMOCER® can be used as a negative photoresist. The process steps known from conventional photoresist processing can be applied to ORMOCER® as well, but with a few notable differences explained below:

1. Spin-coating

ORMOCER® has a high viscosity compared to most photoresists, therefore it has to be diluted in a solvent to produce very thin films. Films below 30 μm , down to 1 μm can be obtained by diluting ORMOCORE resin with propyl acetate [2.13].

2. Soft bake

ORMOCER® contains no solvents (unless specially added to create thinner films), so unexposed ORMOCER® films will not dry. A soft bake is recommended to allow the film to relax and to improve adhesion.

3. *Exposure*

When a standard photolithography mask is brought into contact with the liquid ORMOCER[®] layer, air cavities will form in between the mask and the resin film. Moreover, the mask will be contaminated with uncured material after the exposure. By using proximity exposure (no contact in between the mask and the liquid film) these problems can be avoided. However, the gap has to be flooded with nitrogen, since the oxygen contained in normal air is inhibiting the UV-curing of ORMOCER[®].

4. *Post exposure bake*

The post exposure bake step is not crucial to the process, but it improves adhesion of the replicated structures.

5. *Development*

A strong polar solvent is applied for the development [2.12]. Metha-isobutyl-methylketon (MIBK) diluted 1:1 in isopropanol (IPA) is used as developer.

6. *Hard bake*

Hard baking is longer than with most other photoresists. Typically, ORMOCER[®] is hard baked for 8 hours at 150 °C, compared to 1 hour at 95 °C for SU-8.

2.3.4 Contact photolithography

By combining the casting/replication process with photolithography steps, new applications become possible. As is shown in Figures 2.10 and 2.11, complex microstructures can be created with very few process steps.

As starting point, the ORMOCER[®] casting process is applied, but a chrome mask instead of completely transparent mold is used. Essentially, a contact photolithography process is applied, but with dispensing instead of spin-coating the liquid material. Further complexity can be added to the resulting structures by using a mask incorporating a 3D relief structure. This mask also serves as mold for the replication of the surface relief at the same time.

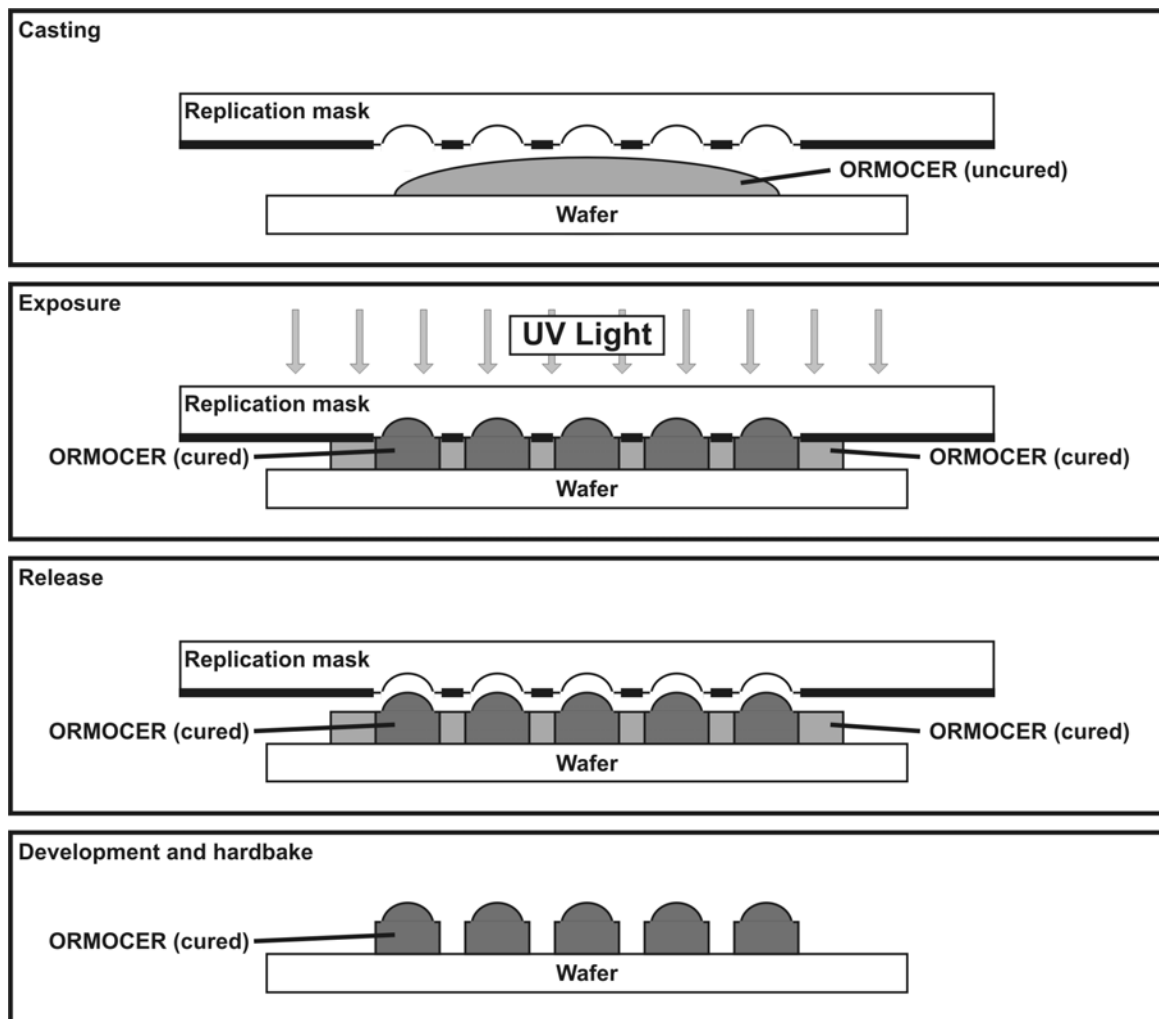


Figure 2.10: ORMOCER® contact photolithography using a relief mold master. After dispensing the ORMOCER® material on the wafer, the replication mask is pressed onto the liquid film. The replication mask incorporates a 3D relief structure as well as a chrome pattern. By illuminating the ORMOCER® through the mask, only the parts not covered by the chrome pattern will be cured. The unexposed material is then dissolved in developer solution and the remaining microstructures are hard baked.

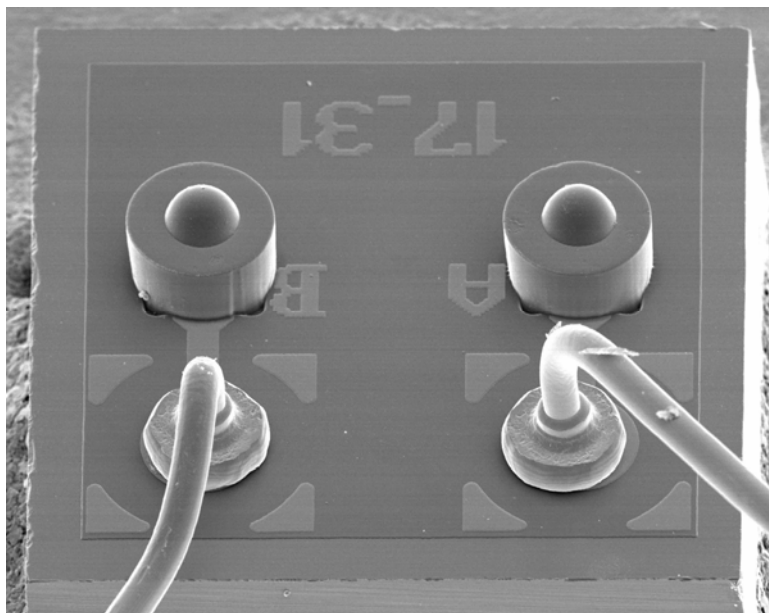


Figure 2.11: Example of a replicated microstructure made by ORMOCER[®] contact photolithography. Two microlenses have been replicated onto vertical cavity surface emitting lasers (VCSELs). The spherical lenses have been defined by a relief in the mold mask used to make these lenses. The outline of the cylindrical base structures has been defined by the chrome pattern on the mask. Only the emitting laser surfaces are now covered with ORMOCER[®] material, dicing lines and bonding pads are free.

2.3.5 Contact photolithography on sacrificial layers

By using a multi-layer approach, free-standing microstructures can be created in ORMOCER[®] material (Figures 2.12 and 2.13). A sacrificial layer of photoresist is applied on the substrate before the casting/molding step. The high viscosity positive photoresist forms a temporary spacer layer of up to 40 μ m in thickness. This sacrificial layer is patterned using a standard photolithography process to create apertures to the substrate. The UV-curable ORMOCER[®] material is then dispensed on top of the sacrificial layer. By illuminating the Sol-Gel material with UV light through the mold mask, the exposed parts are cured. After demolding, both the unexposed polymer material and the sacrificial layer are dissolved away in the same developer solution. Finally, the resulting free-standing ORMOCER[®] structures are hard baked.

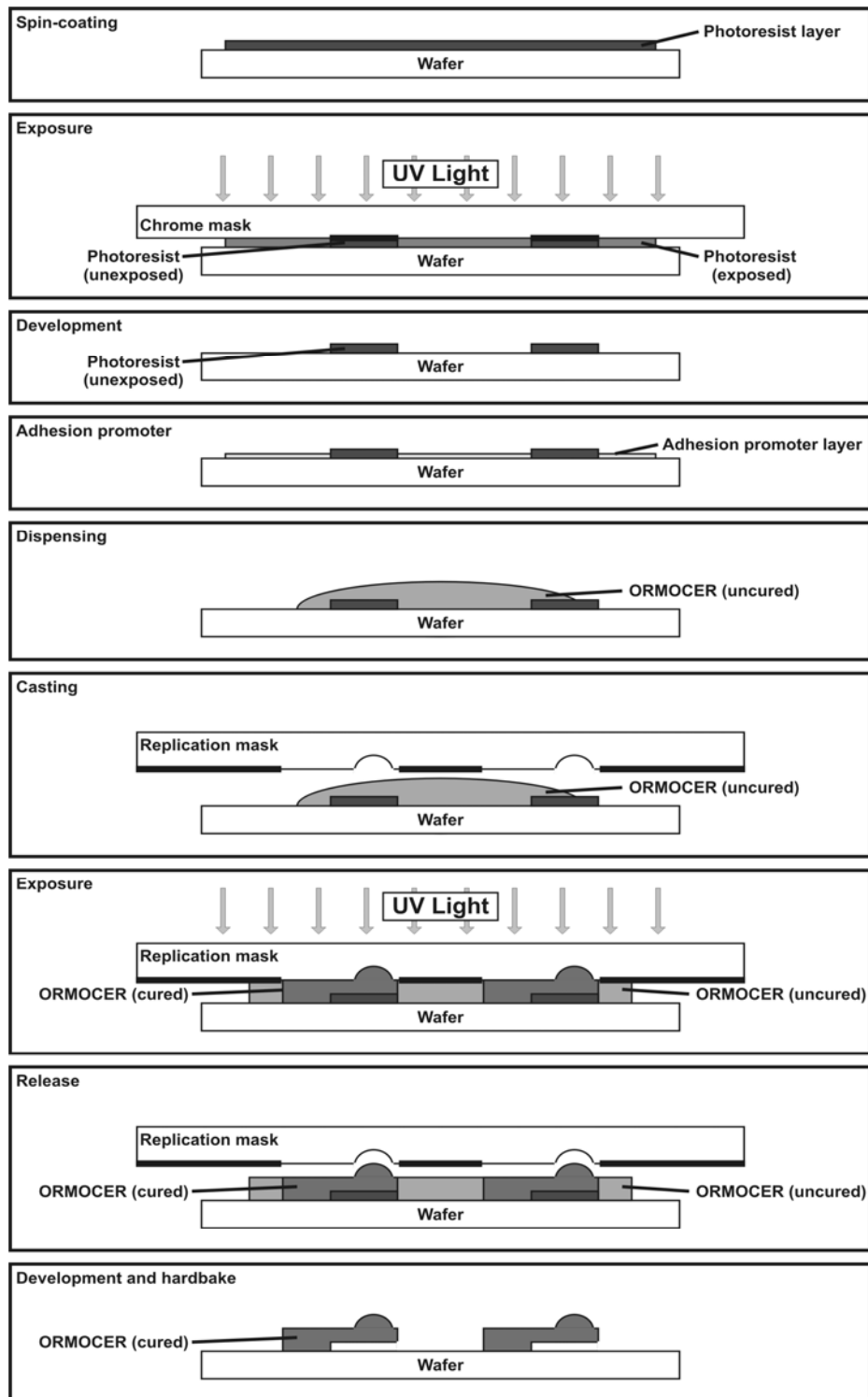


Figure 2.12: ORMOCER® processing including a sacrificial layer. Before the contact photolithography process is performed, the wafer is coated with a sacrificial layer consisting of positive photoresist. On the zones of the wafer that are covered with photoresist will be free-standing elements of the final ORMOCER® structures.

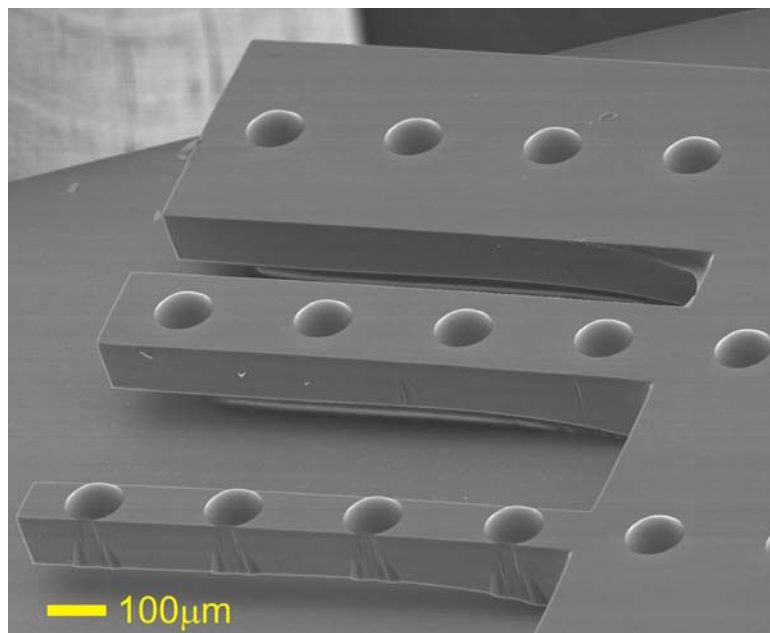


Figure 2.13: Test structures made by ORMOCER[®] contact photolithography on a sacrificial layer. The gap below the beams was defined by a photoresist layer of 30 μm in thickness.

2.4 Conclusions and outlook

ORMOCER[®] Sol-Gels are the result of long research in the field of material sciences. The fabrication processes described here are important steps for the development of microstructures, devices and products using ORMOCER[®] materials. ORMOCER[®] resins can be used like any other negative photoresist, but in combination with other process steps, more interesting applications become possible. The low amount of shrinkage (2 - 8 %) of the material during curing makes it an excellent candidate for UV-casting processes. The selective curing of the material (photolithography) is a very simple way to pattern the microstructures. No etching processes are needed.

Cured ORMOCER[®] material resists temperatures of up to 300 °C [2.1, 2.9, 2.12] and is biocompatible [2.7]. This aspect is very important for the integration of this new material into existent manufacturing processes and for the industrialization of new products. The temperature resistance of up to 300 °C means that it is compatible with lead-free soldering processes, which is rare for such an easy-to-use polymer. However, many challenges remain concerning the different process steps. Good adhesion of the resulting

microstructures on the wafers is very important in most applications. It strongly depends on the surface contamination. Excellent surface preparation and cleaning are therefore crucial for successful manufacturing. During the casting processes, the release step is the most challenging. Wear of the release layer may destroy either the mold or the replica. To improve both the adhesion on the substrate as well as the release from the mold, a good understanding of the molecular chemistry of ORMOCER® resins is essential.

During this work, several goals have been reached: Different processes for the application of ORMOCER® materials have been demonstrated. Photolithography, UV-casting and combinations of both. The next steps in the research (test structures to investigate the technological limits of ORMOCER® material) are elaborated in the next chapter.

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Chapter 3

Material testing and various applications

3.1 Introduction

In this chapter, the assessment of basic material properties of ORMOCER[®]s is made using several test structures. The fabrication processes described in the previous chapter were tested and used to create these elements. After the measurement of the material properties, examples of applications of ORMOCER[®] materials are proposed.

Microlenses are typical examples of high-precision micro-optical elements that can be fabricated in ORMOCER[®] materials. Replication is a cost effective way to produce such elements because one expensive high-resolution master can be used to create many replicas. To expand this cost-effective manufacturing approach towards other types of microstructures and other areas of applications, different fabrication processes have been developed (see previous chapter).

Different application areas also have different requirements. For example, to build micromechanical devices, reliable data of basic mechanical properties (above all Young's modulus) have to be known and the design of functional elements is limited by these properties. For each area of application, limits of the fabrication processes have to be determined, so that design rules for devices can be established. Minimal feature sizes and maximal aspect ratios of generic patterns are important parameters to be evaluated. The shrinkage of ORMOCER[®] materials during curing can significantly affect any type of microstructure and has to be taken into account during design and manufacturing. By manufacturing an assortment of test structures, such basic information has been gathered, and then rules for the design of micro-optical as well as micro-mechanical devices in ORMOCER[®] material have been derived.

3.2 Measurements of Young's modulus of ORMOCER[®] material

An essential parameter for micromechanical devices is the Young's modulus (E) of the structure material. To establish the Young's modulus of ORMOCORE and ORMOCOMP, different tests have been made and their results have been compared. Such measurements depend on many parameters, meaning that the results of these tests may vary a lot and have to be interpreted with care.

3.2.1 Traction tests on bulk samples of ORMOCORE

To measure the mechanical properties of ORMOCORE, traction tests on macroscopic samples have been made. These traction tests have been carried out by the Group of Composites & Polymers at EMPA, Dübendorf, Switzerland.

The measurement of the Young's modulus (E) and the tensile strength (σ_{max}) of a certain material by traction tests is a well-known and well-established technique [3.1]. Usually, bars of the sample material with a uniform cross-section are fixed at both ends and increasing tensile strain is applied. The resulting stress is recorded and a so-called stress-strain curve is plotted. From such a graph, the E and σ_{max} values are obtained and deductions about the behavior of the material under strain (elastic or plastic deformation) can be made.

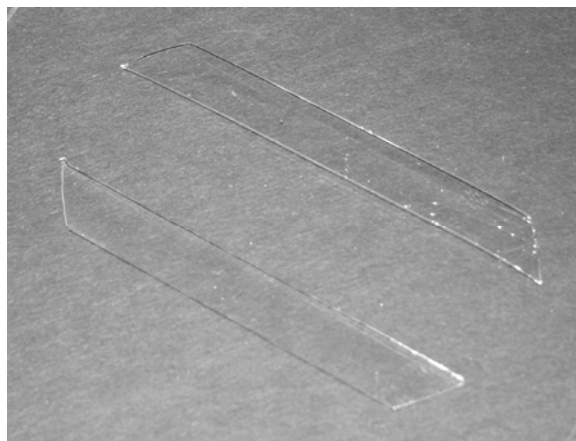


Figure 3.1: Strip of cured ORMOCORE material. The samples were 400 μm in thickness, 10 mm in width and 60 - 90 mm in length. These ORMOCORE pieces have been fabricated with a photolithography process on a glass

plate coated with a PFTE release layer. They were peeled off the glass before the hard bake step.

Here, bulk samples of ORMOCORE with dimensions of 400 μm in thickness, 10mm in width and 60 - 90 mm in length were analyzed (Figure 3.1). Figure 3.2 shows the stress-strain curve of these tests.

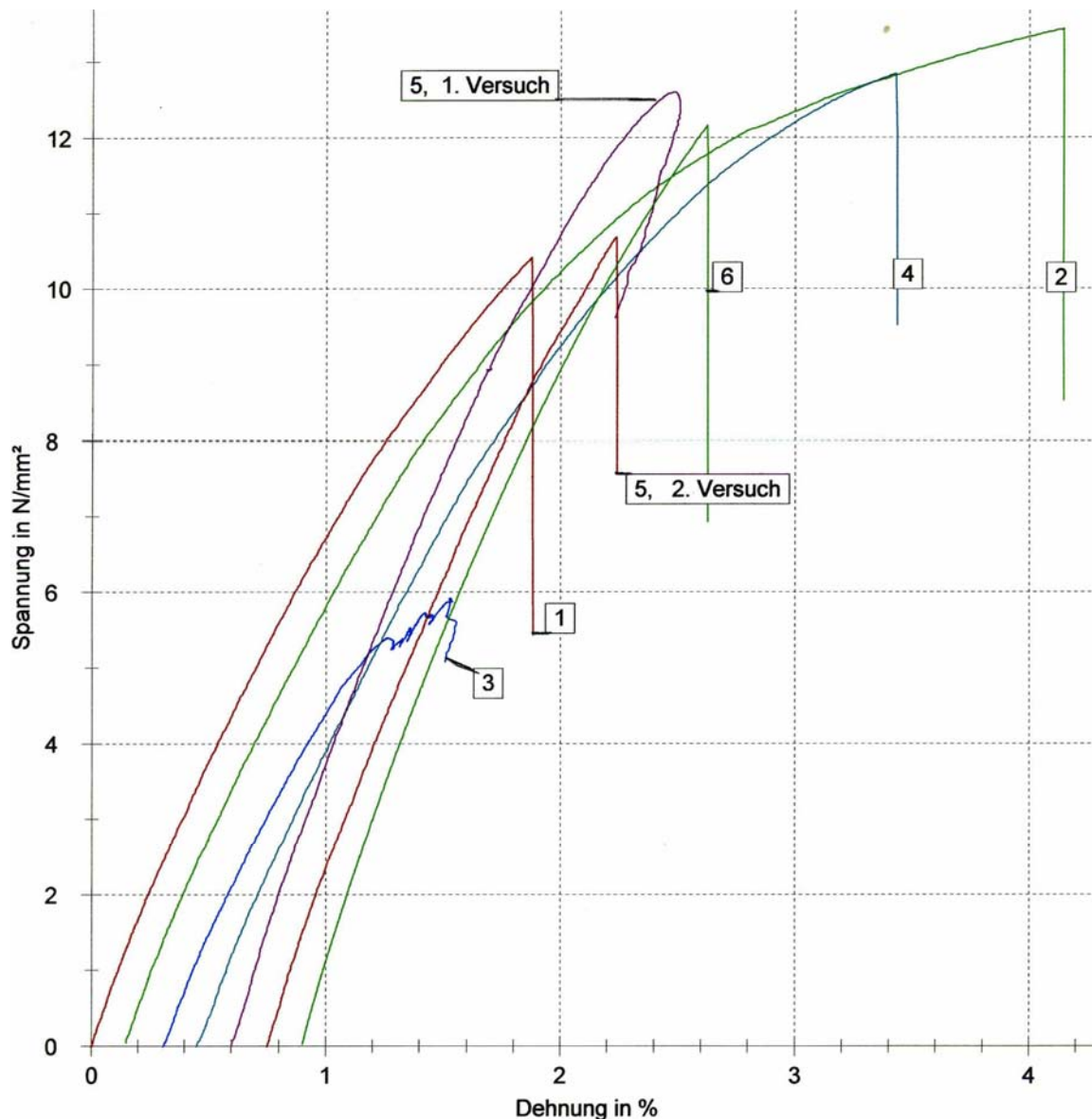


Figure 3.2: Stress-strain curve of ORMOCORE. 6 samples were tested. Sample 3 and 5 had small defects. The Yong's modulus of the tested material is corresponds to the slope of the curve at the initial point. For this series of samples, the slope is almost constant at the start of the curves.

