Wafer-level heterogeneous integration of MEMS actuators

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ISBN 978-91-7415-493-1
ISSN 1653-5146
TRITA-EE 2010:002

Submitted to the School of Electrical Engineering
KTH—Royal Institute of Technology, Stockholm, Sweden,
in partial fulfillment of the requirements for the degree of Doctor of Philosophy
Stockholm 2010
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Abstract

This thesis presents methods for the wafer-level integration of shape memory alloy (SMA) and electrostatic actuators to functionalize MEMS devices. The integration methods are based on heterogeneous integration, which is the integration of different materials and technologies. Background information about the actuators and the integration method is provided.

SMA microactuators offer the highest work density of all MEMS actuators, however, they are not yet a standard MEMS material, partially due to the lack of proper wafer-level integration methods. This thesis presents methods for the wafer-level heterogeneous integration of bulk SMA sheets and wires with silicon microstructures. First concepts and experiments are presented for integrating SMA actuators with knife gate microvalves, which are introduced in this thesis. These microvalves feature a gate moving out-of-plane to regulate a gas flow and first measurements indicate outstanding pneumatic performance in relation to the consumed silicon footprint area. This part of the work also includes a novel technique for the footprint and thickness independent selective release of Au-Si eutectically bonded microstructures based on localized electrochemical etching.

Electrostatic actuators are presented to functionalize MEMS crossbar switches, which are intended for the automated reconfiguration of copper-wire telecommunication networks and must allow to interconnect a number of input lines to a number of output lines in any combination desired. Following the concepts of heterogeneous integration, the device is divided into two parts which are fabricated separately and then assembled. One part contains an array of double-pole single-throw S-shaped actuator MEMS switches. The other part contains a signal line routing network which is interconnected by the switches after assembly of the two parts. The assembly is based on patterned adhesive wafer bonding and results in wafer-level encapsulation of the switch array. During operation, the switches in these arrays must be individually addressable. Instead of controlling each element with individual control lines, this thesis investigates a row/column addressing scheme to individually pull in or pull out single electrostatic actuators in the array with maximum operational reliability, determined by the statistical parameters of the pull-in and pull-out characteristics of the actuators.

Keywords: Microelectromechanical systems, MEMS, silicon, wafer-level, integration, heterogeneous integration, transfer integration, packaging, assembly, wafer bonding, adhesive bonding, eutectic bonding, release etching, electrochemical etching, microvalves, microactuator, Shape Memory Alloy, SMA, NITINOL, TiNi, NiTi, cold-state reset, bias spring, stress layers, crossbar switch, routing, switch, switch array, electrostatic actuator, S-shaped actuator, zipper actuator, addressing, transfer stamping, blue tape
... I have not filled this volume with pompous rhetoric, with bombast and magnificent words, or with the unnecessary artice with which so many writers gild their work. I wanted nothing extraneous to ornament my writing, for it has been my purpose that only the range of material and the gravity of the subject should make it pleasing. ...

From “Il Principe”
Niccolò Machiavelli, 1469-1532
Translated by Peter Constantine, “The Prince - A new translation”
To my family
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</tbody>
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List of papers

The presented thesis is based on the following journal papers:

1. *Out of plane knife gate microvalves for controlling large gas flows*  
   S. Haasl, S. Braun, A. S. Ridgeway, S. Sadoon, W. van der Wijngaart and G. Stemme  

2. *Wafer-scale manufacturing of bulk shape memory alloy microactuators based on adhesive bonding of Titanium-Nickel sheets to structured silicon wafers*  
   S. Braun, N. Sandström, G. Stemme and W. van der Wijngaart  
   *IEEE/ASME Journal of Microelectromechanical Systems*, accepted for publication.

3. *Design and wafer-level fabrication of SMA wire microactuators on silicon*  
   D. Clausi, H. Gradin, S. Braun, J. Peirs, G. Stemme, D. Reynaerts and W. van der Wijngaart  
   *IEEE/ASME Journal of Microelectromechanical Systems*, accepted for publication.

4. *Localized removal of the Au-Si eutectic bonding layer for the selective release of microstructures*  
   H. Gradin, S. Braun, G. Stemme and W. van der Wijngaart  

5. *Single-chip MEMS 5×5 and 20×20 double-pole single-throw switch arrays for automating telecommunication networks*  
   S. Braun, J. Oberhammer and G. Stemme  

6. *Row/Column addressing scheme for large electrostatic actuator MEMS switch arrays and optimization of the operational reliability by statistical analysis*  
   S. Braun, J. Oberhammer and G. Stemme  

The contribution of Stefan Braun to the different publications:

1. part of fabrication, all experiments, part of writing
2. major part of design, major parts of fabrication and experiments, all writing
3. part of design, fabrication, experiments and writing
4. part of design, fabrication and experiments, major part of writing
5. major part of design, all fabrication and experiments, major part of writing
6. major part of design, all fabrication and experiments, major part of writing
The work has also been presented at the following international conferences:

1. **Small footprint knife gate microvalves for large flow control**  
   **S. Braun**, S. Haasl, S. Sadoon, A. S. Ridgeway, W. van der Wijngaart and G. Stemme  

2. **MEMS single chip microswitch array for re-configuration of telecommunication networks**  
   **S. Braun**, J. Oberhammer and G. Stemme  

3. **MEMS single-chip 5x5 and 20x20 double-switch arrays for telecommunication networks**  
   **S. Braun**, J. Oberhammer and G. Stemme  

4. **Smart individual switch addressing of 5x5 and 20x20 MEMS double-switch arrays**  
   **S. Braun**, J. Oberhammer and G. Stemme  

5. **Robust trimorph bulk SMA microactuators for batch manufacturing and integration**  
   **S. Braun**, T. Grund, S. Ingvarsdotir, W. van der Wijngaart, M. Kohl and G. Stemme  

6. **Wafer-scale manufacturing of robust trimorph bulk SMA microactuators**  
   N. Sandstrom, **S. Braun**, T. Grund, G. Stemme, M. Kohl and W. van der Wijngaart  
   *Proceedings of the 11th Int. Conf. on new Actuators (ACTUATOR)*, Bremen, Germany, June 2008, pp. 382–385.