Only 6 such samples were tested. Nevertheless, important conclusions can be made from the results of the measurements:

- The slope of the curve at the initial provides the value for E . The values of the measurements were in the range of: $E = 860 \pm 120$ MPa
- The stress value at highest point of the curve is called the tensile strength σ_{max} . The mean value of the measurements was: $\sigma_{max} = 12$ MPa.

Compared to other polymer materials like polycarbonate ($E = 2000 - 2200$ MPa, $\sigma_{max} = 60 - 65$ MPa) or photoresists like SU-8 ($E = 4000 - 4900$ MPa, $\sigma_{max} = 34$ MPa), the Young's modulus of ORMOCORE is slightly smaller. The value of σ_{max} , however would indicate a very brittle material. It is suspected that this value is due to the difficult nature of these tests and does not represent the true tensile strength of the material. Slightly rugged edges of the test samples can lead to premature breaking during the traction tests and falsify the results. But the shape of the curve is very similar for each sample, meaning that the measurements are repeatable and the results are valid. The slope represents E , so the decreasing slope of the curves indicates a softening of the material, signifying a plastic deformation. The fact that the material shows a plastic deformation before breaking is very useful for the design of microstructures. A very low value of tensile strength has been measured, but much higher values can be obtained in practice, due to this plastic deformation.

3.2.2 Deflection measurements on cantilever beams in ORMOCOMP

To measure the Young's modulus (E) of ORMOCOMP, deflection tests have been made on small cantilever beams at the Group of Mechatronics at the CSEM in Neuchâtel, Switzerland. Different sizes of cantilever beams attached to small sockets had been fabricated with the process described in Chapter 2.3.5 (Figure 3.3). An array of beams was designed with lengths of 200, 300 and 500 μm and widths of 100, 200 and 300 μm . The thickness of the beams was 135 μm . The gap under the free-standing beams was 40 μm .

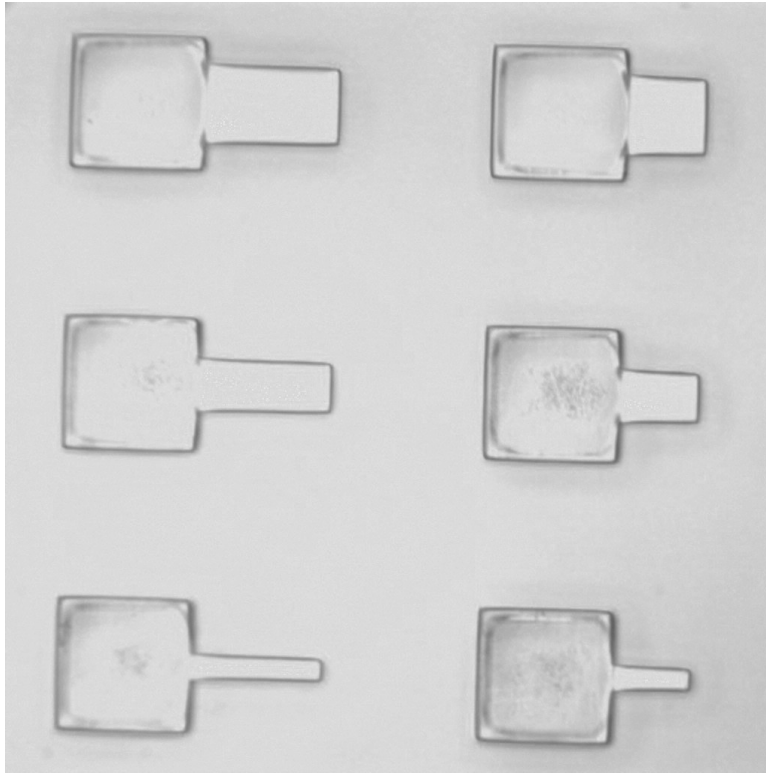


Figure 3.3: Test array of cantilever beams in ORMOCOMP. Each beam is attached to a 500 by 500 μm square socket in the same material. The length of the beams is 500 μm in the left column and 300 μm in the right column. The width of the beams is 300, 200 and 100 μm and the thickness 135 μm . In between the beams and the substrate is a gap of 40 μm .

A gentle force was applied in vertical direction with a force sensor and the deflection was measured. These tests were repeated several times and showed that the deformation of the ORMOCOMP material was elastic and the movement was completely reversible (Figure 3.4).

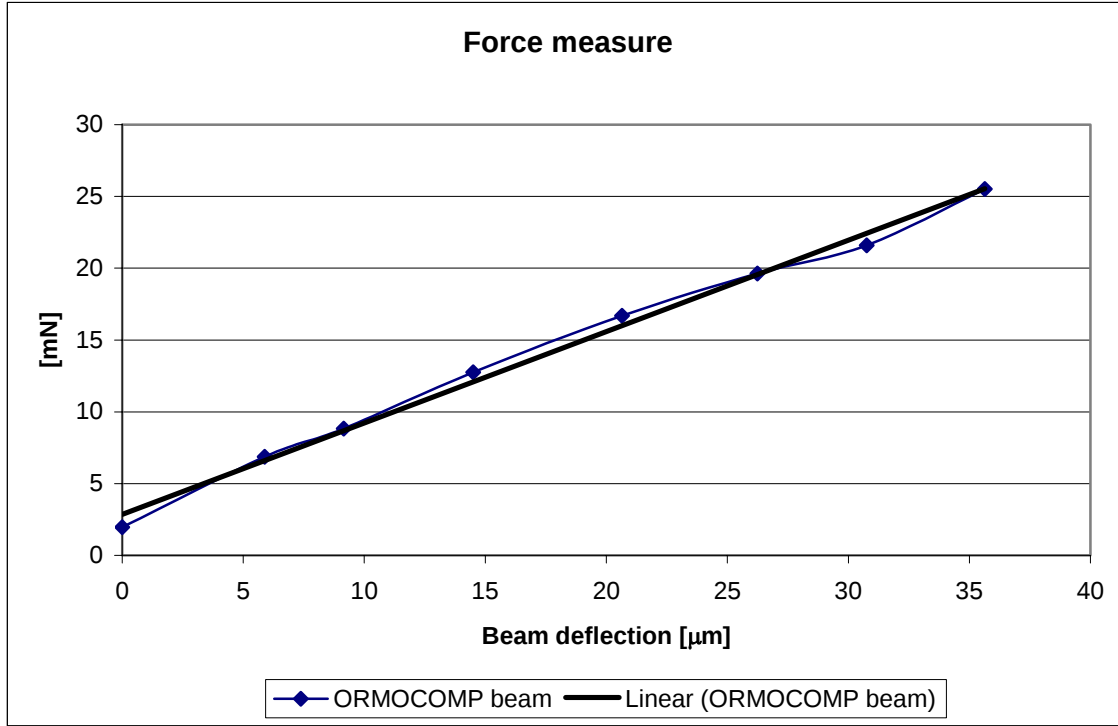


Figure 3.4: Force - displacement diagram of a cantilever beam in ORMOCOMP material. The graph shows that the force increases almost linearly and that Hooke's law is respected.

If the deflection for a certain force is known, E can be calculated. The deflection z of the cantilever beam for a force F is given by [3.2]:

$$z = \frac{Fl^3}{3EI}, \quad (3.1)$$

where l is the length of the beam, E is the Young's modulus and I is the moment of inertia. For a vertically bent beam with rectangular cross-section of width w and height h , I is [3.2]:

$$I = \frac{wh^3}{12}. \quad (3.2)$$

By measuring the deflection z and the force F , the Young's modulus can be calculated as:

$$E = \frac{4Fl^3}{zwh^3} \quad (3.3)$$

For a series of measurements, Young's modulus for ORMOCOMP has been found to be in the range of 925 +/-100 MPa. For these measurements, E depends on the cube of l/h . Very precise values of l and h (and w) have been

measured (with an accuracy better than $\pm 1 \mu\text{m}$). However, the contact point of the force sensor has probably not been applied exactly at the edge of the beams. For the calculations to be correct, only the length of the beam that is effectively bent has to be taken into account. For example, if the point of contact of a beam of $200 \mu\text{m}$ in length has been at a distance of $20 \mu\text{m}$ from the edge, the effective length of the beam has been 10% lower and E is 27.1 % lower, around 675 MPa instead of 925 MPa.

3.2.3 Resonance frequency measurements on cantilever beams in ORMOCOMP

The resonance frequency f_n of a defined structure depends only on its mass, its geometrical dimensions and on the Young's modulus [3.3]. If the resonance frequency of a cantilever beam is known, the E of the material can be calculated.

The resonance frequency f_n of a cantilever beam is given by:

$$f_n = c_n \sqrt{\frac{E}{\rho}} \cdot \frac{h}{l^2} \quad (3.4)$$

$$\text{with } c_n = \frac{(K_n)^2}{2\pi\sqrt{12}} \quad (3.5)$$

Where h is thickness of the cantilever beam (in direction of the vibration), ρ is density of the material and l is length of the beam. The resonance frequency is independent of the width of the beam.

K_n is a constant, depending only on the mode of the vibration [3.4]. For the first mode: $K_n = 1.8751$ and: $(K_n)^2 = 3.516 \rightarrow c_n = 0.1615$.

With constant $c_n = 0.1615$, the Young's modulus E is:

$$E = \frac{f_n^2 \cdot l^4 \cdot \rho}{c_n^2 \cdot h^2} \quad (3.6)$$

$$\text{or } E = \left(\frac{f_n \cdot l^2}{c_n \cdot h} \right)^2 \cdot \rho \quad (3.7)$$

To measure the resonance frequency on a small ORMOCOMP cantilever beam, a part of the wafer was attached to a piezo element and a frequency

sweep from 28 to 54 kHz was carried out. The beam deflection was measured with a laser interferometer (Figure 3.5).

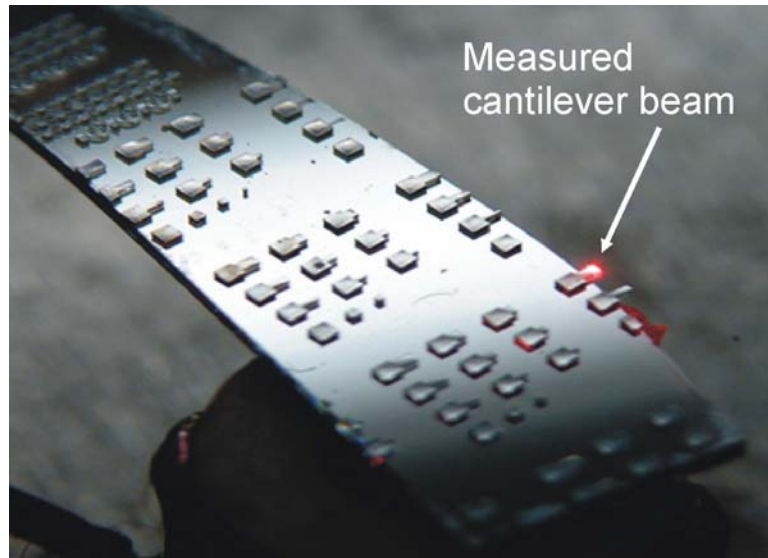


Figure 3.5: Part of a wafer with cantilever beams in ORMOCOMP material glued onto a piezo resonator. The whole wafer has been coated with a thin film of nickel for better reflection of the laser on the structure surface. Here, one cantilever beam is illuminated with a laser for the measurement.

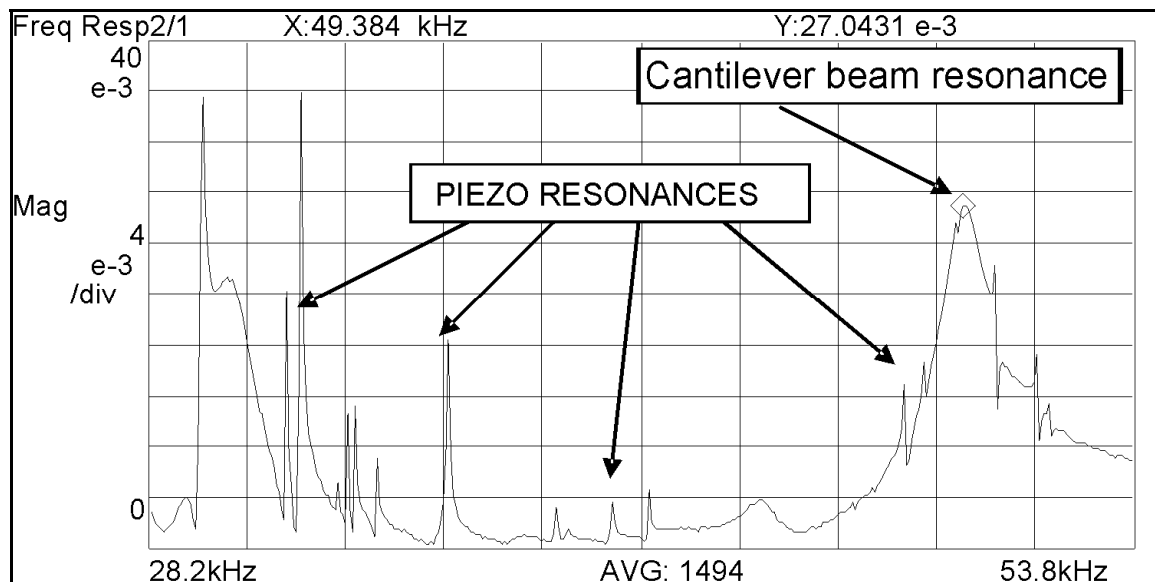


Figure 3.6: Frequency sweep plot from 28 to 54 kHz. The peak to the right shows the resonance of the cantilever beam at 49.4 kHz.

The density of ORMOCOMP is $\rho = 1180 \text{ kg/m}^3$. Figure 3.6 shows the resulting plot from a frequency sweep on a beam of exactly $488 \text{ }\mu\text{m}$ in length and $135 \text{ }\mu\text{m}$ in height. The peak from the cantilever beam resonance can clearly be distinguished at 49.4 kHz .

By using these values in equation (3.7), the resulting Young's modulus E can be calculated as follows:

$$E = \left(\frac{49400 \text{ Hz} \cdot (0.488 \cdot 10^{-3} \text{ m})^2}{0.1615 \cdot (0.135 \cdot 10^{-3} \text{ m})} \right)^2 \cdot 1180 \frac{\text{kg}}{\text{m}^3} = 343.56 \cdot 10^6 \frac{\text{kg}}{\text{m} \cdot \text{s}^2} = 343.56 \text{ MPa}$$

This value of $E = 343.56 \text{ MPa}$ is far lower than the value given by the deflection test. There are several possible reasons for this difference:

- The boundary conditions of the measurement are very important. The glued wafer piece might reduce the resonance frequency of the entire setup. E depends on the square of f_n , so a slight reduction of f_n will greatly reduce value of E . However, to reduce E from 925 to 343 MPa (-63%), a frequency shift from 81.1 kHz to 49.4 kHz (-39.1%) is needed. Such a high difference in frequency is improbable.
- The beam dimensions have a big impact on f_n . The length l of the beam is very well known, but small variations in the beam height h cannot be excluded. To inquire this problem, FEM simulations have been made. The model in Figure 3.7 showed that a reduction of the thickness of the beam at the point of attachment from 136 to $120 \text{ }\mu\text{m}$ reduces f_n to 54 kHz for a hypothetical $E = 900 \text{ MPa}$. This model also takes into account that the socket and the cantilever form one monolithic block that resonates as one piece. The calculations above are only valid for a fixed socket. If the socket is made of the same material as the beam, the measured resonance frequency is lower for the same E .

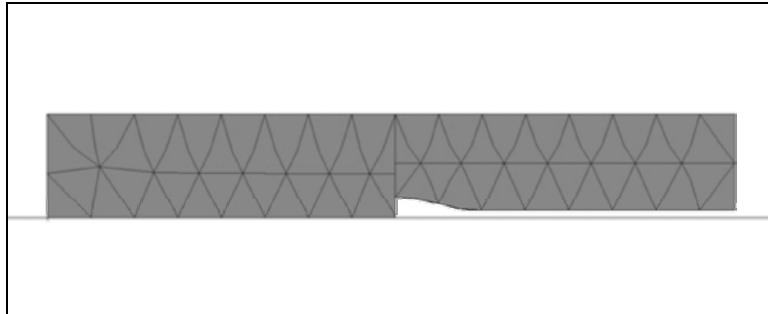


Figure 3.7: Cantilever beam model composed of about 1200 solid TETRA10 elements for NASTRAN simulations.

In conclusion, the measured values of Young's modulus for ORMOCORE and ORMOCOMP materials are very similar (Table 3.1). For ORMOCOMP, the measured values of the deflection tests are much higher than the results for the resonance frequency measurements. This difference can be justified partially by possible measurement errors (contact points, boundary conditions). Nonetheless, the geometrical errors in both types of measurement are identical. One part of the difference remains unexplained, and the results presented here have to be seen as approximations. In Chapter 4, calculations of the mechanical behavior of microstructures in ORMOCOMP have been made with a simple estimation of E with a value of 1 GPa.

Table 3.1: Young's modulus (E) for ORMOCORE and ORMOCOMP materials.

Material:	ORMOCORE	ORMOCOMP	ORMOCOMP
Type of measurement:	Traction tests	Deflection tests	Resonance frequency
Young's modulus (E):	860 +/- 120 MPa	925 +/- 100 MPa	Around 343 MPa

3.3 Test structures for minimal features sizes

To find the limits of the fabrication processes described in Chapter 2.3 and to test the stability of the structures made with these processes, several series of different test structures have been made in ORMOCOMP material. The goal of these tests has been to establishing design rules for future microsystems using ORMOCER[®] contact photolithography. Cantilever beams and small beams that are attached on both sides were made with this combined molding/photolithography approach. In an array of beams, the main parameters of the structures were varied to find minimal feature sizes and maximal aspect ratios achievable. (Figure 3.8)

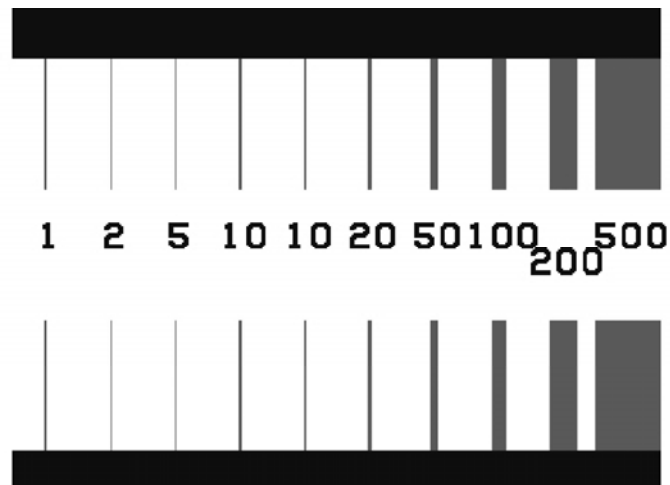


Figure 3.8: Example of a test mask pattern. Here, arrays of cantilever beams of 1 mm in length were designed. The width of the beams was varied in between 1 μm and 500 μm .

The width of the beams was 1, 2, 5, 10, 20, 50, 100, 200, 500 and 1000 micrometers. The length of the beams (and the width of the grooves between the ORMOCER[®] structures) was 10, 20, 50, 100, 200, 500 and 1000 micrometers. The gap below the beams for these test runs was 10 μm (Figure 3.9).

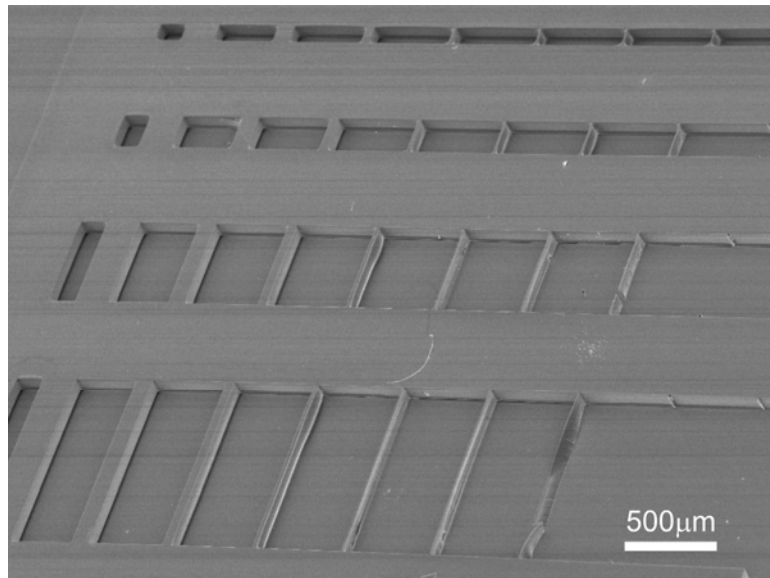


Figure 3.9: Series of bridge beams. The realized bridge beams were very well defined.

The longest beams are 1 mm in length. Beams in width down to 10 μm are stable. 5 μm wide beams tend to break, and even thinner beams cannot be fabricated.

Different factors are limiting the minimal structure size in ORMOCER[®] material: If the size of an ORMOCER[®] structure created by photolithography is compared to the size of the pattern on the chrome mask, a certain loss of dimension can be measured. This dimensional deviation is due to two causes:

- The material is shrinking during the exposure with UV light and during hard baking. This shrinkage can be expressed as a percentage of length or of volume.
- On the edge of the chrome pattern the exposure dose with UV light is slightly lower than in the fully exposed parts. This part will be washed away by the developer solution. This dimension loss is almost constant (around 1 μm for ORMOCOMP).

By exposing ORMOCER[®] with UV light through a chrome mask, the exposed parts will cure instantly. During curing, the crosslinking will shrink the polymer. Because of this slightly higher density, the refractive index of the cured material is also slightly higher than for uncured material. So the exposed material acts as waveguide for the UV light coming from the top. The UV light is guided towards the inside of the cured structure. Overexposure effects known from other negative photoresists is avoided almost completely because of this effect in ORMOCER[®]. On the other hand, the structures tend to have slightly negative sidewalls. (Figure 3.10)

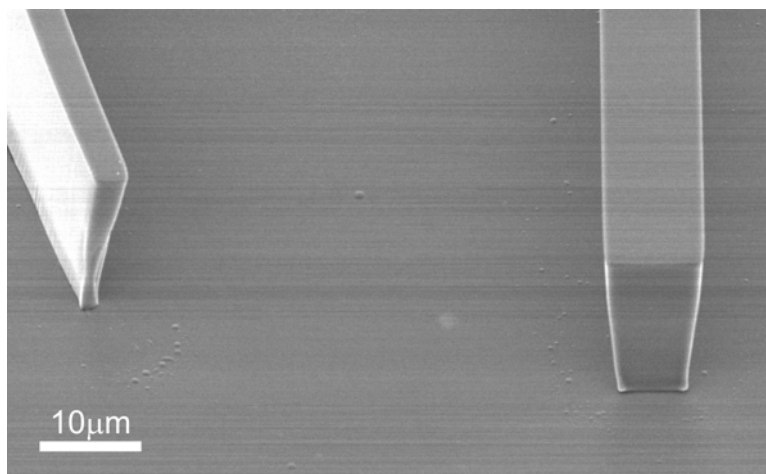


Figure 3.10: Profile of two lines in ORMOCER[®] material. The lines are 5 μm and 10 μm in width and 50 μm in height.

When the beams are short and the distance in between two fixed ORMOCER[®] structures is small, the material tends to fill these spaces (Figure 3.11). The shortest distance in between two fixed ORMOCER[®] structures is around 50 μm . It is difficult to explain why grooves as large as 50 μm are filled with cured material, when lines of 10 μm are very well defined with almost vertical sidewalls.

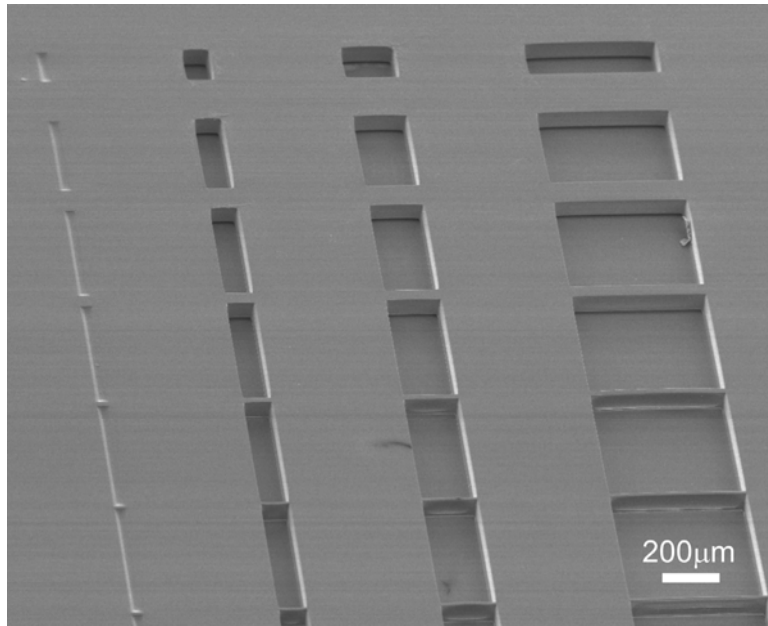


Figure 3.11: Series of bridge beams. The longest beams here are 500 μm in length. The narrow space (50 μm) in between two lines is filled with cured ORMOCER[®] material.

ORMOCER[®] materials are cured by triggering to the photostarter molecules with UV radiation (Chapter 2.2.1). However, oxygen molecules in the resin are inhibiting this reaction by blocking the radicals. A certain threshold of UV dose has to be surmounted before the polymerization starts. This threshold, combined with the auto-waveguiding effect explained above results in this digital behavior of the photosensitive ORMOCER[®] resins.

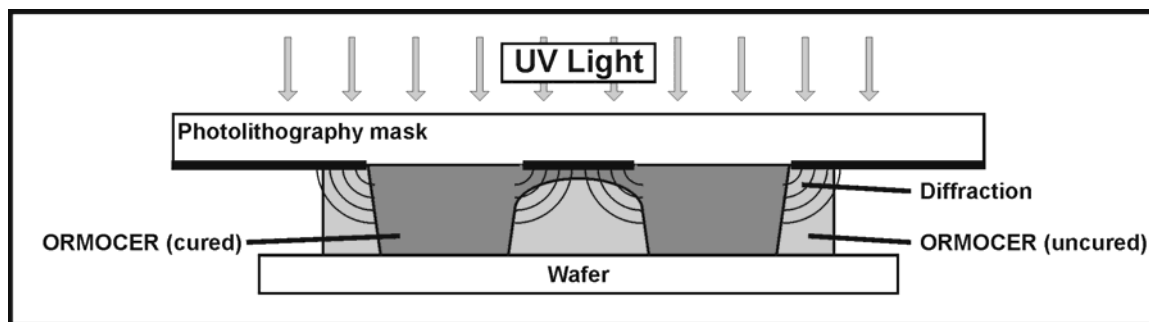


Figure 3.12: UV exposure of ORMOCER[®] through a photolithography mask. The diffracted light at the edge of the chrome pattern is not enough to cure the material. If two structures are too close to each other, the intensity of the two overlapping diffraction sources is enough to cure the ORMOCER[®].

Two lines in ORMOCER[®] material created by a contact photolithography process are very well defined if they are far apart. Very little UV light is diffracted at the edges of the chrome mask pattern; the rest is guided downwards. The low dose of diffracted UV light is not enough to overcome the curing threshold imposed by the inherent oxygen inhibition of the resin. If the two lines are in proximity of each other, the diffraction of the UV light at the chrome mask pattern is cumulative for these two lines, and the curing threshold is surmounted (Figure 3.12). Once the curing starts also in horizontal direction, the UV light is no longer focused in vertical direction and the zone of cured ORMOCER[®] material is widening more and more, resulting in completely cured material in between the lines.

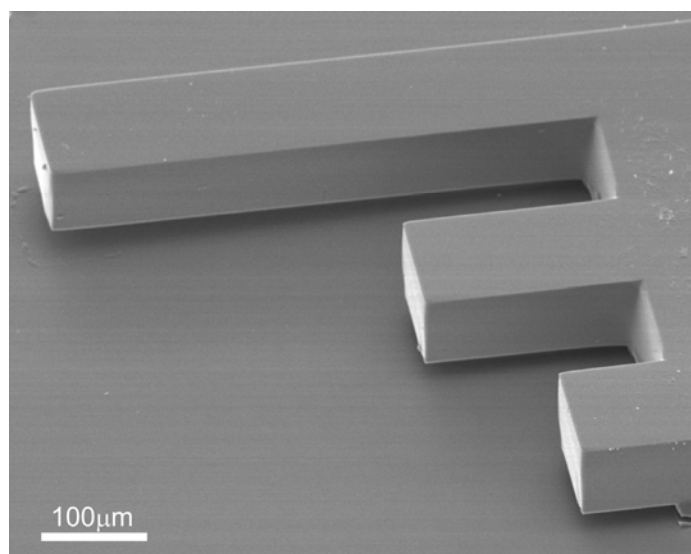


Figure 3.13: Cantilever beams of 500 μm , 200 μm and 100 μm in length. All beams are 100 μm wide. The gap below each beam is 10 μm .

Cantilever beams in ORMOCER[®] materials have been fabricated in various sizes (Figure 3.13). Beams up to a certain length can be produced in a repeatable manner. Beams with a length-to-width ratio that is too high are bending down during the fabrication process and will be in contact with the substrate after curing and hard bake (Figure 3.14).

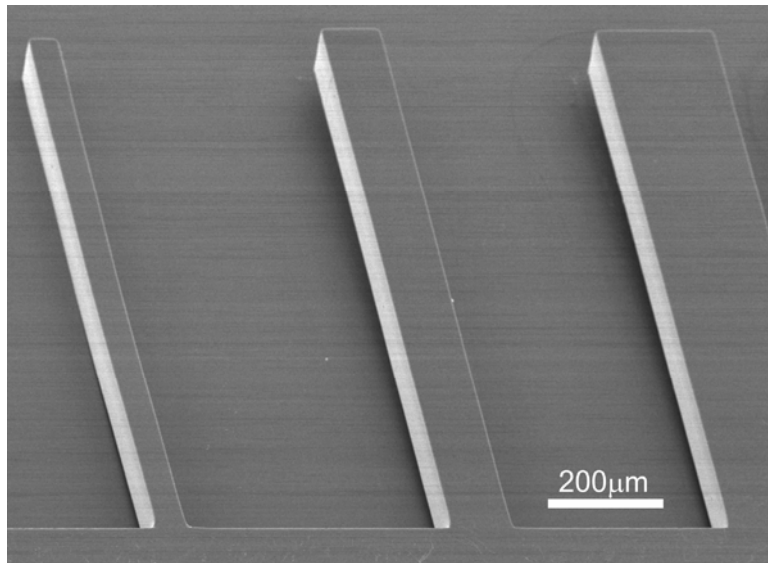


Figure 3.14: Cantilever beams with a length of 1 mm. The thinnest beam (50 μm) is too weak to sustain itself.

An extension of the ORMOCER[®] cantilever fabrication technology is the monolithic integration of high precision micro-optical features on top of the structures using the process described in Chapter 2.3.5 (Figure 3.15). Such structures can be used in MOEMS devices and for optical stacks.

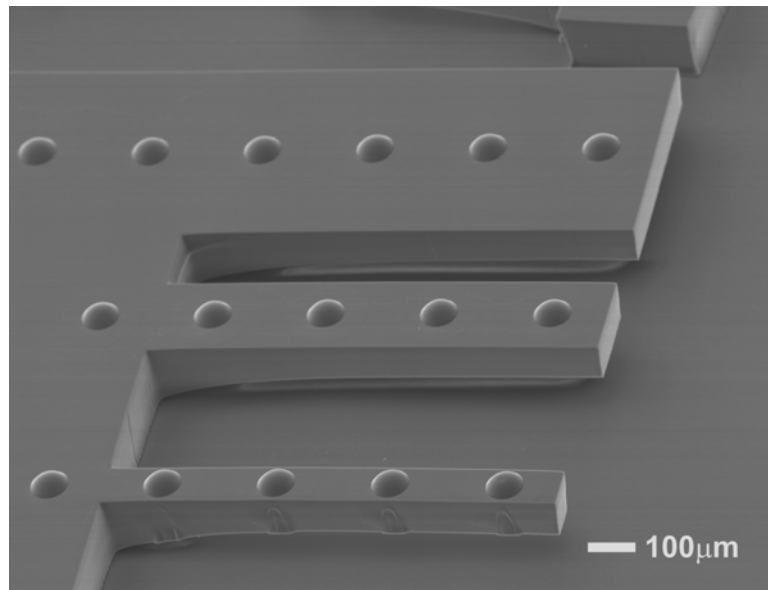


Figure 3.15: Replicated ORMOCER[®] cantilever beams with microlenses on top. The beams are 1 mm in length, 50 μm in height and 500, 200 and 100 μm in width. The gap under the beams is 30 μm . The microlenses are 80 μm in diameter.

3.4 Shrinkage measurement by strain conversion microstructures

The shrinkage of ORMOCER material during processing can be very limiting for the design of microstructures. The test structures presented here have been used to analyze this shrinkage. At the same time they illustrate very well how a relatively simple device design can be drastically deformed by the material shrinkage of only a few percent. The structures shown in Figure 3.16 convert tensile strain into compressive strain. These free-standing ring structures with a center beam across were distributed on different locations on the substrates. If the center beam is too slim, it will buckle [3.5] [3.6]. In this example, rings with a diameter of 800 μm have been fabricated and analyzed. The beams that are 20 μm in width and smaller are buckled; beams of 50 μm and more in width remain stable. These two values are used to calculate two corresponding values of strain. The effective strain (and the equivalent shrinkage) lies somewhere in between the two resulting values.

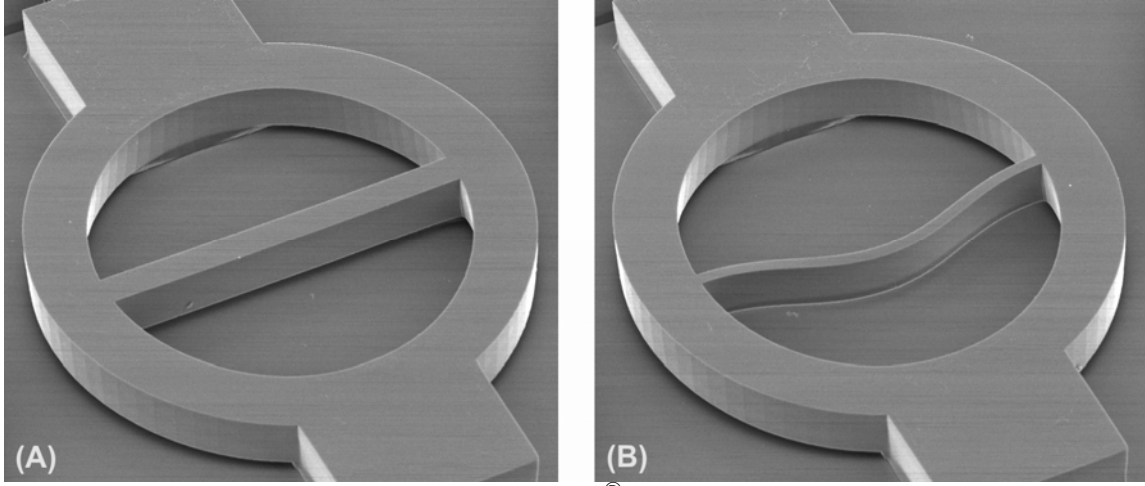


Figure 3.16: Free-standing ORMOCER[®] rings with central beam. The outer diameter of these rings is 800 μm . Such structures convert tensile strain into compressive strain. If the compressive strain is too high, the beams are buckling.

The theory of these structures was established by Guckel et al. [3.7]. Here, a first approximation for the rings was used to calculate the resulting strain. For a very slender ring, the tensile strain in the ORMOCER[®] material is

$$\varepsilon_0 = \frac{\Pi^2 \cdot b_b^2}{12 \cdot g(R) \cdot R^2} \quad (3.8)$$

where b_b is the width of the center beam, R is the radius of the ring and $g(R)$ is the conversion efficiency of tensile strain into compressive strain. For an ideal ring $g(R) = 0.918$.

Strain values found in the fabricated test structures lie in between 0.25 % and 1.8 %, resulting in calculated volume shrinkage in between 2.2 % and 5.3 %. Note that the formula (3.8) is an approximation for a very slender ring. The conversion efficiency of the real rings is probably lower and the resulting strain values should be higher [3.8].

3.5 Refractive microlenses in ORMOCER[®] material

One interesting application of the basic ORMOCER[®] wafer scale replication process (Chapter 2.3.2) is the fabrication of arrays of refractive microlenses. Starting from an array of original lenses (typically reflow lenses [3.9] or lenses etched into fused silica [3.10]), a negative copy of these lenses is

made in ORMOCER[®]. By using this negative form as original for the next replication step, a positive copy of the original lens array is fabricated. Depending on the size of the replicated lenses, the final replica is either diced into individual lenses or into microlens arrays.

The Center for Computational Physics at the Zürcher Fachhochschule Winterthur, made finite element simulations of the shrinkage during curing and studied how the shrinkage affects the final form [3.11]. For these simulations NM Seses FEM software was used (NM Numerical Modeling GmbH). The simulation results have been verified with measurement data of replicated microlenses.

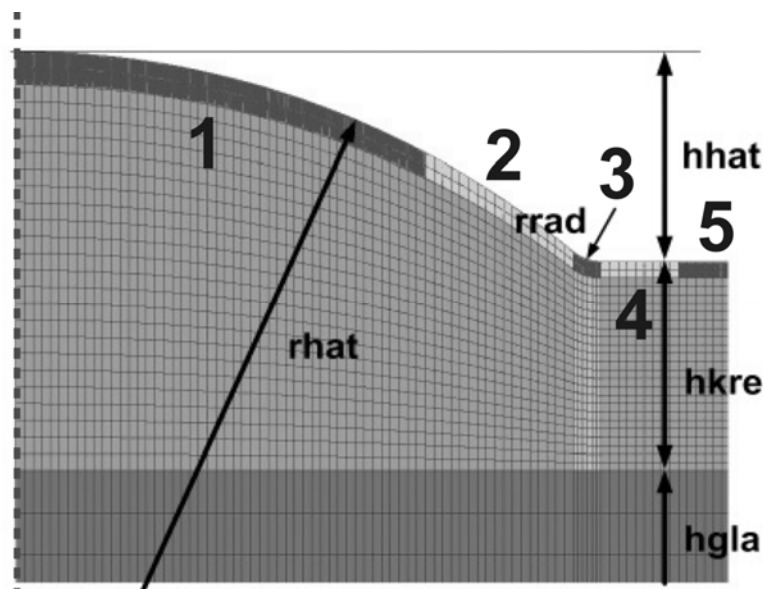


Figure 3.17: Fine mesh model of a convex microlens for FEM simulations. The radial symmetry of the lenses simplifies the model.

For the FEM simulations, the lens topography has been divided into 5 areas (Figure 3.17):

1. Lens center
2. Lens curvature
3. Lens edge
4. Base layer (close to the lens edge, stress is linked to lens deformation)
5. Base layer (has no influence on lens deformation)

The simulations have shown that only tensile stress appears after the shrinkage. The stress is highest at the lens edge for convex microlenses

(Figure 3.18) and at the lens center for concave microlenses (Figure 3.19). For both types of microlenses the lens radius increases slightly with each replication step. The simulations also have shown that the base layer does not have any influence on the deformation of the microlens if the surface covered by the base layer around the lens is big enough. For example, a base layer of 50 μm in thickness around a microlens needs to cover a surface up to a minimum distance of 185 μm from the lens edge.

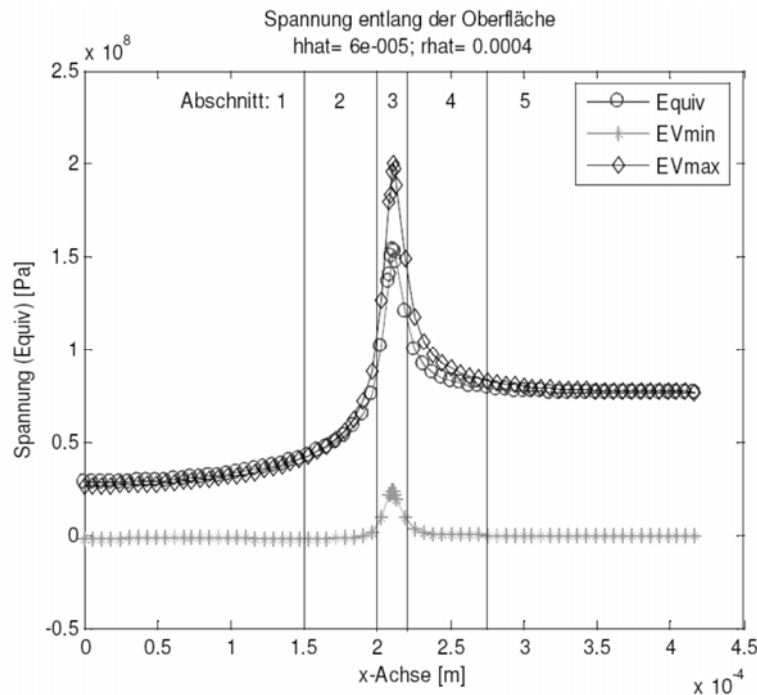


Figure 3.18: Stress at the surface of a replicated convex microlens. The maximum stress is at the lens edge.

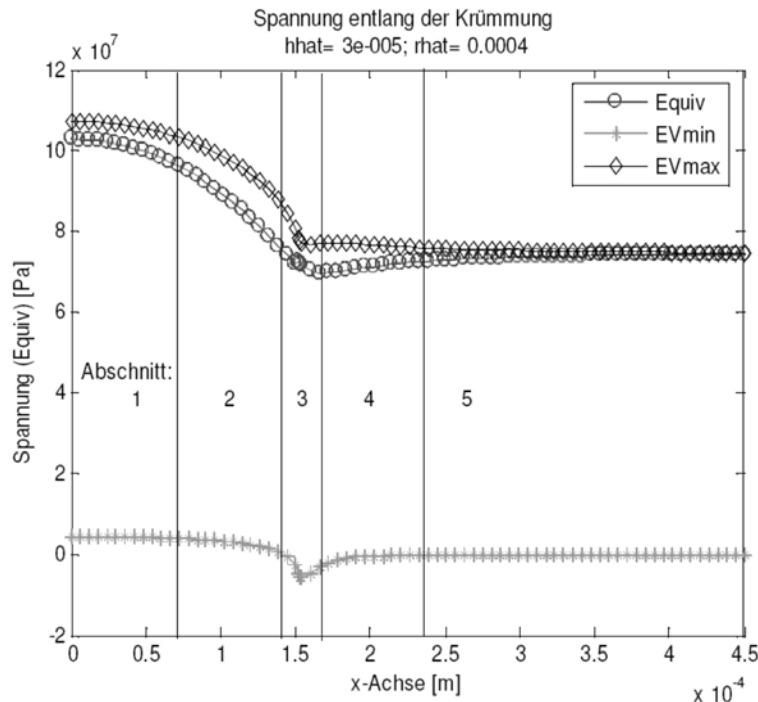


Figure 3.19: Stress at the surface of a replicated concave microlens. The highest stress is at the lens center.

An application for replicated lens arrays is the replication of lenses directly onto VCSEL (Vertical Cavity Surface Emitting Laser) chips [3.12]. The wafer scale replication process combined with photolithography (Chapter 2.3.4) is used to create such structures. By applying microlenses onto VCSELs, the laser light can be collimated or focused for lens coupling for example. Larger microlenses (2 mm in diameter) have been fabricated for optical surface mounted devices for optical geodesy systems [3.13].

3.6 ORMOCER[®] for diffractive optics

Due to its low shrinkage during curing, ORMOCER[®] material it is suited very well for the replication of extremely small features. ORMOCER[®] has been used successfully for the replication of diffractive gratings with feature sizes as small as 80 nm. Diffractive optical elements are replicated in ORMOCER[®] using wafer scale casting processes (Chapter 2.3.2). From one master, a series large of replicas can be produced. Various types of masters can be used, for example quartz plates, nickel shims or silicon wafers. In this thesis, only one brief example of a replicated diffractive optical element in

ORMOCER[®] material is shown. Results of the development of such applications reported in: [3.14] (low-cost polarizers), [3.15] (grating couplers), [3.16] and [3.17] (diffractive lenses). Diffractive optics in ORMOCER[®] materials are also used for anti-reflective coatings and features for security applications [3.18].