7. **Microactuation utilizing wafer-level integrated SMA wires**  
   D. Clausi, H. Gradin, **S. Braun**, J. Peirs, G. Stemme, D. Reynaerts and W. van der Wijngaart  

8. **Selective electrochemical release etching of eutectically bonded microstructures**  
   H. Gradin, **S. Braun**, M. Sterner, G. Stemme and W. van der Wijngaart  
   *The 15th IEEE Int. Conf. on Solid-state Sensors, Actuators and Microsystems (TRANSDUCERS)*, Denver, USA, June 2009, pp. 743–746
9. Full wafer integration of shape memory microactuators using adhesive bonding
N. Sandström, S. Braun, G. Stemme and W. van der Wijngaart
The 15th IEEE Int. Conf. on Solid-state Sensors, Actuators and Microsystems
(TRANSDUCERS), Denver, USA, June 2009, pp. 845–848
Wafer-level heterogeneous integration of MEMS actuators
1 Introduction and structure

This thesis presents research in the field of microelectromechanical systems (MEMS), also referred to as micromachines in Japan or Micro Systems Technology (MST) in Europe. MEMS technology uses the tools and techniques that were developed for the Integrated Circuit (IC) industry and allows for high volume parallel production of devices, potentially resulting in low fabrication costs per device. MEMS technology includes components with typical sizes between 1 to 100 μm (1 μm = 0.001 mm), which are combined to form MEMS devices such as pressure sensors, inertial sensors, switches, pumps, valves and many more with dimensions in the mm range.

While IC devices can be considered as the 'brain' of a microsystem, MEMS devices provide the 'arms' and the 'eyes' to allow the IC device to sense and manipulate the environment. This thesis focuses on the 'arms', i.e. actuators which typically convert electrical energy into mechanical movement. Methods were developed to integrate actuators with silicon structures to fabricate microvalves for controlling large gas flows and crossbar switches for automating parts of copper-wire telecommunication networks. The actuators are not integrated using the conventional monolithic fabrication, but using concepts of heterogeneous integration. Thus, the actuators are fabricated separately and finally bonded onto the silicon structures to functionalize.

This thesis is divided into two parts. The first part provides detailed background information and informative references to facilitate a better understanding of the second part, which contains the appended journal applications.

The first part contains four chapters.

In chapter 2, common MEMS actuator technologies are introduced with focus on electrostatic and shape memory actuation, which are crucial elements of the MEMS devices presented later on.

Chapter 3 introduces heterogeneous integration with reference to the other integration methods, which are monolithic and hybrid integration. The chapter provides background information about heterogeneous integration concepts and technologies including wafer-bonding methods and releasing of structures to be manipulated by integrated actuators.

Chapter 4 introduces the concept of knife gate gas microvalves, methods to heterogeneously integrate bulk shape memory sheets and wires for actuation and the combination of both. Other microvalve types and shape memory integration methods are discussed. First prototypes are presented and their performance is compared to other microvalves with respect to performance per consumed silicon footprint area. The work is discussed and an outlook on future work is given.

Chapter 5 introduces a MEMS crossbar switch for automating parts of copper-wire telecommunication networks. The chapter presents in detail the application, the integration of arrays of electrostatically actuated switches and a method to individually actuate one out of the 400 switches in the array without underlying CMOS addressing circuits. The work is discussed and an outlook on future work is given.
Wafer-level heterogeneous integration of MEMS actuators
2 MEMS actuators

Actuators and sensors are transducers which convert one type of energy into another one. Sensors are mostly used to measure a physical parameter and report it in form of an electrical signal. Actuators work the other way, typically converting electrical energy into mechanical work output. The term 'MEMS actuators' summarizes all actuators which typically are submillimeter sized and fabricated with MEMS technologies.

The following chapters will provide a short summary of the main MEMS actuation principles, with focus on electrostatic and shape memory actuation which are important parts of this thesis.

2.1 Common microactuation mechanisms

MEMS technology offers a wide range of microactuators which can be classified into electrostatic, thermal, piezoelectric, magnetic and shape memory alloy actuation methods. Table 1 and the following paragraphs present a brief overview of the principles according to [1]. A more detailed review of all the different microactuators and their principles would go beyond the scope of this thesis and the interested reader is referred to literature for deeper information [1,2,3,4,5,6,7].

The piezoelectric actuation utilizes the coupling of mechanical deformation and electric polarization in certain materials. When applying a mechanical stress to the material, it generates an electrical voltage. This effect is called direct piezoelectric effect and is used for sensing and energy harvesting applications. However, for actuation the inverse piezoeffect is deployed: by applying a voltage the material generates mechanical movements. The stroke of piezoelectric actuators is in general very small, however, relatively large forces can be obtained with a very precise displacement resolution. Furthermore, these actuators are fast, allowing for high cycling frequencies and making them very feasible for repetitive actuation. An example of a commercial application deploying the advantages of piezoelectric actuation is the smallest Piezo LEGS® linear motor, which allows for linear travel distances limited only by the length of the displaced element (comes with a 50 mm long element) at a speed of 20 mm/s with 10 N force and a resolution smaller than 1 nm.

For MEMS applications, the integration of piezoelectric actuators is challenging. After the deposition the ceramic material, which most commonly is lead zirconate titanate (PZT), must be sintered at high temperatures (> 600 °C), which limits the
Table 1. The different principles commonly used for microactuation. The real work density might be substantially lower.