An example of a replication master is shown in Figure 3.20. With this master, some of the smallest features in ORMOCER[®] so far have been fabricated. (Figure 3.21)

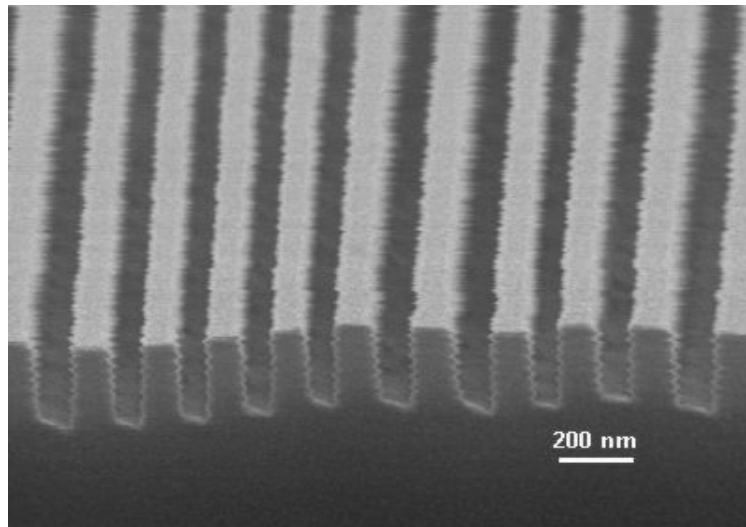


Figure 3.20: SEM picture of the surface of a quartz replication master. The grating period is 200 nm. This master was produced by holographic exposure of photoresist and subsequent etching of the line pattern into the quartz.

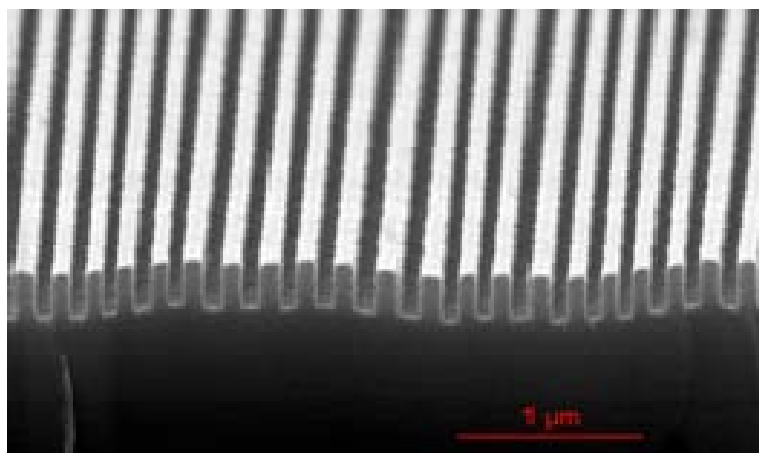


Figure 3.21: SEM picture of the surface of a replicated grating in ORMOCORE. The grating period is 200 nm. The linewidth is around 80 nm and the depth of the trenches is 240 nm.

3.7 Various applications

3.7.1 AFM tips in ORMOCER[®] material:

Atomic force microscopes (AFMs) are very useful devices to examine surfaces of various types of materials at very high resolutions [3.19].

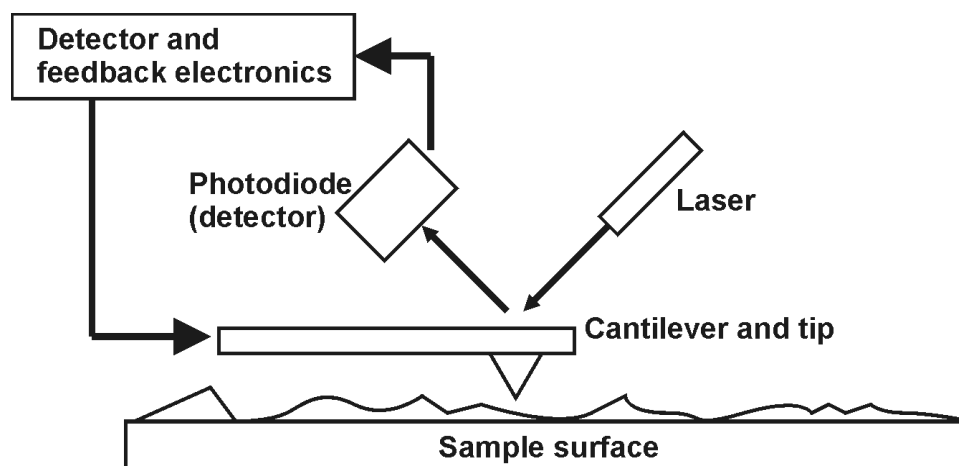


Figure 3.22: Atomic Force Microscope block diagram.

The key part of an atomic force microscope is the tip that is situated on a cantilever beam. The tip is in close proximity of the surface of the sample (Figure 3.22). The Van der Waals forces between the tip and the sample leads to a deflection of the cantilever beam. The deflection can be measured by using a laser spot reflected from the top of the cantilever beam into a detector. An alternative deflection measurement method is by piezoresistive strain gauges on the cantilever beams.

The cantilever beam is the most vulnerable part of the device. Depending on the application, the tip shows wear or the beam can break. In commercial AFMs, the whole beam can be replaced by exchanging a cartridge. Common devices use cantilever beams with tips etched into silicon.

If the device is used in difficult conditions, where one measurement contaminates the tip to the point where a replacement is needed, the cost of one such measurement increases drastically. The solution is to produce cheaper cantilever beams with suitable tips. The fabrication by ORMOCER[®] replication processes would make such disposable one-shot AFM-tips possible.

The feasibility of cantilever beams in ORMOCER[®] has been demonstrated before (Chapter 2.3.5). Therefore, the focus here is on the fabrication of the tips. The wafer scale replication process (Chapter 2.3.2) was used to make replicas of pyramidal microstructures. The original structures were etched into silicon wafers by anisotropic etching at SAMLAB at the IMT Institute of Microtechnology at the University of Neuchâtel. By using a photoresist etch mask with square apertures, the anisotropic etch process used on silicon wafers with [100] crystalline orientation creates holes with a pyramidal shape [3.20]. After the application of a release layer, replicas of the tip structures have been made in ORMOCOMP and ORMOCORE material (Figure 3.23)

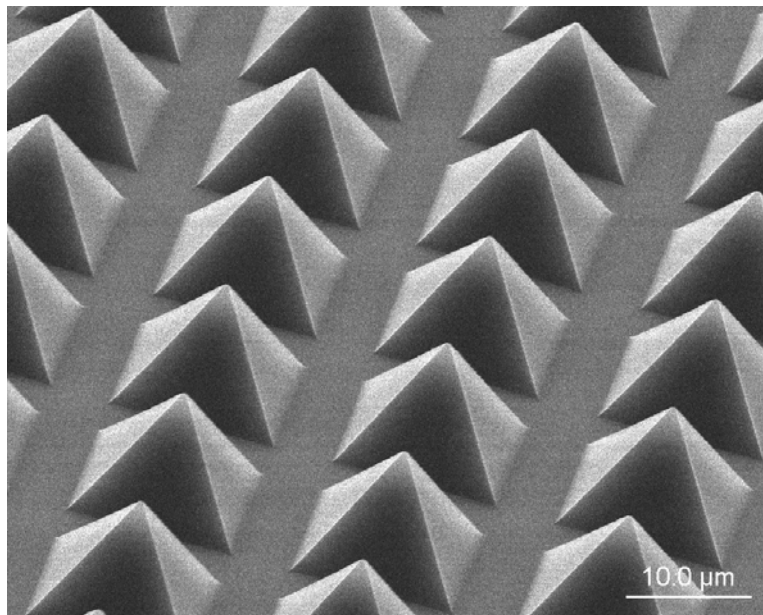


Figure 3.23: Array of replicated pyramidal tips in ORMOCER[®].

The wafer scale replication process was used successfully for these types of structures. Demolding worked fine. No mayor defects were observed neither in the replicated structures, nor in the mold after processing. The tip radius of the replicated ORMOCER[®] structures was found to be in the range well below 1 micrometer (Figure 3.24). Even if the values of the radii are not in the range of state of the art AFM tips, for the target applications of low-cost disposable tips, tip radii in the range of 10 to 50 nm are suitable. Exact values of radii are difficult to measure. However, it can be observed that the tips structure is not identical in x and in y direction. In one direction the tip edge does not show a clear peak, but a so-called knife edge. This non-

uniformity is probably due to the fact that the original square mask apertures for the anisotropic etch process were not exact squares.

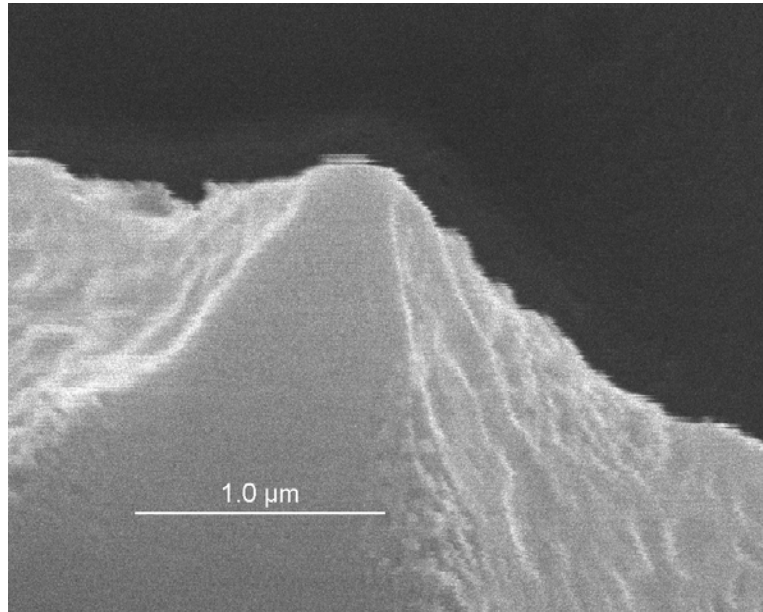


Figure 3.24: Close-up SEM micrograph of an ORMOCER[®] tip. The structure does not converge in one point to form a clear tip. Instead a so-called knife edge structure is appearing.

The replicated ORMOCER[®] tip structures are promising for the target application in low-cost, disposable AFM tips. Using one etched master wafer to create many replica wafers is very cost-effective. The parameters of the replicated tips suit the target application also very well. Furthermore, the possibility to combine the pyramidal tips with a cantilever beam into one monolithical structure (as demonstrated in Chapter 3.3 with microlenses) makes this approach even more interesting. Replicated low-cost, disposable AFM tips could help to expand the application fields of AFM devices into the promising research domain of biomedical applications.

3.7.2 Parallel plate electrostatic actuators

ORMOCER[®] materials are attractive for many different microsystem devices and applications. Microstructures of various types can be integrated onto cantilever beams and other 3D structures. But to build a complete microsystem, it is necessary to integrate additional functionality like sensing

or actuating. An interesting extension of the cantilever beam technology is the creation of parallel plate actuators.

Parallel plate actuators are very common types of actuators for silicon microsystems. They are used in devices like:

- Micro relays [3.21]
- Digital micromirror devices (DMD) [3.22]
- Tunable capacitors [3.23]
- Gas Valves [3.24]

The basic structure of the electrostatic parallel plate actuator is the well-known parallel plate capacitor. In a capacitor charged with charges Q , the positive and negative charges are attracted to each other and a force F_E pulling the two capacitor plates together is created [3.23]:

$$F_E = -\frac{1}{2}U^2 \frac{\varepsilon_0 S}{(g-x)^2} \quad (3.9)$$

Assuming an ideal capacitor that is part of an infinite plane without fringe effects in the electric field, U is the voltage and g the gap in between the two capacitor plates, ε_0 is the local dielectric constant, S is the active surface of the capacitor and x is the displacement.

The mechanical part of the system can be described as a spring with a restoring force F_M according to Hooke's law:

$$F_M = -kx, \quad (3.10)$$

where k is a constant depending on the geometry and the material of the actuator.

Equalizing the two equations (3.9) and (3.10), results in the following general term for the parallel plate actuator:

$$(g-x)^2 x = \frac{\varepsilon_0 S}{2k} U^2. \quad (3.11)$$

At a displacement of $x = g/3$, the maximum voltage is reached and the so-called pull-in effect occurs: from this point on the voltage required to further pull the two plates together is lower than the voltage already applied. The plates will snap together instantly, effectively limiting the working range of such an actuator.

The voltage at the maximum working range is called pull-in voltage and can be expressed as [3.25]:

$$U_{pull-in} = \sqrt{\frac{8kg^3}{27\epsilon_0 S}}. \quad (3.12)$$

For typical microsystem device, the maximum voltages used should not exceed 100 V, so that expensive amplification electronics can be avoided. On the other hand, for a versatile device, a large working range is needed. Here, a trade-off in between the two parameters has to be found.

ORMOCER[®] is a very good electric insulator, (dielectric constant of 3.2 at 10 kHz) so to build parallel plate actuators with ORMOCER[®] material, metal layers have to be integrated into the system.

Two types of parallel plate actuators in ORMOCER[®] material have been designed. The first category consists of a cantilever beam with the parallel electrodes below (Figure 3.25).



Figure 3.25: Electrostatic cantilever beam parallel plate actuator. For the calculations, it is assumed that the electrodes are covering the whole length and width of the cantilever beam.

The constant k in Hooke's law for this type of deflected beam is [3.2]:

$$k_{b1} = \frac{8EI}{l^3}, \quad (3.13)$$

where E is the Young's modulus of the structure material, I is the moment of inertia of the beam and l is the length of the beam.

The moment of inertia of a deflected beam with a rectangular cross-section is [3.2]:

$$I = \frac{h^3 w}{12}, \quad (3.14)$$

for a beam with height h and width w .

The resulting pull-in voltage of a cantilever beam electrostatic actuator is:

$$U_{pull-in,b1} = \frac{4}{9} \sqrt{\frac{E}{\epsilon_0} \cdot \frac{h^3 g^3}{l^4}} \quad (3.15)$$

A beam with a big height and a large gap between the plates will increase the pull-in voltage. A long beam will decrease the pull-in voltage. It is noteworthy that the beam width doesn't have any influence, if the electrode plate is covering the whole beam.

A more stable device consists of a bridge beam structure (also called fixed-fixed beam) with the parallel plate actuator beneath it:



Figure 3.26: Electrostatic bridge beam parallel plate actuator.

The constant k in Hooke's law for a deflected bridge beam is [3.2]:

$$k_{b2} = \frac{384EI}{l^3}, \quad (3.16)$$

meaning that the spring force is 48 times higher than for a cantilever beam. The resulting pull-in voltage is

$$U_{pull-in,b1} = \sqrt{48} \cdot \frac{4}{9} \cdot \sqrt{\frac{E}{\epsilon_0} \cdot \frac{h^3 g^3}{l^4}}. \quad (3.17)$$

The process flow to build such devices consists of the following steps (Figure 3.27): The lower electrode plate is fabricated directly on the substrate. In the devices built here, borofloat glass wafers were used. The first process step was the coating of the wafers with the metal for the electrodes. A layer of 400 nm in thickness of aluminum was deposited using e-beam evaporation. To guarantee good adhesion of the aluminum, a thin layer (15 nm) of chrome was evaporated first. Standard microfabrication techniques were used for the structuring of the electrodes: photolithography with positive photoresist (Shipley S1805), aluminum etch (PAN etch solution), chrome etch (ceric sulfate tetrahydrate solution) and resist stripping.

The following process steps are similar to the fabrication method for free-standing ORMOCER[®] beams introduced in chapter 2.3.5: A high viscosity photoresist is used as sacrificial layer. The next step is the most crucial in the fabrication of the parallel plate structure: To connect the upper electrode to the bonding pads on the substrate, the wiring has to cover an almost vertical step. To achieve this link, the metal layers are evaporated through a shadow mask. After this evaporation, the beams are fabricated by

ORMOCER[®] contact photolithography, the resist of the sacrificial layer is removed, and the final structures are hard baked.

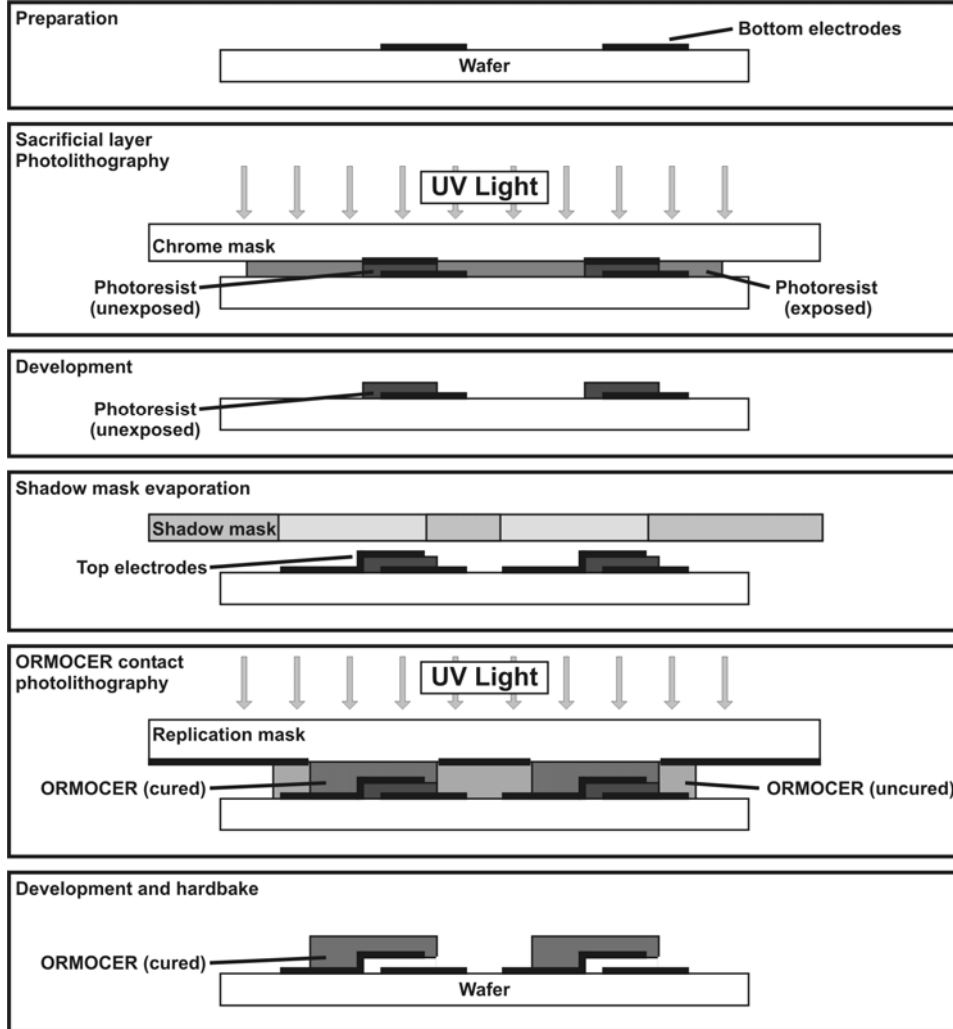


Figure 3.27: Process flow of the fabrication of parallel plate actuators on ORMOCER[®] beams. After the patterning of the bottom electrodes, the sacrificial layer is coated on the wafer. On top of the sacrificial layer photoresist, the top electrodes are applied by shadow evaporation. The final structures are defined by an ORMOCER[®] contact photolithography process, and then the sacrificial layer is removed.

Arrays of beams including metal layers have been fabricated (Figure 3.28). The structure parameters of a typical device parameters are approximately: Beam height: $h = 70 \text{ } \mu\text{m}$, beam length: $l = 500 \text{ } \mu\text{m}$. Gap below the beam: $g = 9 \text{ } \mu\text{m}$. E is estimated at 1 GPa, ϵ_0 in air is $8.85 \cdot 10^{-12} \text{ C/Vm}$.

According to equation (3.15), such a system has a pull-in voltage of around 300 V, which is much too high to operate in a reasonable device.

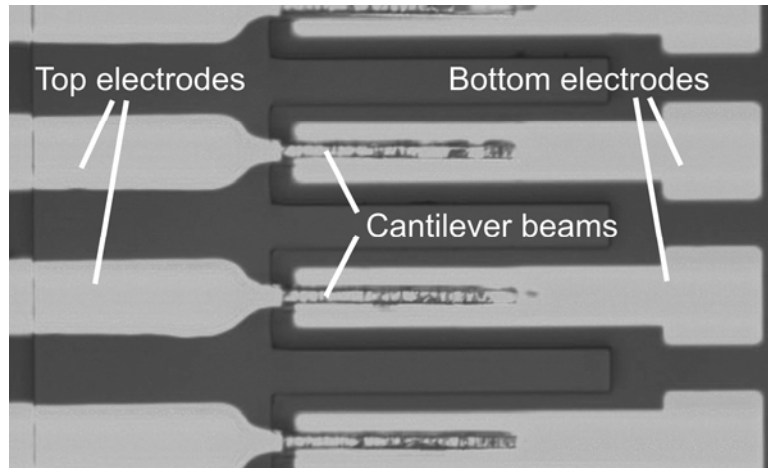


Figure 3.28: Array of cantilever beams including metal layers (top view). The beam structure is made in ORMOCER[®] material (500 μm in length and 50 μm in width). The two electrodes consist of a 400 nm thick layer of aluminum. The buckling of the slender top electrodes below the cantilever beams is clearly visible.

Stable microstructures that are suitable for electrostatic actuation are difficult to obtain. The resulting cantilever beams are all bent upwards due to the shrinkage of the ORMOCER[®] material during curing and hard bake (Figure 3.29). The thin film metal strip below the beam is compressed and many structures on a wafer are buckled or peeled off.

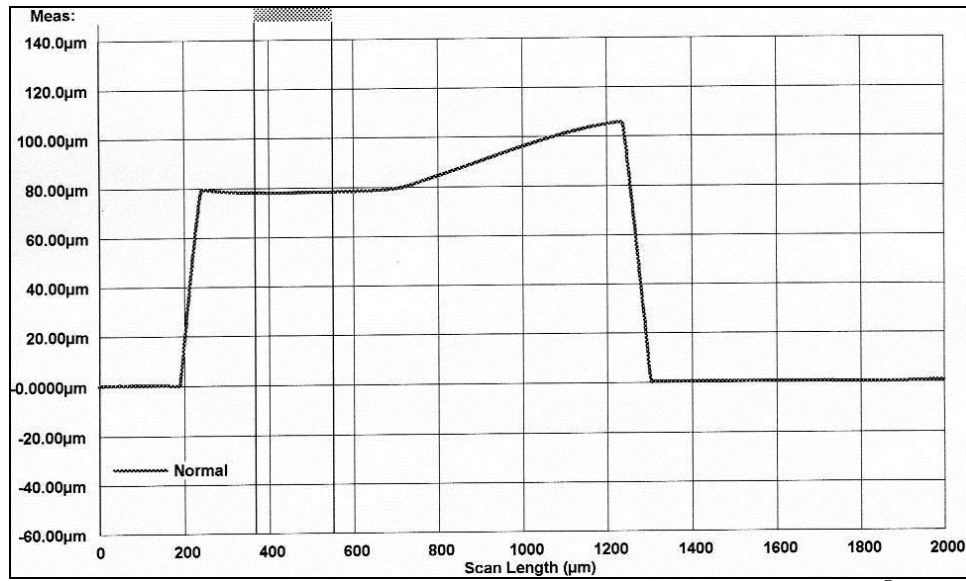


Figure 3.29: Surface profile measurement of a ORMOCER[®] cantilever beam of 500 μm in length and 70 μm in height. The metal layer below the beam bends the beam upwards for more than 20 μm .

The fabricated bridge beams are more stable but the metal electrodes are also peeled off on many devices. Even a delamination of a very small part of the electrode will result in device failure because of the relatively high voltages needed for actuation. According to equation (3.17), the pull-in voltage of a bridge beam actuator is almost 7 times ($\sqrt{48}$) higher than for an equivalent cantilever beam device. For smaller, easier to realize bridge beams, the pull-in voltage will increase even more. The device shown in Figure 3.30 with parameters: beam height: $h = 80 \mu\text{m}$, beam length: $l = 240 \mu\text{m}$ and a gap in between the plates of $g = 9 \mu\text{m}$ has a pull-in voltage of around 11 kV.

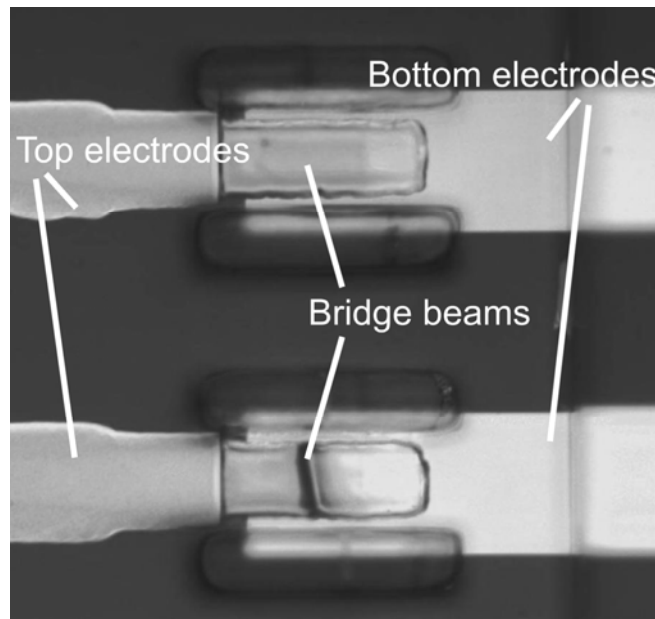


Figure 3.30: Bridge beams with electrodes below. One structure is stable, the top electrode the other is buckled due to the shrinkage of the ORMOCER[®] materials during curing.

No working parallel plate actuator ORMOCER[®] micro-beam device was obtained from the first fabrication test runs. There is much potential for optimization, but the fabrication process for such beams with integrated electrode is very complex and has many risks that result in a low yield. At present, it is not suitable for a large scale production.

A better design of such a parallel plate actuator on an ORMOCER[®] bridge beam structure would be with the following parameters: beam length: $l = 700 \mu\text{m}$, beam height: $h = 40 \mu\text{m}$ and gap: $g = 3 \mu\text{m}$, resulting in a pull-in voltage of around 45 V. According to equations (3.15) and (3.17), the length l of the parallel plate actuators is the biggest factor to reduce the pull-in voltage. Decreasing the gap below the beams, as well as the beam thickness will also reduce the pull-in voltage.

3.8 Conclusions and outlook

ORMOCER[®] material can be used for the fabrication of various types of microstructures and devices. Here, different types of structures have been demonstrated. The fabrication of many of these microstructures in ORMOCER[®] materials represents a new development; so many open questions had to be addressed.

Knowledge of material properties is essential for the design of new devices. The ORMOCER[®] materials used for this project had initially been developed for the fabrication of waveguides. To use them as structure material, the mechanical properties had to be measured first. The measurement of the Young's modulus proved to be difficult, but with different measurement methods it was possible to obtain an approximation of this essential parameter that can be used for the design of more complex microstructures (Chapter 4).

Furthermore, the traction tests showed that there is a part of a plastic deformation in the behavior of the material. This means that ORMOCER[®] is not as brittle as comparable materials. ORMOCER[®] is also softer (has a lower young's modulus) than comparable materials like PMMA or SU-8.

However, the material is very versatile. Processes can easily be adapted to make optical microstructures like microlenses or diffractive optical elements. By using a combined fabrication approach like contact photolithography, the optical elements can be applied on free-standing mechanical structures. An extension on this method is the fabrication of pyramidal tips for atomic force microscopes or the fabrication of parallel plate actuators.

To create such a wide scope of microstructures, the limits of the fabrication processes have to be known. Various microstructures have been made to establish design rules. In an attempt to find the limits of the lithographic processes, an array with structures in decreasing sizes has been made. The lithographic definition of the material shows results that are comparable to other negative photoresists. Structures with almost vertical sidewalls, resulting in very high aspect ratios (20:1) can easily be obtained with the photosensitive ORMOCER resin. Critical dimensions are linewidths of 5 μm for beams and 50 μm for grooves. The fact that the grooves cannot be made as thin as the beams can be explained with the inherent material properties of ORMOCER.

The results of the molding steps show that feature sizes below 100 nm can be reproduced. The combination of molding and photolithography is a very versatile option for the design of optical microstructures. Several

process steps can be avoided by such a combined approach (etching, sawing, glueing). The monolithic integration of the 3D relief and the bulk material also improves stability.

The tests showed excellent results, but for some structures the limits of ORMOCER[®] materials have clearly been shown. Usually, a tradeoff in between size, function and stability has to be established. The use of traditional approaches in the design of microsystems, such as silicon micromachining design rules can be misleading when applied to ORMOCER[®] materials. The shrinkage of ORMOCER[®] is low enough to allow the replication of extremely small features, but it still imposes limit for the design of microstructures.

The shrinkage of the ORMOCER[®] material during curing can be limiting for some applications. The analysis shows that it is possible to manage the design by adapting for the shrinkage. For the replication of microlenses, the original lens has to be designed with a bigger radius to allow the material to shrink during curing. Some types of complex freestanding microstructures are deformed by the shrinkage of ORMOCER materials, this effect can be used to measure the strain due to the shrinkage, which lies around 5 % in volume.

The use of ORMOCER[®] materials for the creation of microstructures still needs a lot of experience from the designer. For some applications, further analyses of the material properties are needed. Life time tests were not elaborated here but represent an important part in the development of devices. For special applications, the tested designs have to be adapted.

Modifications of the material are possible. Only two commercially available resins of the ORMOCER[®] brands have been used to make tests and to fabricate different microstructures. If the material properties of these two types do not suit the target applications, it is always possible to modify the base material and to use a different mix of precursors, for example to change the refractive index or to adapt the mechanical properties. However, after such modifications, the fabrication parameters have to be adapted as well.

The different structures and test devices presented here all represent different opportunities for further developments. By focusing on the strong points of ORMOCER[®] material (excellent optical properties, easy processing, stability) new applications can be found.

One application has been developed more in detail. In Chapter 4, the use of ORMOCER[®] material for the design of clipping structures for the assembly of microchips and optical parts is described.

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Chapter 4

Assembly of microsystems with clipping structures in hybrid polymers

4.1 Introduction

In this chapter, a novel wafer-scale assembly technology for microsystems is presented. Based on the developments presented before (Chapter 2 and 3), miniature clipping structures in ORMOCER[®] Sol-Gel hybrid polymer material have been fabricated on semiconductor and glass wafers by contact lithography processes. Then, the wafers have been cut into individual dies. The clipping structures will allow fast, reversible, adhesive-free assembly of active or passive microchips.

Assembly and packaging are major cost and time factors in the production of micro-systems. Unlike the packaging of ICs (integrated circuits), where die and wire bonding are established standards, optical microsystems and MEMS (Micro Electro Mechanical Systems) come in more varied forms and with special requirements, making standard packaging difficult. For optical microsystems, MEMS, sensors and transducers, the interaction with the environment is often an important aspect of the function of the device. In this case a complete sealing of the chip is to be avoided.

For example:

- Microfluidic outlets (in biochemical sensors) [4.1] [4.2] [4.3]
- Air channels (in pressure sensors) [4.4]
- Mechanical contacts (in atomic force microscopes / AFMs) [4.5]
- Transparent parts (in optical microsystems) [4.6]

But contact with the environment means also a possible contamination or even damage to the device. If the system as a whole is expensive, the replacement of damaged parts only becomes a viable option. For example in AFMs, the microfabricated cantilever beams with the tips are replaced when damaged.

Most assembly methods today are either glueing or soldering [4.7]. Adhesives have to be applied carefully to avoid device contamination. As

glueing is not a reversible process, glued systems are not repairable. The curing process can be quite long and induces thermomechanical stress. Compared to standard IC production, production yield in complex microsystems is often quite low. Soldering is not a reversible process either, unless special precautions are taken.

To avoid these problems, an assembly technology based on clipping structures has been developed. Instead of gluing two chips together like in conventional bonding approaches, both parts are fitted with an appendage to clip both pieces together. Clipping can be reversible, which means that the chips can be separated again to replace broken or contaminated parts. Hybrid systems, consisting of an expensive and a low-cost part are good examples where clipping can be very useful:

For example the microchannels in a biomedical microfluidic device are contaminated after use. If this contaminated low-cost part can be removed from the expensive sensing part (electronic or optical detection) of the device and replaced by another disposable channel subsystem, the cost for one measurement decreases drastically.

Other examples are complex optical microsystems systems. They are difficult to fabricate, and if one optical part of a micro-camera is not within specifications or was damaged during the assembly process, the optical function is distorted and the complete device has to be discarded. Often, such devices can only be tested after assembly, resulting in a low production yield. If the assembly technique used is reversible and out-of-specification parts can be replaced, the overall yield will be increased at little additional cost.

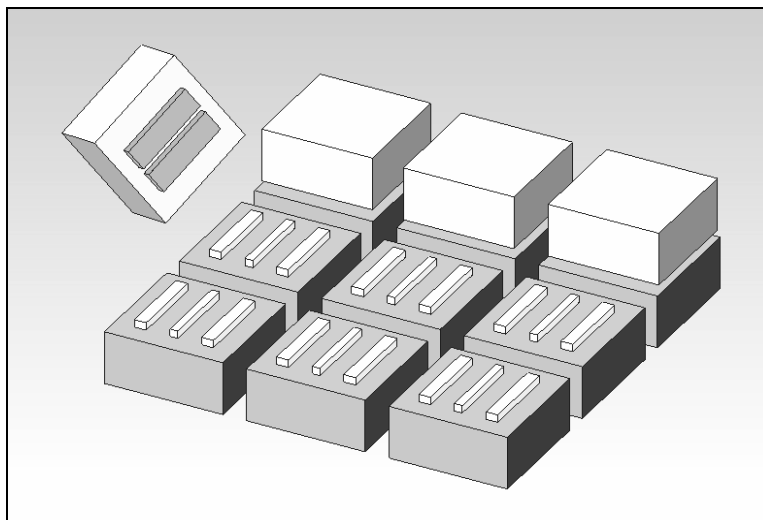


Figure 4.1: Schematic representation of chips coupled by clipping structures. The clipping mechanisms presented here allow the assembly of semiconductor or glass chips.

The clipping structures which will be presented here consist of pairs of complementary micromechanical features for joining two microchips (or optical parts) to form a stable assembly (Figure 4.1). The clips are added to the microchips during the fabrication process, before the device wafers have been cut into individual dies. A wafer scale ORMOCER[®] contact photolithography process is used to make the clipping structures. The contact photolithography process has been reported previously in Chapter 2.

A further step in the development of this technology will be the bonding of two (or more) wafers into stacks before dicing. Dicing after assembly is more cost-effective but has not been attempted yet.

A microchip-clipping system is composed of two complementary parts (Figure 4.2): On the “top” chip one part of the clip structure and on the “base” chip the matching counterpart is added. It is possible to design a clipping system where both parts are identical. Typical dimensions of the clipping features are between 10 micrometers and 1 millimeter.

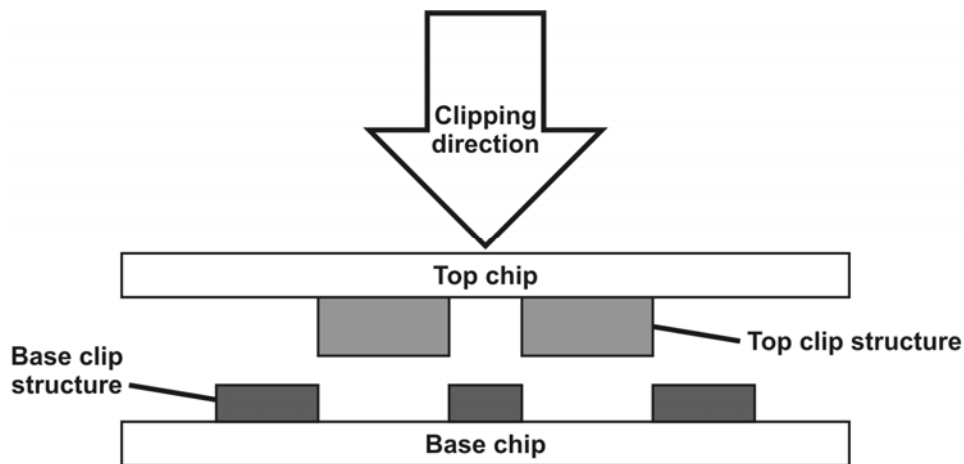


Figure 4.2: Diagram of a clipping system to link two microchips. Two complementary structures on the top chip and on the base chip form the clipping device.

As is shown schematically in Figure 4.2, the microsystem is assembled from individual pieces simply by pressing the parts together with moderate force. The required lateral precision can be designed to allow even positioning by hand. During engagement, the clipping structure is deformed. The elastic properties of the material ensure that the deformed element acts as spring. Either a narrow band of the structure material is bent or a free-standing

element (beam) is deflected. The horizontal component of the spring force acts on the counterpart to push the components into the correct place. The chips are held in the vertical direction by friction (Figure 4.3).

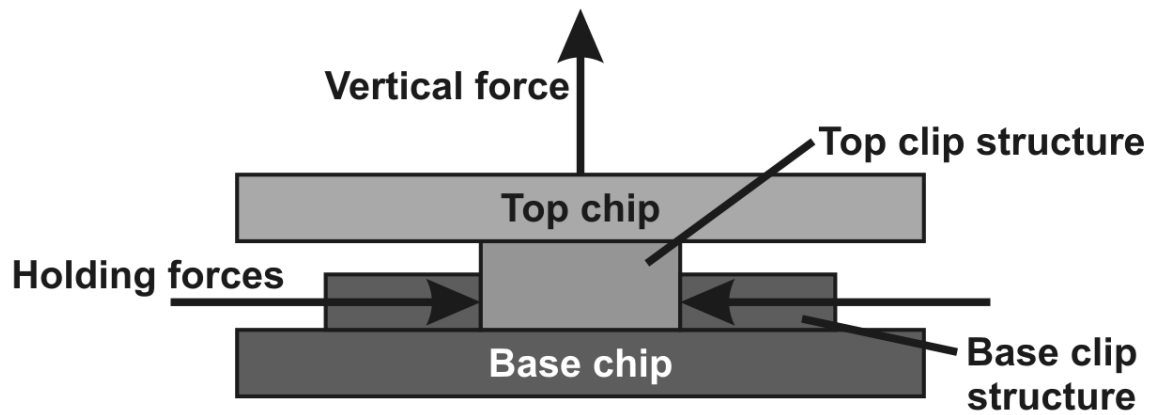


Figure 4.3: Forces on the clip. Two flexible parts of the base clip structure apply a force in horizontal direction on the top clip structure. This holding force fixes the top chip in vertical direction by friction.

Once assembled, the pieces can be pulled apart again, making repairable microsystems possible. The assembly process is very fast, because no curing time is required. Proper design of the clipping structures ensures high holding forces. The wafer scale fabrication approach makes this technology ideally suited for large scale production.

A positioning robot with a precision below 5 - 10 μm can be very expensive, especially if it has to be operated a high speed for high volume production. But wafer-scale manufacturing processes in the semiconductor industry are known to be extremely accurate [4.8]. The clipping structures presented here are made with similar processes (photolithography). The feature sizes of the fabricated clips are within tolerances below 1 μm (Chapter 3.3). These highly accurate clipping structures define the final position of the assembled chips. As stated before, the clips allow a certain deformation during assembly due to the elastic properties of the structure material. Therefore, a pre-positioning within 10 - 20 μm is good enough to assemble the chips with a final precision of a few microns. Some types of clips can even be assembled by hand. With this approach, a high final precision can be achieved even by using an assembly mechanism with limited precision.

Several designs for a reversible clipping system were evaluated and 2 designs were fully developed. Vertical latching mechanisms with

interlocking hooks were considered, but were deemed to be too difficult to realize. In Chapter 3.3 of this thesis, it has been demonstrated that free-standing beams in ORMOCER[®] materials with a gap of up to 30 μm to the substrate can be made. To create a clipping mechanism, the counterpart has to be smaller than this gap. Clip designs with such small interlocking features were rejected, due to the challenging fabrication process required.

The constraints given by the ORMOCER[®] processes were also limiting the possible designs of clipping structures. Photolithography allows large freedom in design for x and y direction, where almost any kind of shape can be drawn, but in vertical direction, only one value of height can be defined. Due to this restriction, the vertical latching mechanism was converted into an in-plane sliding clip, where the clipping force is generated by laterally deflected elastic beams (called *slide-clip* from here on). The clipping force has been calculated to be high enough to hold the system together in vertical direction by friction (Chapter 4.2.3).

The other clipping mechanism was inspired by the design of LEGO[®] bricks, where the lateral clipping force is generated by elastic rings (called *ring-clip* from here on). Such structures are ideally suited for the fabrication by ORMOCER[®] contact lithography processes. This design is very versatile due to its symmetry, and engaging the clip is simple; a motion in only one direction is required.

The development presented for these two systems can easily be adapted to further types of clipping mechanism. Simple designs like the ring-clip can be adapted for special needs or upscaled into arrays.

4.2 Slide-clip system

4.2.1 Slide-clip system design

The slide-clip system contains a male and a female part. They are fabricated on two different chips (Figure 4.4). The female part on the base chip consists of a U-shaped frame structure, which allows the insertion of the male part from one side. On one side of the frame, the wall structure is partly replaced by a free-standing beam that acts as spring to hold the inserted male part in place. On the free-standing beam a triangle shaped feature is added to define the forces required to engage or disengage the clips. The male part consists of a plug-like structure with four cam-like protrusions that act as points of contact with the female part.

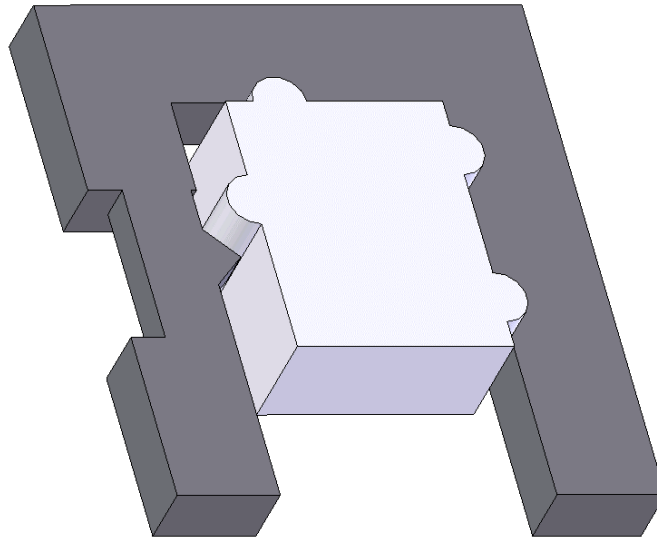


Figure 4.4: 3D model of the slide-clip system. The outer frame is attached to the base chip and the inner piece is attached to the top chip. (The coupled chips themselves are not shown).

To assemble the two parts, the male part plug is placed face down in front of the female part and then pushed forward. The slide-clip is designed to guide the plug automatically into the correct position. However, a gentle pressure from the top is needed to hold the chip in place during insertion.



Figure 4.5: Top view of the slide-clip system. Left: before insertion. On the left part of the frame, the free standing beam with a triangle shaped protrusion blocks the counterpart. Right: engaged clip. The free-standing beam of the frame is deflected and acts a spring to hold the counterpart in place.

During the insertion step, a protrusion on the plug will be blocked by the triangle shape on the spring-beam. A certain force is needed to deflect the beam laterally. If the triangle is symmetric, the same force will hold the chip in position. The final alignment of the assembled chips is given by the three other points of contact in between the male and female part (Figure 4.5).

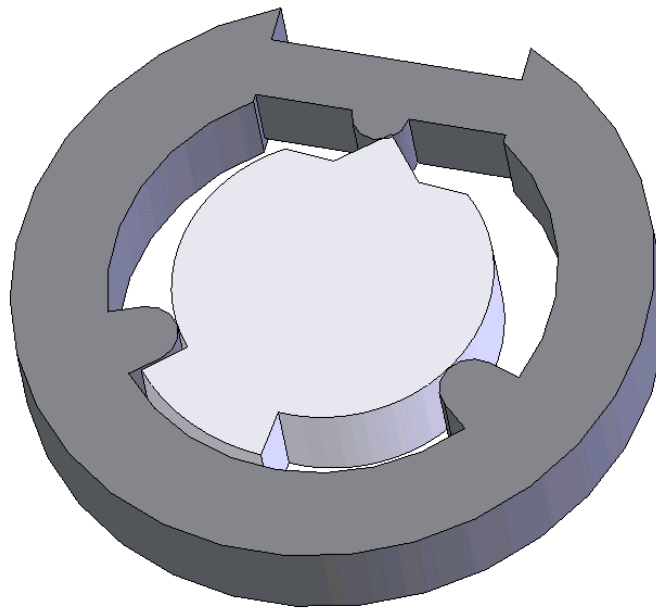


Figure 4.6: 3D model of a rotational variant of the slide-clip system. The outer ring is attached to the base chip and the inner disc is attached to the top chip. (The coupled chips themselves are not shown). The top part is placed into the base part form above and fixed by a rotation. On the base part, a suspended beam attached at both ends acts as spring. By rotating the top part, a cam-like protrusion of the beam is sliding on an inclined plane. The correct alignment and rotation of both chips is guaranteed by contact of 4 points in between the two parts.

A special variety of the slide-clip has also been designed (Figure 4.6). This rotational type works in a similar way and can be fabricated with the same process. However, due to the inherent limitations of this form (it can not be assembled in arrays or at wafer scale), it was not developed further.

4.2.2 Fabrication of the slide-clip

The clipping structures have been fabricated by an ORMOCER[®] contact photolithography process (Chapter 2.3.2). The clipping structures all consist of two complementary parts that are fabricated independently, so these two parts can have a different structure height. The advantage of using two different structure heights is that there is only one plane of contact in between the two clipping parts (Figure 4.4).

A two-step ORMOCER[®] photolithography process is required to fabricate the frame of the female part including the free-standing spring beam. As described in Chapter 2.3.5, a sacrificial layer of photoresist is added to the wafer before applying the ORMOCER[®] material. This sacrificial layer will define the free-standing beams that will then be used as springs (Figure 4.7). The male part plug on the top chip is created by a single mask ORMOCER[®] contact photolithography process.