<table>
<thead>
<tr>
<th>Method</th>
<th>Principle</th>
<th>Work density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrostatic</td>
<td>Attractive force between bodies with different electrostatic charges.</td>
<td>( \approx 10^5 \frac{J}{m^3} )</td>
</tr>
<tr>
<td>Piezoelectric</td>
<td>Shape change under an electric field (inverse piezoeffect).</td>
<td>( \approx 1.2 \times 10^5 \frac{J}{m^3} )</td>
</tr>
<tr>
<td>Thermal</td>
<td>Thermal expansion of single material (includes sealed liquid) or difference in CTE between two materials or phase change.</td>
<td>( \approx 5 \times 10^6 \frac{J}{m^3} )</td>
</tr>
<tr>
<td>Magnetic</td>
<td>Interaction with magnetic fields.</td>
<td>( \approx 4 \times 10^5 \frac{J}{m^3} )</td>
</tr>
<tr>
<td>Shape memory</td>
<td>Temperature dependent crystal phase transformation with macroscopic shape change. Belongs technically to thermal actuation.</td>
<td>( \approx 10^7 \frac{J}{m^3} )</td>
</tr>
</tbody>
</table>

range of compatible materials and processes. Furthermore, the ceramic shrinks during sintering, resulting in very high mechanical stresses if the ceramic is constrained by the substrate prior to sintering.

Magnetic actuation is based on interaction with magnetic fields which are generated by either permanent magnets or coils. The energy density of magnetic actuation is in the same order of magnitude as electrostatic actuation. For some applications magnetic actuation is considered as an alternative to electrostatic actuation because of advantages such as non-existence of electric discharges, possibility of operation in liquid and long-range forces. However, integrating magnetic field sources or low reluctance materials on-chip is a major challenge; the coils are three-dimensional structures which are complicated to fabricate and the hard or soft magnetic materials are difficult to integrate with MEMS structures [8].

Thermal actuation is based on volume or phase change of materials upon heating or cooling. The displacement is analog to temperature change and thereby sensitive to environmental influences. Typically, thermal actuators provide large stroke and large forces, however, with a rather limited displacement resolution. Heating of the actuators can be very fast by a high applied power, however, cooling is in most cases passive and the cooling time severely slows down the actuator and decreases the actuation frequency.

Examples of MEMS thermal actuation approaches are the 'heatuator' [9] using one material, bimorph using different materials [10], thermopneumatic actuation and shape memory alloys. The 'heatuator' is a U-shaped lateral thermal actuator fabricated in one material, with one arm of the 'U' considerably narrower than the other. Current is passed through the actuator, and the higher current density in the narrower
'hot' arm causes it to heat and expand more than the wider 'cold' arm. The arms are joined at the free end, which constrains the actuator tip to move laterally in an arcing motion towards the cold arm side. The bimorph actuation scheme is based on the difference in coefficients of thermal expansion (CTE) between two joined layers of different materials. When changing the ambient temperature, one layer expands or shrinks more than the other and the resulting interface stress causes bending of the stack. The amount of bending can be controlled by choosing the appropriate CTE combination and by the applied temperature/electrical power. The thermopneumatic actuation scheme is based on the thermal expansion of a fluid sealed inside a cavity. Heating causes volume expansion or even phase change, exerting a large force on the cavity walls and causing a bending of a deformable membrane. Shape memory alloys are materials which undergo a phase change upon temperature changes. This phase change comes with a macroscopic shape change of the device and provides the highest energy density of all MEMS actuators. SMA actuation is an important part of this thesis and is presented in detail in the next subsection.

2.2 Shape Memory Alloy actuation

Technically, shape memory alloy (SMA) actuators are thermal actuators, since thermal energy triggers a crystal phase change in the material. However, since SMA actuation is an important part of this thesis, it is presented on its own.

2.2.1 Shape Memory Effects

Structures made from Shape Memory Alloys exhibit the shape memory effect (SME), which is the ability of certain materials to 'remember' their initial shape after they have been deformed. Take a spring made out of SMA and pull it. It will be easy to deform and it will stay deformed. Now heat the spring above a specific transformation temperature and it will rapidly recover the initial shape.

The underlying mechanism of the shape memory phenomenon is a martensite to austenite and vice versa phase transformation. Figure 1 illustrates the different crystal states and their connected macroscopic shapes by means of a SMA spring. In the hot state, the SMA crystal structure thermodynamically prefers a more ordered phase and transforms to the austenite crystal form with the macroscopic shape connected to it. This phase is also called parent phase and it is possible to set the desired macroscopic shape by a specific treatment involving mechanical constraining and heating. When the spring is cooled again and there is no external force applied, it will still have the same shape as in the hot state, however, its crystal is not in the cubic form anymore. Instead, the layers in the material are tilted, with the tilting direction alternating between each layer. Because of these alternated tilts, the spring remains its shape even though the crystal form has changed. The material of the spring is now in a macroscopically non-deformed, low-temperature phase referred to as self-accommodated martensite [5] or 'twinned' martensite [11], since its characteristic alternated layers are called 'twins'. In this phase, the material features a very low yield strength and can easily be plastically deformed after straining it above a very narrow elastic strain range - therefore the spring can be pulled very easily. After the external force is removed, the spring will stay deformed except for a very small elastic strain.
Wafer-level heterogeneous integration of MEMS actuators

Figure 1. Illustration of the transformation processes in martensitic transformation, including all the shape memory effects.

recovery. During the deformation, the alternated layers of the twinned martensite are moved and the macroscopic shape of the structure is changed. Now the material is still in a martensitic phase and easily deformable. Since the alternated layers called twins are removed, this martensitic phase is called 'detwinned' martensite.

Figure 2 displays the hysteresis behavior of the phase transformation versus the temperature. The transformation from martensite (cold) to austenite (hot) starts at the austenite start temperature $A_s$ and finishes at the austenite finish temperature $A_f$. Vice versa, the transformation from austenite (hot) to martensite (cold) starts at the martensite start temperature $M_s$ and finishes at the martensite finish temperature $M_f$. Hence, there is no single transformation temperature. However, in practice it is referred to a temperature $T_0$, which is the thermodynamic equilibrium temperature of martensite and austenite state ($T_0 = \frac{M_s + A_s}{2}$) [5].

There are three different shape memory effects, which are illustrated in the overview in figure 1. In the example above, the spring must be deformed with an external force and performs work only in one direction from detwinned martensite to austenite. Thus, this effect is called the one-way effect. However, the material can be trained to assume a certain shape in the cold state [12,13]. Then, the crystal transforms directly between austenite and detwinned martensite. Hence, the material performs work in two directions and this effect is called the two-way effect. The third effect is called superelasticity or pseudoelasticity and is only present if the SMA is always at temperatures above the austenite finish temperature $A_f$. Then, if an externally applied stress overcomes a critical stress, the crystal transforms from austenite to detwinned
2.2.2 Actuation aspects of Titanium-Nickel alloys

The shape memory phenomenon was first discovered in the 1930s in brass alloys. In 1962, Buehler and his colleagues found the shape memory effect in alloys of Nickel and Titanium [14] and in honor of their employer they named these alloys NiTiNOL (Nickel Titanium Naval Ordinance Laboratory). Nowadays, these alloys are also known under the acronyms TiNi (Titanium-Nickel) or NiTi (Nickel-Titanium). In this thesis, the term TiNi is used. Besides TiNi, there are a number of other materials showing the shape memory effect, such as other metallic alloys, polymers and even bacteria [15,16]. However, TiNi based SMA devices are dominating the market because of several advantages over other alloy systems. TiNi alloys allow to adjust the transformation temperature $T_0$ over a wide range only by changing the ratio of nickel atoms. If the alloy consists of half nickel and half titanium atoms, the transformation occurs near 100 °C. However, adding slightly more nickel atoms decreases the transformation temperature to below 0°C. Furthermore, these alloys can be fabricated with standard metalworking techniques, they exhibit better shape memory strain performance than other known alloys and consist of the affordable elements Nickel and Titanium. TiNi is a biocompatible material, making it interesting especially for medical applications. All the following reflections and work presented in this thesis are based on TiNi alloy.

SMA actuation is generally based on the one-way effect, i.e. when heated upon deformation the structure recovers its initial shape, yet upon cooling the shape does not change by itself. The approaches to utilize the one-way SME are usually summarized in three different categories, depending on the load which is applied upon the SMA during shape recovery [5,11,17].

1. In free recovery, a deformed SMA device is not constrained by any external load during the shape recovery and therefore the SMA does not provide any force.
2. In constrained recovery, the shape recovery of a deformed SMA device is blocked by an external constraint, triggering large forces from the SMA.

3. In cyclic work production, the shape recovery is constrained. However, upon heating the SMA can overcome the external force for the shape recovery. Upon cooling, the external force deforms the SMA again until the next temperature cycle. The external force is called bias spring or cold-state reset.

The combination of SMA and bias spring described under cyclic work production is the basis for SMA microactuators. The methods providing the cold-state reset can be summarized as intrinsic and extrinsic methods [18].

Using intrinsic methods, the crystal of the material is modified to prefer a certain cold-state crystal orientation, which results in a preferred shape of the structure in the cold-state. An example of an intrinsic cold-state reset is the two-way shape memory effect [19, 20], where a cold-state shape is trained into the material using long-term cycling processes. However, compared to extrinsic cold-state reset methods, the two-way effect is very unstable [19, 20], exhibits considerably less recoverable deformation and furthermore the required training process is difficult to integrate with a batch fabrication process for MEMS applications [5, 21]. Therefore this method will not be further discussed in this thesis.

Most of the SMA actuators deploy extrinsic biasing methods, where the SMA material is coupled with an additional mechanical element. A widely used biasing scheme, especially in MEMS applications, is coupling of the SMA with an external biasing spring element. This topic will be addressed in detail below. Another interesting scheme is the antagonistic biasing, where two SMA elements are coupled together. While element A remains cold and very easy to deform, element B is heated and pulls the cold element A without requiring high forces. Then, after cooling, both elements maintain their current shape until element A is heated, thereby deforming the cold and soft element B. Since the SMA bias spring is very easy to deform over relatively large strains (of course only within the elastic range), large deflections can be obtained. Yet, in MEMS applications it is difficult to couple two SMA elements in combination with a good thermal isolation between them.

The achievable work density of the TiNi is very much depending on the load case. Table 2 [22] shows the different cases. Under pure tension or compression load, the highest forces can be obtained, however, with relatively small displacements. Larger displacements, yet with lower forces, can be obtained under torsion or bending load. Bending load provides the lowest energy density of the three different load cases, since only fractions of the material are used for work production.

Another important aspect to consider when designing the actuator is the fatigue of the material. Fatigue in TiNi is usually divided into structural and functional fatigue [23]. Structural fatigue refers to the mechanical failure of the TiNi after cyclic loads, similar to any other engineering material. But unlike normal engineering materials, shape memory alloys show different properties in different temperature ranges, which also influences the fatigue characteristics.

Functional fatigue refers to a decrease in functional properties, which is the shape
Table 2. Comparison of work density and energy efficiency of TiNi wires for three different load cases [22].

<table>
<thead>
<tr>
<th>Load case</th>
<th>Work density ($\frac{J}{kg}$)</th>
<th>Energy efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension/Compression</td>
<td>466</td>
<td>1.3</td>
</tr>
<tr>
<td>Torsion</td>
<td>82</td>
<td>0.23</td>
</tr>
<tr>
<td>Bending</td>
<td>4.6</td>
<td>0.013</td>
</tr>
</tbody>
</table>

Table 3. Allowable stress and strain for a targeted amount of actuation cycles [22].