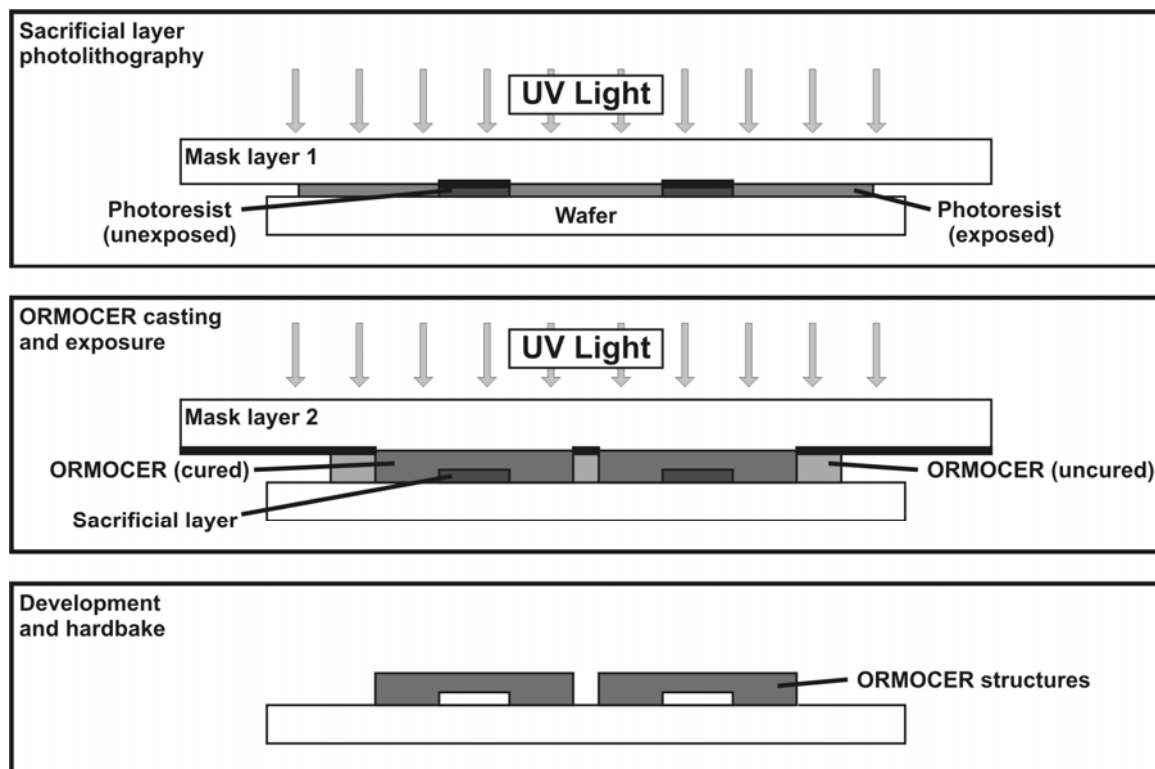


Figure 4.7: Fabrication process flow of the female clipping parts of the slide-clip. To fabricate the male clipping parts, the photoresist sacrificial layer is omitted.

4.2.3 Slide-clip holding force

The essential parameter of the slide-clip system is the spring force generated by the deflected beam. This force in horizontal direction holds the system in place in vertical direction by friction (Figure 4.8). The spring force depends only on the dimensions of the beam and on the beam material. To design and test the clipping devices, dummy glass chips were used. A series of clips with beams of different dimensions has been fabricated on such glass chips.

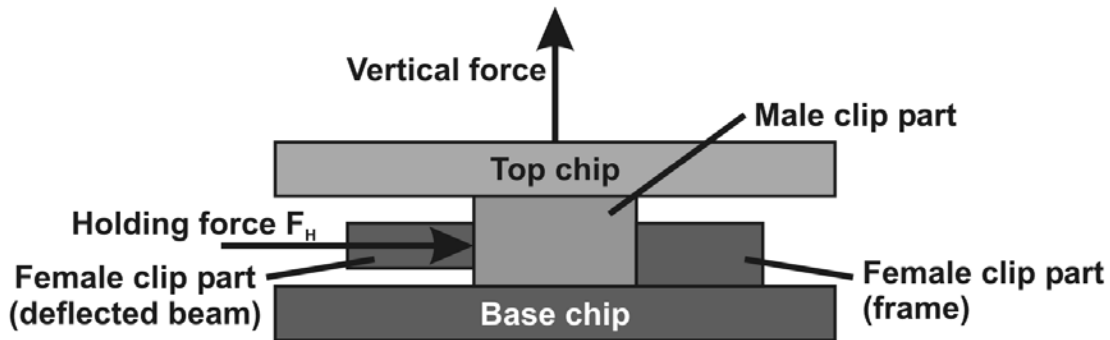


Figure 4.8: Forces on the slide-clips. The male part of the clip is clamped by the female part with a force F_H . This holding force keeps the chip in place in vertical direction by friction.

The force needed to hold a chip is calculated as follows:

The dimensions of the glass chips used to test the clipping devices are: 1.4 by 1.4 by 1.1 mm. The mass of such a chip with a density of $\rho_g = 2.2 \cdot 10^3 \text{ kg/m}^3$ (glass) is approximately: $m = 5 \text{ mg}$. The mass of the male part of the clip itself is neglected.

Assuming a friction coefficient for ORMOCER[®] on ORMOCER[®] of $\mu = 0.25$, the force to hold the chip vertically under an acceleration of 1 g ($1 \text{ g} = 9.81 \text{ m/s}^2 \cong 10 \text{ m/s}^2$) is approximately:

$$F_H = \frac{m \cdot g}{\mu} \Rightarrow F_H = 0.2mN \quad (4.1)$$

To withstand vibrations of 20 g in vertical direction, the spring has to generate a force of at least 4 mN to hold the chip in place.

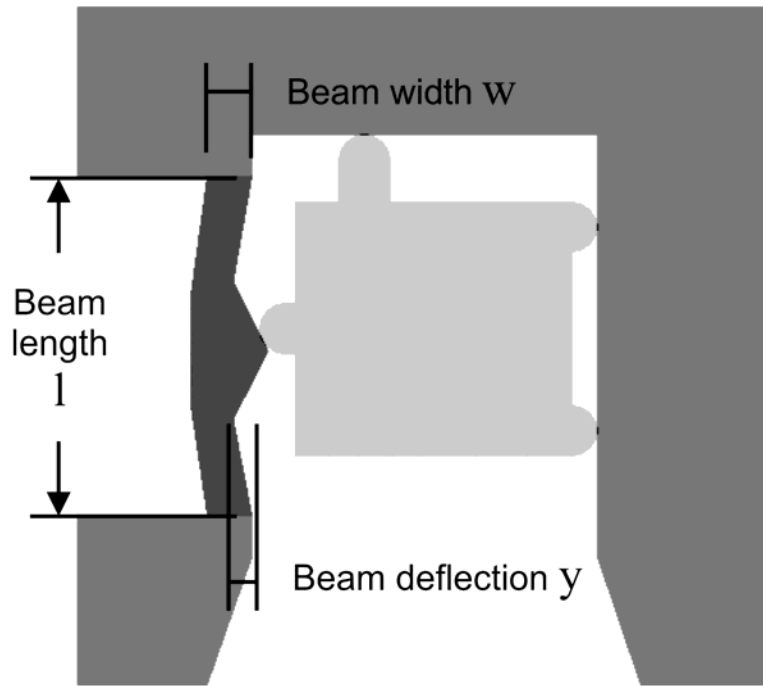


Figure 4.9: Slide-clip design layout. The main parameters of the slide-clipping system are: The deflection y , the length l and the width w of the deflected beam.

For a female clip part with a footprint of 800 by 800 μm , the following set of parameters for the beam that acts as spring have been defined (Table 4.1):

Table 4.1: Parameter range of the female part of the slide-clip

Width (w)	20, 32, 50, 80 μm
Length (l)	200, 400 μm
Height (h)	50 μm
Young's modulus (E)	1 GPa
Deflection (y)	5, 8, 12, 20 μm

The triangle shape for the clipping is neglected (Figure 4.9).

The spring force F_S is given by Hooke's law:

$$F_S = k \cdot y, \quad (4.2)$$

where k is the spring constant.

For a beam fixed at both ends, the spring constant is given by [4.9]:

$$k_b = \frac{192EI}{l^3}, \quad (4.3)$$

where I is the moment of inertia of the deflected beam. For a beam with rectangular cross-section it is:

$$I = \frac{w^3h}{12}. \quad (4.4)$$

So the spring force of a beam fixed at both ends is given by:

$$F_s = 16 \cdot Eh \frac{w^3}{l^3} \cdot y. \quad (4.5)$$

The spring force is highly dependent on the width and the length of the beam. A high force can be generated by designing a relatively short and wide beam. The height and the deflection of the beam increase the spring force only linearly.

Of the given set of parameters, combinations have been chosen that give spring forces in range of 5 mN to 150 mN in the engaged position.

4.2.4 Slide-clip engaging force

The force F_A needed to engage or to disengage the clip depends on the angle of the triangle shape on the beam (Figure 4.10) [4.9]:

$$F_A = F_s \tan(\alpha + \rho), \quad (4.6)$$

where α is the contact angle and the friction coefficient is

$$\mu = \tan(\rho). \quad (4.7)$$

If the contact angle α and the friction coefficient μ are too high so that $\alpha + \rho \geq 90^\circ$, the force F_A becomes infinite and the system is blocked.

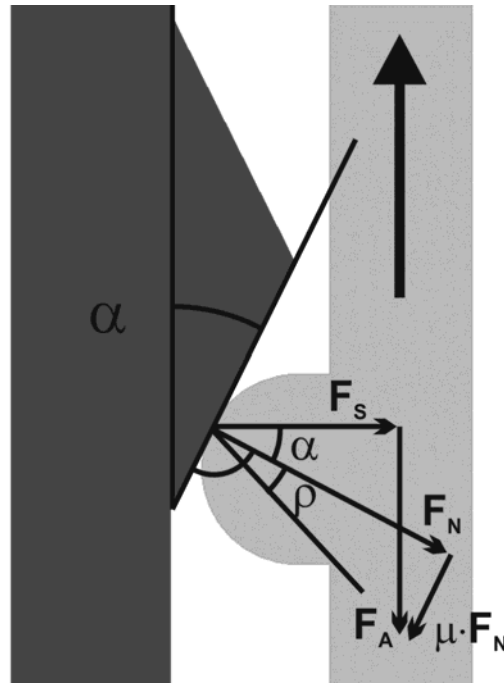


Figure 4.10: Force diagram at the contact point in between the male and female clipping parts of the slide-clip. A friction force μF_N is generated at the point of contact.

For the slide-clip systems realized in ORMOCER[®] materials, the angle α has been chosen to be 30° . The friction coefficient μ is assumed to be around 0.25 resulting in an angle ρ of approximately 14° . By using these values in equation (4.6), the force needed to engage the clips can be calculated:

$$F_A = F_s \tan(30^\circ + 14^\circ) = F_s \tan(44^\circ)$$

$$\rightarrow F_A \cong F_s$$

The force to engage the slide-clips is almost the same as the spring force.

4.2.5 Calculation of maximum stress

To calculate the maximum stress values in the spring beams, again a simplified model of the beams was used (Figure 4.11). The triangular shapes are omitted and the force is applied in the middle. The elongation of the beam as a whole is neglected.

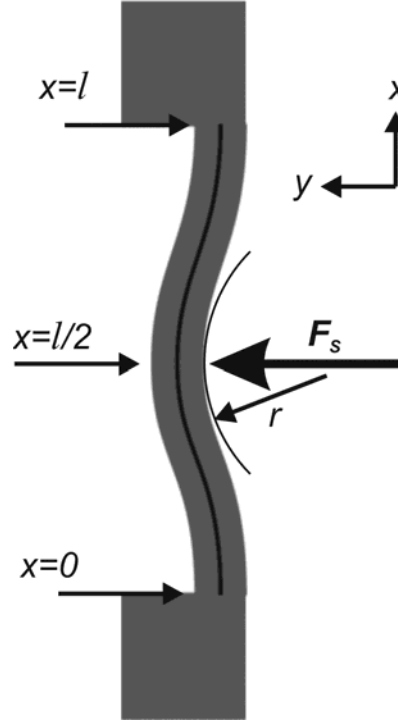


Figure 4.11: Model of a bent beam of length l fixed at both ends. The Force to deflect the beam F_s is applied at the middle of the beam. The structure is symmetrical, so that the calculations can be simplified.

The maximum stress σ_{max} in the beams is located where the radius of curvature r is the smallest. For small values, the second derivative $y'' = f''(x)$ of the deflection $y = f(x)$ is a good approximation of $1/r$. For these types of beams, the deflection for a force F_s applied in the middle is given by [4.10]:

$$y(x) = \frac{F_s}{EI} \left(\frac{lx^2}{16} - \frac{x^3}{12} \right), \quad (4.8)$$

for values of: $0 \leq x \leq l/2$. E is the Young's modulus of the structure material, I the moment of inertia in the direction of the deflection and l the length of the beam. Calculations at values $> l/2$ are equivalent, since the structure is symmetrical.

The first derivative of $y(x)$ is:

$$y'(x) = \frac{F_s}{8EI} (lx - 2x^2) \quad (4.9)$$

Chapter 4

The second derivative (curvature of the beams) is:

$$y''(x) = \frac{F_s}{8EI}(l - 4x) \quad (4.10)$$

The radius of curvature $r = \frac{1}{y''(x)}$ is smallest (and the stress is highest) for $x = 0$ and $x = l/2$ (and also for $x = l$, for symmetry reasons). At $x = l/4$ (and $x = 3/4 l$) the radius is infinite and the beam is straight. Stress is zero at these 2 points because the elongation of the beam as a whole is neglected.

The stress is defined the strain ε multiplied by the Young's modulus E as:

$$\sigma = E \cdot \varepsilon \quad (4.11)$$

The surface of a beam of width w with radius of curvature r is under a strain:

$$\varepsilon = \frac{\Delta \xi}{\xi} = \frac{w}{2r}, \quad (4.12)$$

where $\Delta \xi$ is the local length difference at one point of the surface and w the width of the beam. So the stress at the surface is:

$$\sigma = E \frac{\Delta \xi}{\xi} = E \frac{w}{2r} \quad (4.13)$$

$$\rightarrow \sigma = \frac{Ew}{2} \frac{1}{r} = \frac{F_s w}{16I}(l - 4x) \quad (4.14)$$

For a beam with rectangular cross-section the moment of inertia is:

$$I = \frac{w^3 h}{12}. \quad (4.15)$$

Using equation (4.15) in equation (4.14) results in a stress value of:

$$\sigma = \frac{F_s w}{16I}(l - 4x) = \frac{3}{4} \frac{F_s}{w^2 h}(l - 4x) \quad (4.16)$$

At the point where the beam is attached ($x = 0$) the stress is maximized:

$$\sigma_{\max} = \frac{3}{4} \frac{F_s}{w^2 h} l \quad (4.17)$$

Again, at the center of the beam and on the other attachment point the stress is the same for symmetry reasons.

The maximum stress $\sigma_{\max}$ has been calculated with values is in between 30 MPa (for a beam of length 400 μm , width 32 μm height 50 μm , and a spring force of 5 mN), and 180 MPa (for a beam of length 200 μm , width 50 μm , height 50 μm , and a spring force of 150 mN). In the traction tests made in Chapter 3.2.1, tensile strength values of only 12 MPa were reported. Even if this value is underestimated due to microcracks in the

samples used for the traction tests, this means that theoretically, the beams presented here are not strong enough to withstand such large bending. Nevertheless, in practice it has been observed that the beams easily resist even higher deflections.

There are two possible reasons for this “toughness”:

- The boundary conditions of the model used here are not completely respected: The beams are not fixed on a rigid socket, but the complete structure consists of the same, flexible material. When the beam is deflected, the socket is deformed as well, and the resulting stress values in the beams are significantly lower.
- Probably a plastic deformation of the structure material takes place, so that the real stress values in the beams are again much lower: The traction tests have shown that the material withstands a strain of up to 4 % (Figure 3.2). This value is more than 3 times higher than the maximum strain calculated only with elastic deformations:

$$\varepsilon = \frac{E}{\sigma} = \frac{12\text{MPa}}{1\text{GPa}} = 1.2\% \quad (4.18)$$

In conclusion, the stress in the beams of the examples above is reduced at least 3 times by the plastic deformation and even more by the flexibility of the socket structure, resulting in lower values than the measured tensile strength of 12 MPa.

4.2.6 Slide-clip design rules

The slide-clip structures hold the chips together by exerting a lateral force (Figure 4.8). For the system to function correctly, the width of the plug and the width of the gap in the frame have to be fabricated with tight tolerances (See calculations below).

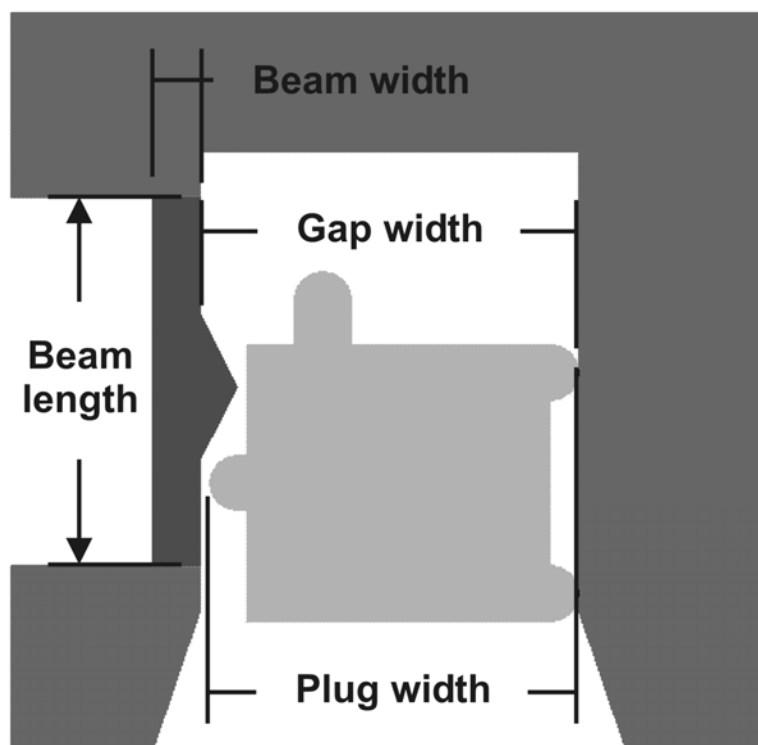


Figure 4.12: Structure dimensions relevant to the calculations of the clipping force of the slide-clip system. The gap has been measured on the whole width; the shrinkage of the triangle shape has been neglected.

The ORMOCER[®] contact photolithography process creates the clipping structures from a layout on a chrome mask (Chapter 4.2.2). However, the final structures will be slightly different to the original design due to the inherent shrinkage of the ORMOCER[®] casting material and the limits of the fabrication process (Chapter 3.3). A first series of slide-clip structures has been designed and fabricated (Figure 4.13). As expected, the resulting ORMOCER[®] devices were significantly off the required tolerances. These prototype clips could not hold the counterparts in engaged position due to a lack of clipping force generated.

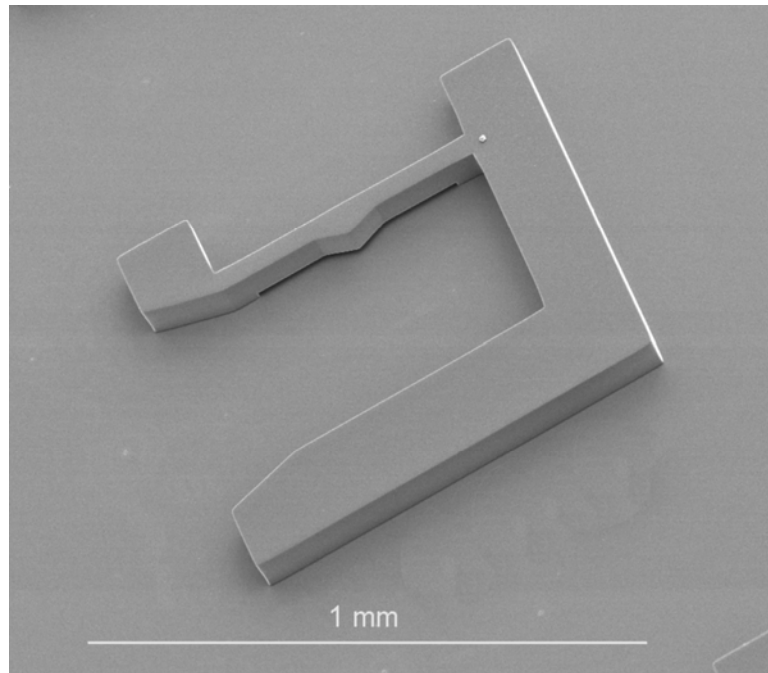


Figure 4.13: SEM picture of the female part of a slide-clip structure in ORMOCER[®] materials on a glass wafer. The spring beam is 400 μm in length, 50 μm in width and 50 μm in height. The gap below the beam is 10 μm .

As seen in equation (4.5), the most important parameters of the spring force are the beam width (depends on the width cubed) and the beam length (inverse cube dependence). However, these dimensions are not the most difficult to fabricate within the given tolerances. The length of the beam (typically 200 or 400 μm) is defined by the sacrificial layer applied before the ORMOCER[®] photolithography. The photolithography process is very accurate. At worst, the overdevelopment of the positive photoresist will decrease the length by about 2 μm . For a beam of 200 μm in length, this 1 % shorter beam will increase the spring force only by about 3 %.

The width of the fabricated beams has been measured (Table 4.1). Because of the different factors influencing the shrinkage of the ORMOCER[®] structures (Chapter 3.3), the relative shrinkage of the smaller structures is higher. Because of the high dependency of the spring force on the beam width, a shrinkage of only 2.5 μm in a thin beam of 32 μm leads to a loss of spring force of more than 20 %. However, for the whole clipping system, this is not the most critical value. The spring force depends only linearly on the values of the beam height (which is well-defined) and the deformation, but the shrinkage of the male part of the clip is much larger.

Table 4.1: Shrinkage of the width of spring beams in slide-clips (average values).

Designed width [μm]	Measured width [μm]	Shrinkage [μm]	Shrinkage (relative)	Loss of spring force
80	77.0	3.0	3.75 %	10.8 %
50	46.9	3.1	6.20 %	17.5 %
32	29.5	2.5	7.81 %	21.7 %

On the plug (male part), the relevant dimension is the width of the structure from contact point to contact point (Figure 4.12). On the plugs that have been designed to be around 400 μm in width (several slightly different designs have been realized), the resulting elements have all been measured to be 2.2 % +/- 0.1 % smaller. This shrinkage of around 9 μm is reducing the deflection of the beam by 50 % to 150 % (resulting in device failure). By enlarging the male structures in the design step (on the masks), this shrinkage has been compensated.

Due to the simplicity of the clip design, only one dimension of the device is relevant to the function of whole device. On the frame (female part), the relevant dimension is the width of the space where the plug is to be inserted (Figure 4.12). The gaps measured on the tested devices were 2.2 % +/- 0.2 % too wide. This widening of the gap is due to the shrinkage of the spring beam and the frame structure on the other side.

Therefore, a simple design rule for the male clip can parts can be established:

- To achieve the intended structure size, it has to be drawn at 102 % of its original size.
- To compensate for the shrinkage of both parts, it has to be drawn at 104 % of its original size.

An additional series of slide-clips was fabricated and tested successfully, where the male plugs have been designed 4 % too big to compensate for the shrinkage of both parts.

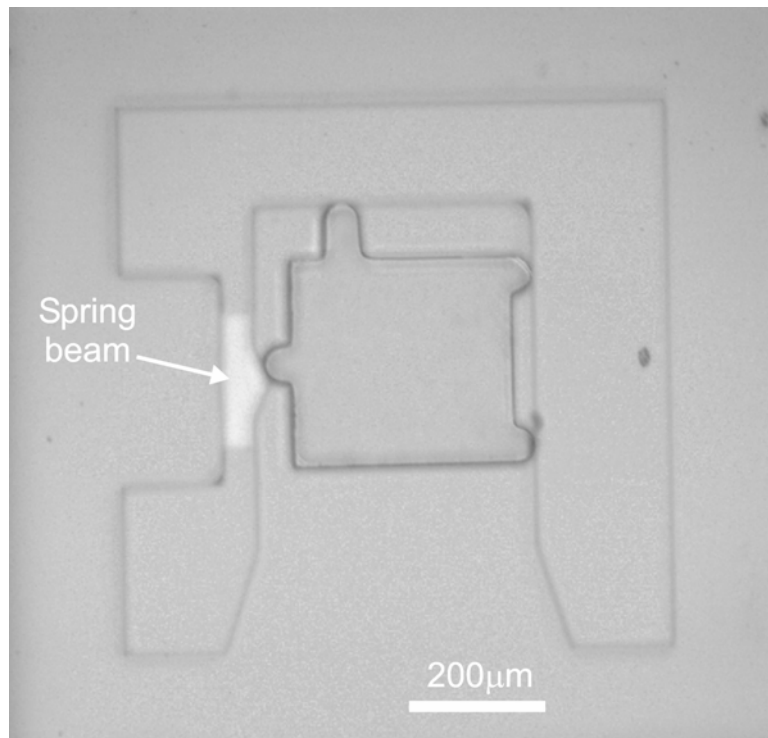


Figure 4.14: Top view of an engaged slide-clip system. The outer frame (female part) is attached to the bottom substrate. The view here is through the top chip, consisting of a piece of glass of 1.5 by 1.5 by 1.1 mm, with the male plug attached. The deflection of the spring beam is barely visible, but strong enough to hold the chip in place.

4.2.7 Slide-clip tests

To assemble the two parts, the male part plug is placed face down in front of the female part and then pushed forward (Figure 4.5). The slide-clip system is designed to guide the plug automatically into the correct position. To hold the chip in place during insertion, a gentle pressure from the top is needed. During the insertion step, a protrusion on the plug will be blocked by the triangle shape on the spring-beam. A certain force is required to deflect the beam laterally. If the triangle is symmetrical, the same force will hold the chip in position. The final alignment of the assembled chips is given by the three other points of contact in between the male and female part.

The engagement of the slide-clips turned out to be more difficult than predicted. The male plug is inserted in two steps: both a vertical movement and an in-plane displacement are needed.

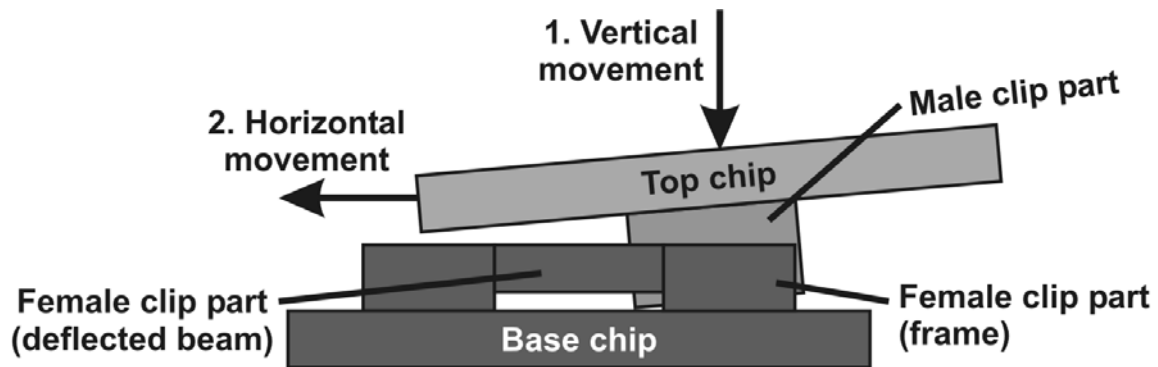


Figure 4.15: Side view of the engagement of the slide-clip: First a vertical displacement is needed to place the male part in front of the frame of the female part, then the top chip is pushed forward, and the spring beam is deflected. If the male part plug is in contact with the base chip, the top chip tends to tilt forward.

The second step is critical. ORMOCER[®] tends to stick to flat surfaces like glass or silicon wafers due to its softness. The high friction of the plug on the flat surface of the base chip can block the in-plane movement and then the top chip will tilt (Figure 4.15).

One solution to this problem is not to apply the plug directly on the flat surface of the base chip, but to leave a small gap. In this case an additional vertical movement is applied onto the top chip after the correct positioning.

The male part is supposed to align itself into the correct position, but this auto-positioning does not work in the predicted way. The friction of the protrusion on the plug that glides on the triangle shape of the spring beam is too high. As a result, the plug has a tendency to rotate into the opposite direction.

The application of a lubricant to reduce the friction may be possible solution to both problems. However, even the application of volatile lubricant like a solvent will complicate the clipping process and increase costs.

In conclusion, the slide-clip system is feasible but has notable limitations: To achieve the clipping, the clips have to be guided by a positioning system that has a high accuracy by itself. Nevertheless, a high degree of automation should be possible with this type of micro-clipping mechanism.

4.3 Ring-clip system

4.3.1 Background

LEGO® bricks are well-known examples of simple but high-accuracy clipping systems [4.11]. They have even been used as positioning devices on optical benches [4.12]. LEGO bricks are fabricated in Acrylonitrile butadiene styrene (ABS) by injection molding and they show little wear even after decades of use.

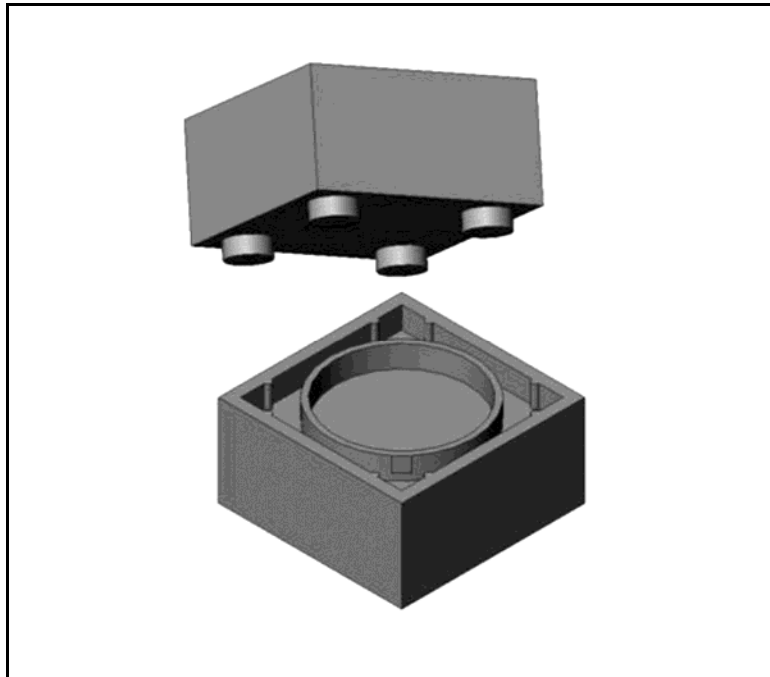


Figure 4.16: Model of the ring-clip system. Four cylinders in quadratic alignment are added to one chip. On the other chip, a central ring structure and a quadratic frame are attached.

The ring-clip system represents a miniaturized version of the clipping design found on LEGO bricks (Figure 4.16). The clipping force is generated by an elastic ring that is compressed by a set of four cylindrical counterpieces. But unlike on a LEGO brick, the male and the female parts of the microscopic clip system are fabricated separately. Both parts are fabricated by ORMOCER® contact photolithography directly on the corresponding chips (Figure 4.17).

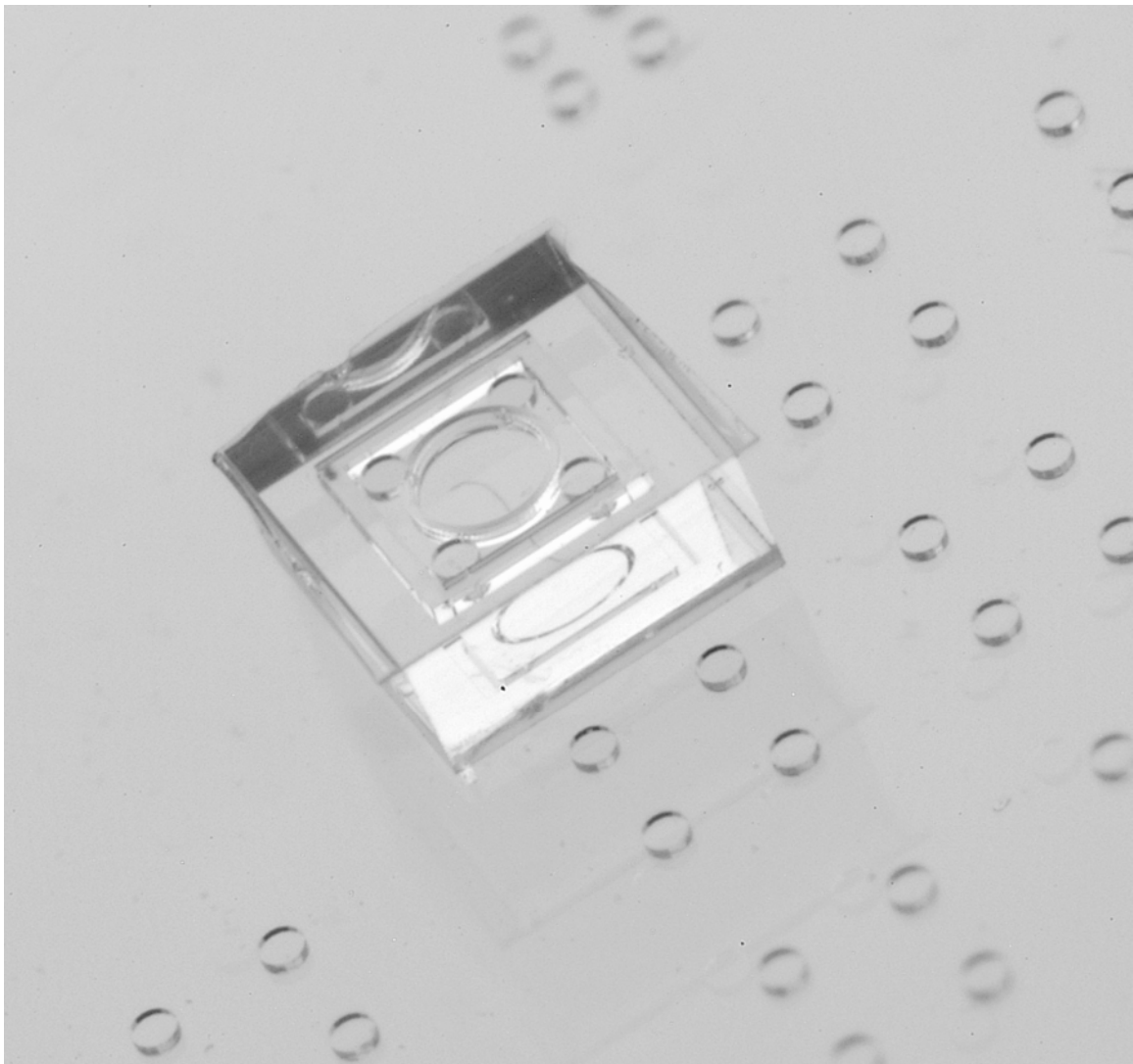


Figure 4.17: Glass chip clipped onto a glass wafer. Due to the transparency of the glass and the ORMOCER[®] clip material, the clipping structures are clearly visible. The female part of the ring-clip was added to the glass chip, male parts (groups of four cylinders) were attached to the base wafer.

To engage the ring-clips, the two structures need to be placed on top of each other with a relatively good precision to be correctly clipped together. The structures are about 1 by 1 mm in size, but under a microscope and with a pair of tweezers, it is still possible to assemble dies with only one clip by hand. After assembly, the devices are held by the holding forces generated by the clips.

4.3.2 Ring-clip system design

The male part of the ring-clip structure consists of 4 cylindrical elements, and the female part consists of a cylindrical ring inside a square frame with alignment pins. Only the ring of the female part is deformed when the clip is engaged. The four cylinders of the male part deflect this ring towards the center and for each cylinder a force in the opposite direction is generated (Figure 4.18). This spring force holds the male clip parts in position in vertical direction by friction (Figure 4.3). The alignment pins on the microstructure are used to guarantee the correct position in x and y direction.

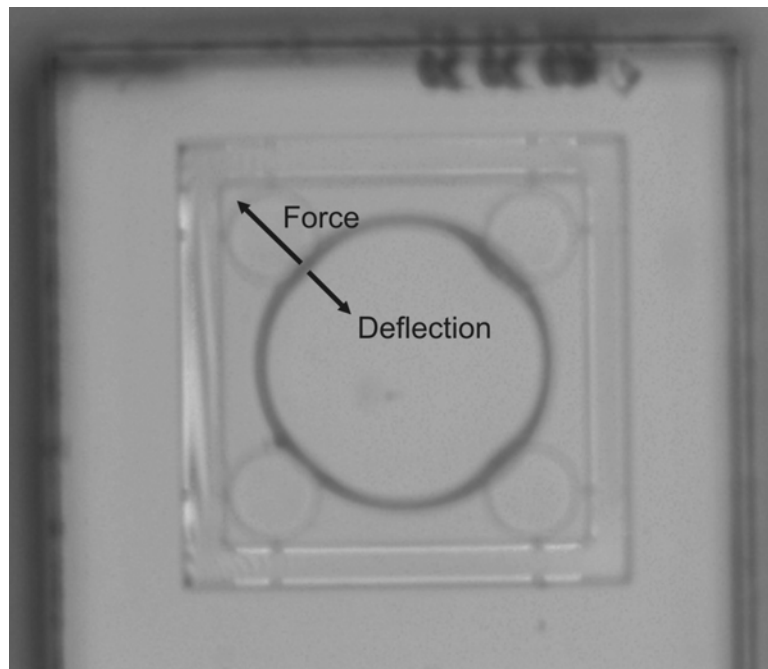


Figure 4.18: Forces generated by the ring-clip structure. In each corner, the same force is generated.

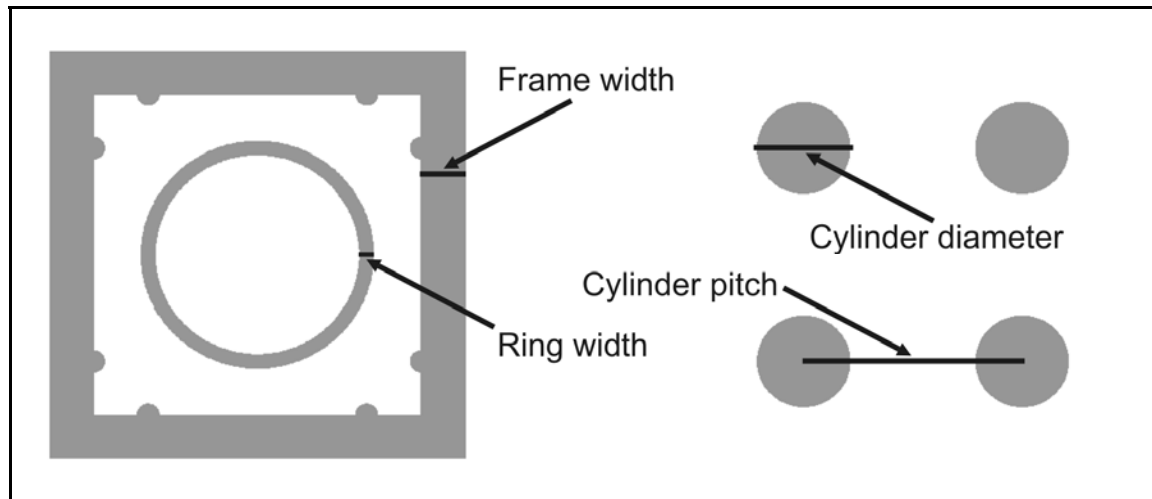


Figure 4.19: Layout and main parameters of the female (left) and male parts (right) of the ring-clip system. The male parts fit into the female part by deforming the center ring structure. These patterns have been used as masks for the ORMOCER[®] contact photolithography fabrication process.

The clip structure has been designed with footprint of about 1 mm². The layout is shown in Figure 4.19. To test ring-clips with different sizes and clipping forces, arrays of female parts with varying structure parameters have been designed (Table 4.2). For the male parts, the dimensions remained constant (Table 4.3).

Table 4.2: Parameter set of the female parts of the ring-clip.

Height of the female parts	100 μm
Width of the square frame	50, 100 and 200 μm
Thickness of the deformable ring	20, 32, 50 and 80 μm
Deformation of the ring	8, 12 and 20 μm

Table 4.3: Parameter set of the male parts of the ring-clip.

Height of the male parts	50 μm
Diameter of the cylinders	200 μm
Pitch of the cylinders	800 μm

The height of the male structure is only half the height of the female structure to limit the deformation of the central ring. The most important parameters are the ring width and its deformation. These two values define the clipping force generated by one clip. For some structures, estimations of

the clipping forces and maximum stresses have been made using FEM simulations. A mathematical model cannot be established easily, even if the square symmetry of the structure allows some simplifications.

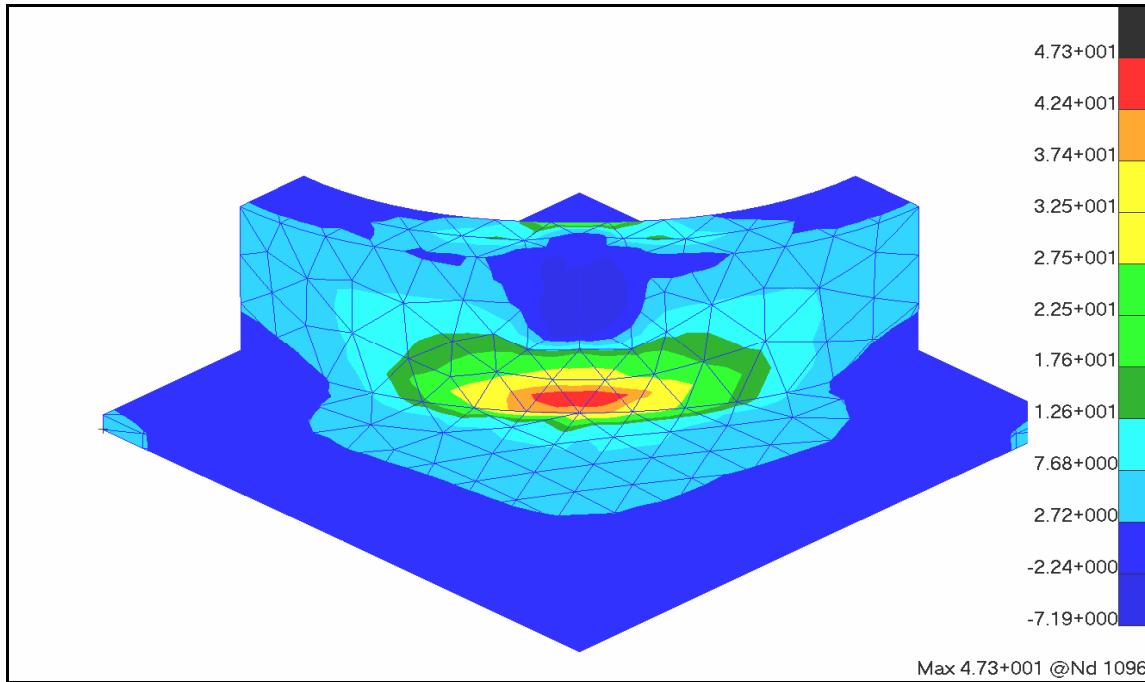


Figure 4.20: FEM simulation in one corner of the ring-clip structure. The width of the ORMOCER[®] ring is 50 μm . A deformation of the ring of 12 μm generates a holding force of 100 mN in one corner of the element. The maximum stress is 47.3 MPa.

One clip design that has been simulated contains a center ring of 50 μm in width that is deformed by 12 μm (Figure 4.20). For these FEM simulations the Young's modulus of the structure materials is approximated at 1 GPa. The calculations showed that 100 mN of lateral force is generated in one corner. By using an estimated friction coefficient of 0.25, a holding force in vertical direction of 100 mN for one such ring-clip system is obtained. The maximum stress value calculated is 47.3 MPa. Again, this stress is higher than the tensile strength of the material obtained with the traction tests in Chapter 3.2.1 (12 MPa). For the simulations, only elastic deformations were considered, resulting in such a high stress. According to the calculations in Chapter 4.2.5, the plastic deformations are reducing the stress more than 3 times, resulting in maximum stress values in the range of the measured tensile strength. It is suspected that the true tensile strength is higher (See Chapter 3.2.1).

4.3.3 Clipping force measurements

For different designs of ring-clips, measurements of the holding forces have been made. The first type had been simulated before, with a center ring of $50\text{ }\mu\text{m}$ in width and a deflection of $12\text{ }\mu\text{m}$ (see previous section). In the second type, the center ring had a width of $32\text{ }\mu\text{m}$ and was deflected by $8\text{ }\mu\text{m}$ (Table 4.4). One wafer with the female structures was diced and the resulting test chips were clipped onto a wafer piece with the male parts. On a test setup, consisting of an x-y-z stage with position measurement, a force sensor and a high-zoom video system, the retaining force of the ring clip was measured (Figure 4.21).