<table>
<thead>
<tr>
<th>Cycles</th>
<th>Max.strain (%)</th>
<th>Max. stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>500</td>
</tr>
<tr>
<td>$10^2$</td>
<td>4</td>
<td>275</td>
</tr>
<tr>
<td>$10^4$</td>
<td>2</td>
<td>140</td>
</tr>
<tr>
<td>$&gt;10^5$</td>
<td>1</td>
<td>70</td>
</tr>
</tbody>
</table>

recovery of the TiNi during cyclic loading. The functional fatigue is of great interest, since it defines how many cycles the actuator can be operated depending on the stress and strain applied to the material. Table 3 [22] shows some experimentally evaluated benchmark numbers for TiNi wires. When straining the wire with the maximum possible 8% or stressing it with the maximum possible 500 MPa, only one shape recovery cycle can be obtained. To maximize the number of actuation cycles, the applied strain should be below 1% or the applied stress should be below 70 MPa.

Thermal energy must be provided to trigger the shape recovery of the SMA. An option is to vary the ambient temperature. However, for cyclic actuation purposes this is rather impractical. The TiNi can be heated by electrically contacting and Joule heating the material itself. However, the stable oxide on the TiNi makes electrical contacting complicated. Therefore, especially for MEMS applications, the heating is sometimes performed indirectly using a separate resistive heater, which can be contacted in a simpler way. The voltages needed to operate SMA microactuators are compatible with microelectronics, however, high currents are necessary to provide the relatively high power for heating of the SMA.

During operation, the TiNi transforms between two states and displays hysteresis behavior as described earlier. Because of the two stable states, the SMA is very suitable for applications that require digital mode operation of the actuator. For such applications, the hysteresis behavior is potentially of advantage; the thermal energy necessary to maintain the austenite state is lower than the initial austenite start temperature $A_s$, which defines the stable state very well even for an unstable thermal energy supply. For applications requiring precise analog-like control over the displacement of the actuator, there are several controlling solutions. One method is the model-based loop, which is based on extensive modeling of the materials behavior to reduce or compensate the hysteresis effect. However, the necessary material param-
2.3 Electrostatic actuation

The electrostatic actuation principle relies on the attraction force between bodies having different electrostatic potential caused by a charge imbalance. A simple example of an electrostatic actuator is a parallel-plate capacitor, as illustrated in Figure 3a, with one fixed plate and the other plate suspended by a mechanical spring with a spring constant \( k \) at an initial distance \( d_0 \). Applying a voltage \( V \) between the two plates results in a vertically attractive electrostatic force, which pulls the moveable plate towards the fixed plate (Figure 3b). Using this simplified model and neglecting fringe-fields, the electrostatic force \( F_{el} \) between the plates can be calculated as [29]

\[
F_{el} = \frac{1}{2} \varepsilon_0 \varepsilon_r \frac{A}{d^2} V^2 \tag{1}
\]

with \( \varepsilon_0 \) the permittivity of free space, \( \varepsilon_r \) the effective relative permittivity, \( A \) the overlap area of the two plates and \( d \) the distance between the two plates.

This formula is the basic formula for all electrostatic actuators and shows that the electrostatic force grows quadratically with decreasing distance between the plates, which makes electrostatic actuation very interesting for MEMS applications with very small gap distances below tens of micrometers.
2.3.1 Parallel-plate, comb-drive and curved-electrode actuators

For electrostatic actuators based on the parallel-plate concept there are several issues to consider. The electrostatic force $F_{el}$ is counteracted by the mechanical spring force $F_s$, which is calculated as:

$$F_s = -k(d_0 - d) \quad (2)$$

For practical designs with a low actuation voltage, small electrode area and a sufficiently stiff mechanical spring, the initial plate distance $d_0$ must be small, which results in small travel distances $d$ (strokes) of typically a few micrometers for the moveable plate. Furthermore, the range in which the stroke of the moveable plate can be controlled is limited. Figure 3c illustrates the deflection of the moveable plate during a full operation cycle. With increasing actuation voltage, the gap between the plates gradually decreases and the two forces $F_{el}$ and $F_s$ will settle in an equilibrium. However, with decreasing $d$, the electrostatic force grows quadratically, whereas the counteracting spring force only grows linearly. At distances smaller than the critical distance $d = \frac{2}{3}d_0$, there no longer exists an equilibrium between the forces and the moveable plate snaps down to the fixed plate. To avoid an electrical short-circuit after snap-down, there must be an electrical isolation layer or at least ‘dimples’ (distance holders) between the plates. The critical distance is independent of the geometrical parameters of the actuator and the voltage at which the plate snaps down is called the pull-in voltage, or $V_{pull-in}$ (figure 3c). After the pull-in, the gap $d$ is drastically minimized and therefore, when reducing the applied voltage after pull-in, the electrostatic force remains larger until a force equilibrium is reached again. When further reducing the applied voltage, $F_s$ overcomes $F_{el}$ and the moveable plate is pulled out. Accordingly, the voltage at which the pull-out occurs is called $V_{pull-out}$ (figure 3c).

Some applications require an analog behavior of the actuator and there are efforts to extend the limited analog controllable stroke of parallel-plate actuators [30,31,32]. However, there are also many applications demanding a digital mode operation of the actuator, such as electrical and optical switches which alternate between the ON and the OFF state. In these applications, the hysteresis behavior is actually of advantage; the voltage necessary to maintain the pull-in state is lower than the initial actuation/pull-in voltage, which defines the switching state very well even at unstable control voltages.