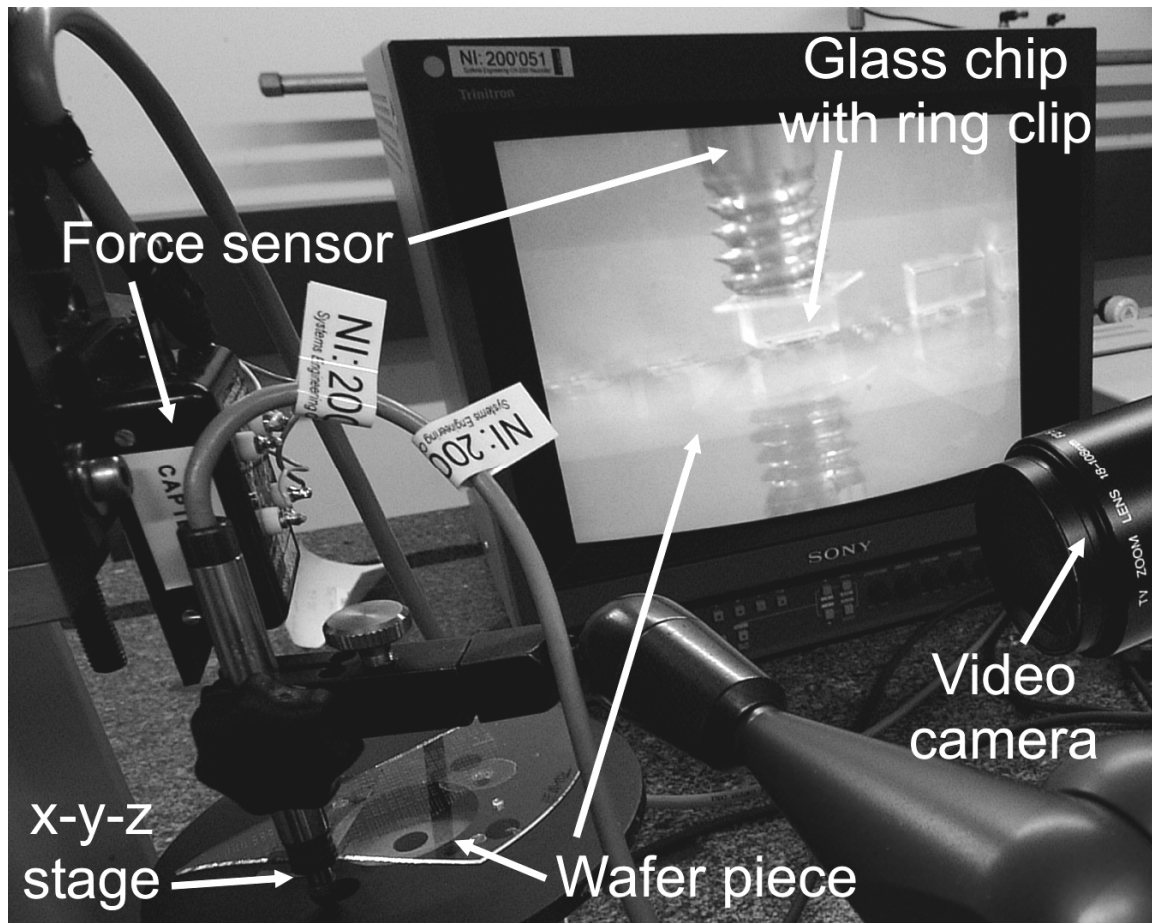


Figure 4.21: Setup for the measurement of the clipping force. A piece of a glass wafer with the male clipping parts is fixed on a positioning table. The glass chip with the female clipping part is attached to a force sensor and pulled from the wafer. The force need to do so is measured.

The clipped dies were attached to the force sensor and pulled vertically from the wafer piece. The chips were then clipped on again for the next measurement. The experiment was repeated for the same clipping structure for 20 times or more. Except for one of the tested device, the clips did not break. The measured clipping force was in the same range for each type of ring-clip (Figure 4.22).

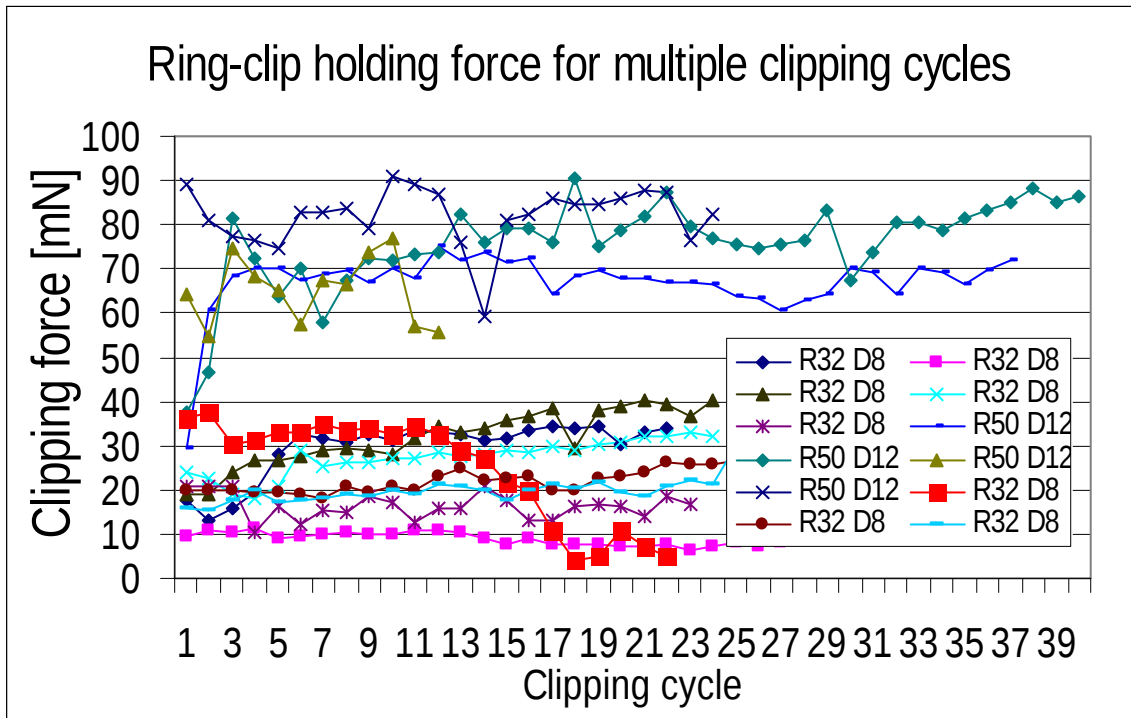


Figure 4.22: Force measurements on ring-clip structures. For one type of clipping structure, the values measured were in the range of 75 ± 15 mN, for the other type 25 ± 20 mN.

This data corresponds quite well to the simulations, where the resulting holding force of the $50 \mu\text{m}$ ring type was 100 mN. However, this value was based partly on estimations of the friction value of ORMOCER[®]. The friction value of ORMOCER[®] on ORMOCER[®] was estimated to be 0.25. So this value is a possible source of error.

Table 4.4: Two types of ring-clip systems with different parameters were tested. For one type, the holding force is around 75 mN, for the other around 25 mN.

Ring width	Ring deflection	Holding force
50 μm	12 μm	75 +/- 15 mN
32 μm	8 μm	25 +/- 20 mN

Nevertheless, a useful model to calculate the clipping force of the ring-clip can be established with these values. By using a friction coefficient of $\mu = 0.20$, the theoretical value of the clipping force is 80 mN, corresponding to the measured value of 75 +/- 15 mN. This lower friction coefficient takes into account other possible sources of error within the clipping structure (fabrication tolerances, residual strain, etc). By doing so, one parameter is used to establish a simple model. But this value cannot be used for other structures or as “general” friction coefficient of ORMOCER[®] on ORMOCER[®].

The range of the measured values within the same series of chips may be explained by fabrication tolerances. The resulting force is very sensitive to lateral variations of the device structures. But these fabrication variations within one series are known to be very small, given the accuracy of the contact photolithography process used. This variation probably occurs because the clips were engaged by hand and during this first step the structures were slightly damaged. It is very positive that the devices resist such a treatment. The thinner structures (32 μm rings) are more fragile and more prone to this error. The variation in the measurement values of one clip lies probably in the margin of measurement error.

4.4 Conclusions

The micro-mechanical clipping structures, made from hybrid polymers ORMOCER[®]s), allow adhesive-free assembly of microsystems at room temperature. Two types of clipping structures have been designed and fabricated in ORMOCER[®] materials in this work. Tests of these two types of clips showed that clipping is a viable approach to assemble microsystem devices. The slide-clip system uses a two step assembly approach: First a vertical positioning and then a horizontal displacement. This method has severe limits: The two step movement is relatively complex and the clip tends to rotate and tilt during insertion. Nevertheless, once the clip is engaged, the holding force is strong enough to fix the assembled chips.

The ring-clip system has been simulated and its holding forces have been measured. The measurements match the values obtained by FEM simulations quite well, meaning that this design approach can be used further to create such clipping microstructures. Holding forces of up to 100 mN per clipping structure have been achieved. Higher retaining forces for larger components can be obtained by using multiple clips for one piece. The footprint of one clipping feature is around 1 mm by 1 mm, resulting in up to 10 N (~1 kg) holding force per cm² of device surface. Arrays of clipping structures are also expected to improve the precision. Relative positioning tolerances of less than 2 µm have been achieved so far.

This assembly approach is inherently fast and cost effective and reduces interfacial mechanical stress which is very often a problem in conventional assembly methods like glueing or soldering. If the interface of two assembled pieces is under strain (for example due to temperature changes), the peak stresses of a glued link can be very high and micro-cracks can be the result. By using clipping structures, the strain is not concentrated on the interface, but distributed on the clipping structures. The elasticity of the clips is reducing the maximum stress.

It has been demonstrated that clipping devices in ORMOCER[®] materials can be used several times without loss in clipping force, which means that the assembly of microsystems with such clips is reversible and attached parts can be removed again, for example to replace contaminated or broken pieces. Potential applications of this technology include opto-mechanical subsystems for VCSELs, LED illumination systems, miniaturized cameras and sensors, as well as and biomedical microsystems with optical detection. With this reversible “plug and play” approach completely customized and modular sensor arrays may become practicable.

4.5 Outlook

The clipping technology presented in this thesis can be seen as a modular technology consisting of several independent building blocks. So far, one vertical clip (the ring-clip) and one horizontal clip (slide-clip) have been designed and fabricated in hybrid polymers by photolithography add-on processes.

The test structures were all assembled after dicing the wafer containing the top clip structures. The individual chips were then clipped on a wafer containing the bottom clips. By dicing both wafers first, the clips can be assembled chip-by-chip. For the industrialization of this process, wafer scale assembly is an important goal. By clipping two (or more) wafers to a stack, and then dicing the complete system, the time consuming chip-by-chip handling can be avoided. Such an approach is only possible for a vertical clipping approach like the ring-clip. Horizontal or rotating clips cannot be used this way.

To further develop and to expand the clipping technology, new clip designs can be conceived, arrays or stacks of clips can be formed, or the structure material and the fabrication processes can be changed and adapted for each application. Not for every device reversible assembly is a mandatory feature. For low-cost applications, it may simply be too costly to disassemble broken parts. In this case the clipping doesn't have to be reversible. For example, by using interlocking features like hooks, clipping structures can be made to withstand higher forces. Even glueing or soldering can be seen as extensions of clipping, even if they are not reversible unless special precautions are taken.

The technology can be expanded by integrating electrical or thermal contacts into the clipping structures or by using separate conducting microstructures that are linked as soon as the chips are clipped together. The same is possible for optical functions like waveguides, collimators or fiber couplers.

Although based on a small number of standard microstructures, the clipping technology gives the component and system engineer a large freedom in design. The clips can easily be adapted for specific applications.

4.6 References

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Chapter 4

Chapter 5

5.1 Conclusions

A compilation of technologies was developed during this thesis. The goal of this study was to build microelectromechanical systems (MEMS) in inorganic-organic hybrid polymer materials (ORMOCER[®]s), that had been developed initially for optical applications. To achieve this, a wide scope of fabrication methods, test structures and prototype applications has been investigated. Many technological branches, such as precision engineering, chemistry and optics were combined with microfabrication technologies to create new and interesting devices.

The strengths of ORMOCER[®] materials are: versatility, UV-curability, transparency, accuracy in replication, toughness, simple processing, chemical and thermal stability. All these points were demonstrated with test structures and devices for special applications. Such work required knowledge and development in many fields of research and was only possible to succeed with an interdisciplinary approach. In addition to understanding fundamental scientific principles (like surface chemistry, electrostatics, structural mechanics or scaling laws), a great deal of engineering know-how had to be established. Finally, an economic perspective for this work was also needed. The driving forces behind such new developments are not only scientific curiosity and technological interest, but also the growing needs of customers, users and markets for innovative *and* economically competitive products.

The ORMOCER[®] materials that were used in this thesis had been introduced on the market only recently and their initial purpose had been for optical waveguides. Here, these materials were used in a much wider fashion, in particular as base materials for MEMS. This is a completely new application for ORMOCER[®]s, important material data on was non-existent, and users with experience in this material were hard to find. Therefore, a major part of the work consisted of basic research to evaluate the material properties of ORMOCER[®]s and to establish design rules for devices and microstructures. To do so, assessment methods had to be defined and test structures had to be designed. Most of the (test) structures had never been made before in these materials. For specific applications (for example clipping mechanisms), the first step was to define what information and which material parameters were needed. In all, a good overview of what devices and structures can be realized in ORMOCER[®] materials is presented in this thesis.

If ORMOCER[®] materials are used in an (almost) standard photolithography process, structures with linewidths of 5 μm , and heights of up to 300 μm can be easily made. By UV-casting methods, feature sizes in the nanometer range ($<80\text{ nm}$) and low roughness micro-optical structures can easily be achieved. From the wafer scale replication process as starting point, different fabrication methods were developed. The contact photolithography approach was used extensively during this work to make clipping microstructures. The possibility to combine photolithography processing with molding of optical microstructures can be used to make hybrid devices like cantilevers incorporating microlenses. Such complex microstructures open new perspectives for applications of ORMOCER[®] materials.

One application was developed more in detail during this study: The assembly of microsystems with clipping structures as an alternative to clueing, soldering and bonding. Such a technique has been rarely considered, in general, let alone with polymer MEMS structures. Within this work, the conception, design, fabrication, and test of novel clipping structures was carried out. Special attention had to be taken to account for the constraints of the fabrication process, the low mechanical stiffness of the polymers in comparison to standard MEMS material (Silicon), while maintaining the goal of wafer scale assembly. By using the fabrication processes presented in the first two chapters of this thesis, complex clipping structures to assemble microsystem devices were successfully made.

The clipping approach was demonstrated and tested successfully. A clipping structure with a footprint of about 1 by 1 mm can generate a holding force of up to 100 mN. The clipping is reversible: The assembled parts can be removed from the microsystem again, for example to remove broken or contaminated pieces or to increase yield in a production process. Arrays of clipping structures are expected to multiply the holding forces and to improve the precision. The idea to use polymer materials for clipping elements is very common in the macro-world, but not in the domain of microstructures. Clipping as a method to assemble micro-devices may be a solution for special and difficult problems to solve and in particular to lower to cost of time-consuming thermal glueing and bonding processes.

All the developments in the use of ORMOCER[®] materials aims in the same direction: reducing the cost of microsystems. As a polymer material, ORMOCER[®] is potentially very cheap, if the volume of produced devices is high. Polymer materials are certainly going to increase in importance in future microsystem developments. The need to reduce the costs in this field

is universal. However, the use of polymer materials for the fabrication of microsystems also presents its own set of risks and limits.

Standard silicon-based MEMS technologies cannot be adapted easily to ORMOCER[®] materials. Compared to other polymer materials such as SU-8 or PMMA photoresists, the Young's modulus is fairly low, and the material seems more brittle. But the strength of ORMOCER[®] materials lies in its versatility. The fact that replication processes can be *combined* with photolithography approaches of standard MEMS applications opens a wide range of possible applications.

In this thesis, important steps in the research of future microfabrication technologies were achieved. Innovative devices, such as clipping mechanisms for microsystems were realized, and it was demonstrated that ORMOCER[®] materials can be used for the fabrication of various types of viable MEMS devices.

5.2 Outlook

The research presented in this thesis is the groundwork for further developments. The technologies presented here are in a way all independent of each other and can be combined for specific applications: These are the next steps in the evolution of this research.

For a specific application, parts of the work can be taken and combined into a new mix of methods and devices, specific for the task and specific for the customer. This is particularly true for the materials used. The developments made here are not exclusively for the application of ORMOCER[®] materials. Other, similar types of materials are on the market (ORMOSILS, Nanomers[®], SI-Link[®]...) and more are certainly going to be developed soon. For some target devices, ORMOCER[®] may not be the ideal material, but most processes and structures shown in this report can be adapted for other types of materials.

A strong point of ORMOCER[®]s, which was probably not emphasized enough in this thesis, is the fact that these materials are tailor-made and can be adapted for specific tasks. Only a small number of commercially available ORMOCER[®]s have been tested here. Some questions about the materials remain open: Despite the good temperature resistance of ORMOCER[®] materials (<300°C), little is known on the real life expectancy of microstructures made with these materials. To industrialize the fabrication methods shown here, further durability tests have to be made and the material has to be adapted where needed.

It is certainly possible to upscale the fabrication methods developed in this study, but specialized equipment will be needed to do so. Mask aligners for larger substrates and imprint processes under vacuum come to mind. The next steps in the development must be to precisely identify the most critical unknown material parameters. For some applications, the material data set shown here is certainly sufficient, but it has to be adapted for other devices. With the know-how acquired here, and the different test structures built, estimations can be made on the behavior of more complex microstructures.

The ORMOCER[®] materials used have a quite low Young's modulus, and maybe it will be necessary to increase this value by changing the mix of precursor materials. Nevertheless, it was possible to create complex microstructures, such as clipping devices with this relatively soft material.

The clipping approach for assembling microstructures is very interesting, but various points have to be addressed: The most challenging step is to try to build wafer-scale assembly structures that allow the bonding

of two wafers before the dicing step. The adhesion of the small ORMOCER[®] structures to the substrates is critical to the whole process. Integration of electrical contacts into the clipping structures may be another very useful extension. The development of the clipping technology can continue easily in small steps, if the technology is seen as a system of independent building blocks.

There is always a need to improve certain technological aspects of existing devices, in particular, in the domain of microtechnology where the pressure on cost-effectiveness is very high and product cycles are very short. A technology building-block system for various types of applications may be a good way to enter in new markets.

Chapter 5

Acknowledgments

This work has been carried out in the Optical Microsystems Section at the Centre Suisse d'Electronique et de Microtechnique SA (CSEM) in Zürich, Switzerland. I would like to address my thanks to all the people who were involved, and who helped and supported me with this research:

I am very grateful to the supervisor of this thesis: Prof. Nico De Rooij, for giving me the opportunity to work on a PhD thesis in the exciting field of micro-engineering, and for his enthusiasm and encouragement.

I wish to express my gratitude to the former section head of the CSEM Optical Microsystems group: Michael Gale, and to his successor Alexander Stuck, for their confidence, for their patience and for their commitment. And wish to express my gratitude to the former heads of the CSEM Photonics Division: Karl Knop, Peter Seitz and to their successor Nicolas Blanc.

I would like to thank the other members of the thesis jury: Prof. Martin Gijs, Prof. Hans-Peter Herzig and Peter Vettiger for kindly agreeing to review my thesis, and for all their expert advice.

I would like to address my special thanks to all the terrific co-workers I had in the Optical Microsystems Group, with whom I shared at great time, and who all contributed a great deal to this work: Thomas Ammer, Flavio Di Prima, Christiane Gimkiewicz, Christoph Keck, Sanida Mahmud, Bruno Satilmis, Marc Schnieper, Pascal Schüepp, Mike Schwank, Jürgen Söchtig, Hans Thiele, Claus Urban, Harald Walter, Susanne Westenhöfer, and Christian Zschokke.

I also would like to thank Andreas Kuoni of the SAMLAB, IMT, University of Neuchâtel for sharing his knowledge on microfabrication and microsystems and for his support.

I am very thankful to Ross Stanley, Head of the MOEMS team at the CSEM in Neuchâtel, for managing the EMIT project and for his last minute advice. I also wish to thank Serge Droz and Yvon Welte of the Mechatronics Group at the CSEM in Neuchâtel, for all their contributions to the clipping mechanisms.

I owe special thanks to my parents, my sisters and all my friends who always encouraged me in my studies and in my work.

I wish to express my warmest thanks to my girlfriend Lynda, for everything.

Last but not least I would like to address my thanks to all the others who made this thesis possible!

Abbreviations

μTAS	Micro total analysis system
ABS	Acrylonitrile butadiene styrene
AFM	Atomic force microscope
CD	Compact disc
CMOS	Complementary metal oxide semiconductor
CIM	Ceramic injection molding
CTE	Coefficient of thermal expansion
DLP	Digital light processing
DMD	Digital micromirror device
DVD	Digital versatile disc
FEM	Finite element modeling
IC	Integrated circuit
LED	Light emitting diode
LIGA	Lithographie, Galvanik, Abformung; German for: (x-ray) lithography, electroforming, molding
MIBK	Metha-isobutyl-methylketone
MIM	Metal injection molding
MEMS	Microelectromechanical systems
MEMO	3-(Trimethoxysilyl) propyl methacrylate
MOEMS	Micro-opto-electro-mechanical systems
NIL	Nanoimprint lithography
ORMOCER	Organically modified ceramic
ORMOCORE	ORMOCER for waveguide cores
ORMOCLAD	ORMOCER for waveguide claddings
ORMOCOMP	ORMOCER for optical components
PMMA	Polymethyl methacrylate
PC	Polycarbonate
PTFE	Polytetrafluoroethylene
SEM	Scanning electron microscope
UV	Ultraviolet (radiation)
VCSEL	Vertical cavity surface emitting laser

Symbols and units

ε		Strain	
ε_0		Vacuum permittivity	$8.85 \cdot 10^{-12} \text{ C/V}\cdot\text{m}$
ε_r		Dielectric constant	
ρ	$[\text{kg/m}^3]$	Density	
ρ	$[\Omega\cdot\text{m}]$	Resistivity	
λ	$[\text{m}]$	Wavelength	
μ		Friction coefficient	
μ	$[\text{Pa}\cdot\text{s}]$	Viscosity	
σ_{max}	$[\text{Pa}]$	Tensile strength	
σ	$[\text{Pa}]$	Stress	
b_b	$[\text{m}]$	Beam width	
c_n		Vibration mode constant	
E	$[\text{Pa}]$	Young's modulus	
F	$[\text{N}]$	Force	
F_A	$[\text{N}]$	Force to engage	
F_E	$[\text{N}]$	Electrostatic force	
F_H	$[\text{N}]$	Holding force	
F_M	$[\text{N}]$	Restoring force	
f_n	$[\text{Hz}]$	Resonance frequency	
F_S	$[\text{N}]$	Spring force	
g		Acceleration due to gravity	
g	$[\text{m}]$	Gap	
$g(R)$		Conversion efficiency	
h	$[\text{m}]$	Height, thickness	
I	$[\text{kg}\cdot\text{m}^2]$	Moment of inertia	
k	$[\text{N/m}]$	Spring constant	
K_n		Vibration mode constant	
l	$[\text{m}]$	Length	
n		Index of refraction	
m	$[\text{kg}]$	Mass	
Q	$[\text{C}]$	Electric charge	
r	$[\text{m}]$	Radius of curvature	
R	$[\text{m}]$	Ring radius	
S	$[\text{m}^2]$	Surface	
$®$		Registered trademark	
U	$[\text{V}]$	Voltage	
$U_{\text{pull-in}}$	$[\text{V}]$	Pull-in voltage	
w	$[\text{m}]$	Width	
x, y, z	$[\text{m}]$	Position, displacement, deflection	

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