In contrast to the parallel-plate actuator, the ideal comb-drive actuator shows no pull-in and hysteresis behavior since the plates are not moving perpendicularly, but parallel to each other and thereby keep the plate distance $d$ constant during the operation. A second fixed plate is added and the moveable plate is interdigitated between the two fixed plates with an initial lateral overlap $x_0$. Figure 4 illustrates the actuator, which is called ‘comb-drive’ since the interdigitated finger-like structures look like the teeth on a comb.

Applying an actuation voltage results in several forces, as illustrated in figure 4b. The two vertical force components $F_{el,y}$ keep the moveable finger centered between the stationary fingers and the lateral force component $F_{el,x}$ pulls the moveable finger towards the fixed fingers and counteracts the lateral bias spring with the spring
Wafer-level heterogeneous integration of MEMS actuators

- **moveable plate, thickness t**
- **fixed plate, thickness t**

\[
\begin{align*}
\text{Fel,}_x & \quad \text{Fel,}_y \\
\text{Fs} & \quad k
\end{align*}
\]

**Figure 4.** Diagram illustrating the operational behavior of an electrostatic comb-drive actuator, without (a) and with (b) applied actuation voltage.

The lateral force \( \text{Fel,}_x \) is independent of the plate overlap and remains constant with increasing plate overlap. The distance between the capacitor plates also remains constant, which allows for large analog controllable stroke, only limited by the elastic range of the bias spring.

However, the large stroke comes at a cost. The fingers are usually fabricated by vertical etching into the silicon substrate using deep reactive ion etching (DRIE). As for all electrostatic actuators, the distance \( d \) between the fingers should be as small as possible and the electrode area \( A \) as big as possible. Consequently, high aspect ratio processes are necessary to produce structures with a minimal distance in between. Since the aspect ratio and the resulting initial distance is limited, the only way to increase the electrode area and the force is the massive parallelization of comb structures, at the cost of silicon footprint.

Both large stroke and large force are provided by curved-electrode actuators, which utilize a flexible beam opposite a fixed electrode. Figure 5 illustrates the principle. One end of the flexible beam is clamped with a very short distance to the fixed electrode. One of the two electrodes is a curved electrode, shaped in a way that the electrode distance is gradually increasing from the clamped end to the free end. Upon applying an actuation voltage, the narrow gap at the clamped end results in large forces and the flexible beam is pulled in. As for the parallel-plate actuator, electrical isolation between the beams is necessary to avoid an electrical shortcircuit. The point of pull-in is moving along the fixed electrode in a zipper-like way and therefore these actuators are also referred to as 'zipper-actuators'. Another name is 'touch-mode' actuator, since these actuators utilize the pull-in and the plates are touching each other only separated by a thin electrical isolation layer or stoppers. The combination of small plate distance at the clamped end, the touching mode with very thin gaps between the electrodes and the large distance at the free end results in large forces and a large stroke, making this actuation scheme very interesting for MEMS applications.

For the most common zipper actuators, the moveable part is moving either laterally or vertically, as illustrated in figure 5 [33]. Besides the orientation of the actuation, the two configurations also differ in the arrangement of fixed and moveable plate as well as in their fabrication. In the lateral zipper approach, the fixed electrode
Figure 5. The two most common fashions of zipper actuators: (a) lateral zipper and (b) vertical zipper. The figure is modified from [33].

is curved and the moveable electrode is a straight cantilever. The fabrication is fairly simple with one photolithographical mask, vertical etching into the device layer of a SOI wafer and sacrificially underetching the buried oxide to release the moveable beam. However, as for the comb-drive actuator, the initial gap and the electrode area are limited by the aspect ratio of the fabrication process. In the vertical zipper approach (illustrated in figure 5b and 6a), the fixed electrode is straight and the moveable electrode is curved, typically fabricated using surface micromachining. The curvature of the moveable electrode results of a controlled, fabrication process related stress gradient and because of the curvature, these kind of actuators are also called 'curled actuators'. In contrast to the lateral approach, the initial gap at the clamped end can be very narrow by utilizing a thin sacrificial layer and the electrode area can be very large, resulting in large forces at relatively low actuation voltages. However, the stress gradient in the moveable electrode and the resulting spring tension counteracting the electrostatic force is difficult to control. Furthermore, stiction could occur between the large area electrodes in close contact.

2.3.2 S-shaped film actuators

The stress gradient in the bending electrodes of standard vertical zipper actuators is difficult to control. A large stress gradient results in a spring with a high pretensioning, counteracting the electrostatic force and resulting in larger actuation voltages to pull in the electrode. A thin and soft membrane would decrease the necessary actuation voltages, however, a weak spring cannot provide a reliable pull-out and suspension of the electrode.

A solution allowing for a thinner and softer membrane is the incorporation of a second fixed electrode at the free end of the membrane, providing a second zipper actuator, as illustrated in figure 6b. The resulting double-zipper actuator provides active actuation of the film in both directions, allowing for a very flexible membrane with a low stress gradient and thereby potentially reducing the actuation voltage yet still allowing for a large stroke. A MEMS concept of such an actuator is illustrated in figure 6b. First, a single zipper is fabricated with a thin and flexible membrane,
yet still with sufficient bending of the free end. Then, the second electrode is added from the top and pushes the membrane in contact with both electrodes and creating the characteristic S-shape of the membrane which inspired the name of the S-shaped actuator.

To allow the membrane to move up and down, the two fixed electrodes must be kept at a distance to each other with an intermediate spacer. The thickness of this spacer allows to tune the distance the membrane can move up and down between the two electrodes, which defines the stroke of the actuator.

In summary, this concept comes with a set of advantages. The touch-mode actuation, with very small initial gaps in both directions, in combination with a thin and flexible membrane potentially results in very low actuation voltages. The stroke of the actuator is basically only limited by the tuneable spacing between the two fixed electrodes.

The S-shaped actuator was shown in 1997 for a gas valve with dimensions in the millimeter range [34]. Another work [35,36,37] utilized the assembly concept of the S-shaped actuators to fabricate an RF MEMS switch by fabricating a single zipper actuator with metal contacts on one substrate and combining it with a second substrate, which contained the second fixed electrode and signal lines to be interconnected. In this work, the spacing between the substrates was provided by a polymer ring, which also encapsulated and packaged the switch.
3 Heterogeneous integration

Heterogeneous integration evolved from monolithic and hybrid integration and refers to the wafer-level integration of different materials, technologies or devices. In monolithic integration a device is fabricated in one piece while in hybrid integration a device is fabricated by interconnecting several separate pieces. The following sections introduce the different integration methods, followed by technical background including methods for wafer-to-wafer bonding, vertical electrical interconnection and releasing of structures for actuation.

3.1 Introduction

The following sections introduce the concepts of monolithic, hybrid and heterogeneous integration. Heterogeneous integration is of high interest for the integration of MEMS and IC and therefore the integration technologies are introduced by means of the specific example of integrating MEMS materials onto IC circuits.

3.1.1 Monolithic and hybrid integration

In monolithic integration, devices are fabricated from one substrate (monolithic = made from one piece). All the processing is typically performed on wafer-level and after the fabrication the wafer is diced into discrete devices (figure 7a), which are ready for further application.

As an example, MEMS and IC are monolithically integrated by combining and customizing the MEMS and IC manufacturing processes. The main technical advantage of monolithic integration of MEMS and IC is the high integration density; electrical interconnections between MEMS and IC are very short, reducing electrical noise and allowing for the handling of small signals. However, monolithic integration of MEMS and IC is relatively complicated [38, 39, 40, 41, 42], since MEMS technology can require IC incompatible material deposition processes and/or temperatures above 450 °C, which is not allowed for the IC components.

A solution to avoid these problems is the hybrid integration (hybrid = combination of different parts), where the devices are fabricated on separate substrates, which are then diced into single chips and combined with each other on chip level (figure 7b).

As an example, MEMS and IC are hybrid integrated by fabricating on separate substrates, which are then diced into single MEMS and IC chips. Conventionally,
Wafer-level heterogeneous integration of MEMS actuators

(a) monolithic integration

(b) hybrid integration

(c) heterogeneous integration

Figure 7. Simplified schematic illustrations of the different methods for integrating MEMS with IC: (a) monolithic integration, (b) hybrid integration and (c) heterogeneous integration.
these chips are glued beside each other on a carrier substrate and electrically interconnected by wire-bonding (see example in figure 8) or by connections integrated in the substrate (Multi Chip Modules [43]). Alternatively, they are stacked on top of each other [43,44] using through-substrate-vias (TSV) [45,46,47,48] for vertical electrical interconnection. The main technical advantage is the uncomplicated integration of different technologies, materials or devices. However, there are applications where hybrid integration is not feasible due to cost-efficiency reasons, limited integration density and parasitic signal noise from the long electrical interconnections.

Heterogeneous integration allows to combine the two approaches and is presented in the next section.

### 3.1.2 Heterogeneous integration

Typically, heterogeneous integration is utilized for integrating materials or technologies which otherwise are very difficult to combine or even incompatible with each other. However, heterogeneous integration also allows to divide the fabrication of MEMS devices into several separate sub-structures, which are optimized for a certain aspect and finally combined to one device. Both aspects are included in this thesis. Chapter 4 addresses the integration of an incompatible actuator material with silicon structures and chapter 5 addresses the separate fabrication of MEMS actuators arrays and their integration to functionalize another MEMS device.

Heterogeneous integration follows the same basic concept as hybrid integration. The devices to be integrated, or parts of them, are fabricated separately. However, in contrast to hybrid integration, the two different substrates are integrated on wafer-level by bonding them on top of each other, followed by removing the substrate of the integrated device and dicing into single chips (figure 7c). This wafer-level hybrid integration method allows to combine the advantages of hybrid and monolithic integration such as separate fabrication and wafer-level processing including high integration density and short electrical interconnections between the devices.

An example to demonstrate all the benefits of heterogeneous integration is the replacement of the mirror material of micromirror arrays from aluminum to monocryst-
Wafer-level heterogeneous integration of MEMS actuators

Figure 9. Simplified illustrations of the fabrication of micromirrors: (a) monolithically fabricated with aluminum mirrors [50] and (b) heterogeneous integration of a silicon layer for the mirrors [51].

talline silicon. The famous digital micromirror device (DMD) for projectors from Texas Instruments [52] features an array of up to 2048×1152 micromirrors and each of these mirrors must individually addressable, which for the DMD is performed using a dedicated IC circuit. Using hybrid integration of the mirrors and the IC would not be feasible since more than one million interconnection wires would be necessary to control each mirror. Therefore, the mirrors are monolithically integrated on top of the IC by sputtering and patterning aluminum as mirror material. Figure 9a [50] shows a simplified example of such a process. Each mirrors control electrode is addressed by a memory cell directly underneath, which eliminates the need to route individual control wires underneath the array. However, after repeated or prolonged mirror actuation, the aluminum mirrors display hysteresis and memory effects, which can be problematic for applications requiring analog mirror deflections. These issues can be eliminated by utilizing monocrystalline silicon for the mirrors. Furthermore, the achievable optical quality, the surface roughness and the uniformity of monocrystalline silicon surfaces is superior compared to most other surfaces. However, since the process temperatures for the material deposition onto IC is limited to about 450 °C to avoid damage to the electronic circuits, many high-performance MEMS materials such as monocrystalline semiconductors cannot be monolithically integrated.

A solution is the heterogeneous integration of monocrystalline silicon mirrors onto the IC driving circuitry by transferring the thin silicon device layer of a SOI-wafer using a IC compatible transfer bonding process. The involved temperatures are always below 450 °C. Figure 9b shows a simplified example of such a process [53,54,55,56,51]
and the analogy to the monolithic fabrication of micromirror arrays.

Heterogeneous integration was enabled with the advent of wafer bonding technologies and is an important technology for the 'More than Moore' trend to integrate non-IC functions onto IC devices in order to increase their capabilities beyond Moore's Law [57]. More information about the technology behind heterogeneous integration is presented in the following section.

3.2 Heterogeneous integration concepts and technologies

3.2.1 Transfer/direct and wafer-to-wafer/chip-to-wafer integration

The illustration of heterogeneous integration in figure 7 shows the transfer integration approach, which allows to transfer layers of one substrate to another substrate. These layers can be closed layers or devices which are fabricated in the same layer. The layer to be integrated is first fabricated on a temporary carrier substrate, which is the source substrate. The source substrate is then bonded upside down onto the target substrate, followed by removal of the source substrate. As a result, the source layer to be integrated is bonded upside down onto the target substrate. If the element should not be integrated upside down, it can be bonded to another intermediate substrate before it is transferred to the final target substrate. An example for transfer integration is the integration of the thin device layer of a SOI wafer onto CMOS substrate for micromirror arrays.

In contrast to transfer integration, in direct integration the substrates are bonded directly on top of each other without intermediate carriers or removing substrates. The substrates can be bonded with the top or the bottom side facing each other, depending on the application. Direct integration allows for wafer-scale encapsulation/packaging of devices as illustrated in figure 10. The source substrate is bonded with the top side onto the top side of the target substrate. The bonding layer is thick and patterned, forming a ring around the devices and encapsulating/packaging the devices after the bonding. Encapsulating MEMS structures by bonding plain wafers with recesses on top of the target wafer is a common wafer-level packaging approach [58]. However, in contrast to only one substrate containing devices, heterogeneous integration allows for both of the substrates containing functional structures.

The integration approaches introduced above allow for integrating wafers to wafers, which is typically cost-efficient if the devices on both substrates feature similar footprint areas or if the total cost per footprint of the substrate with the smaller devices is much lower as compared to the final total cost of the final devices. Figure 11 illustrates this issue: if the device to be integrated features a much smaller footprint area than the device on the target substrate, a lot of expensive substrate material is be wasted.

The conventional alternative to integrate devices with largely different areas would be the hybrid integration. However, this requires robotic pick-and-place of the components, which is a serial process and especially for high volume production may not be cost-effective. Alternatives based on heterogeneous integration are chip to wafer integration methods, where the source substrate with the source devices is diced into single chips, which are which are bonded onto the target devices on the un-diced
target wafer. These methods address the cost issue associated with largely different footprint areas and three examples of such techniques are described below.

One method is mixing pick-and-place and wafer-level transfer integration. The source substrate is diced into single chips, which are pick-and-place bonded onto the target devices on the target substrate. This approach has been developed by IMEC-Ghent University for the integration of optical chips onto IC substrates [59], using an intermediate substrate to bond the chips with the correct side to the target substrate.

Another approach utilizes self-alignment methods, which are part of self-assembly methods [60,61,62,63]. The smaller devices are densely fabricated on a source substrate which is diced into single chips. These single chips are placed on an assembly wafer, without any orientation or order and due to previous manipulations of the assembly wafer the chips orient themselves along defined patterns with defined pitches. Induced vibration or evaporating liquid helps to overcome the friction between the chips and the surface of the assembly wafer. After the chips have oriented and assembled themselves on the assembly wafer, they can be transferred onto the target wafer. Alternatively, the chips are self-assembled directly on the target wafer. Similar methods have been used to transfer monocrystalline silicon onto surface micromachined electrostatic actuators to fabricate micromirrors [64]. Furthermore, there is a report using self-assembly for the integration of MEMS (actuators) with IC [65].

A third method is the ‘selective transfer technology for microdevice distribution’ presented by IBM [66]. Their concept involves the dense fabrication of the smaller devices on a source wafer. This source wafer is aligned to the target wafer in a way, that one small source device is aligned to the larger target device on the target wafer. Then, the source device is released from the source wafer and transferred to the target device. By adapting the pitch of the smaller elements and the target devices, several smaller elements can be transferred in one transfer step. Using this technology, one source wafer can populate a number of target wafers and thereby the
cost of the transferred wafer is distributed over the number of target wafers. IBM showed this method for the distribution of their AFM-cantilevers and, together with FZK Karlsruhe, they showed this method for integrating bulk TiNi actuators onto polymer microvalves [67].

3.2.2 Electrical interconnection

One of the advantages of heterogeneous integration is that the electrical interconnections between the integrated devices can be made very short and dense, reducing parasitic influences. There are applications, where electrical interconnection between the integrated devices is not necessary (such as the integration of SMA, which is described in later sections). Yet, if electrical interconnections are necessary (as for example in the micromirror arrays), these interconnections are in most cases electrically conductive vertical vias. The methods for providing electrical vias can be distinguished in the via first and the via last approach. In the via first approach, all vertical electrical interconnections are fabricated prior to integration and during bonding the devices are electrically interconnected as illustrated in figure 12a. One of the advantages of this approach is that the two substrates can be fabricated completely separately, are then electrically interconnected during the integration and no further post-integration processing is required for the electrical contacting. However, this method requires a careful alignment of the two substrates, which limits the size reduction of the vias.

In the via last approach, only the electrical contact pads on the target substrate are fabricated prior to integration. After the bonding, vias are etched into the integrated substrate and filled with conductive material, as illustrated in figure 12b. In this approach, no precise wafer-to-wafer alignment is necessary and the vias can be made considerably smaller than in the via first approach. However, the integrated substrate
Wafer-level heterogeneous integration of MEMS actuators

Electrical contacts

Preparing electrical contacts prior to integration

Substrate removed

The devices are electrically interconnected during the bonding

(a) Via first

Electrical contacts

Preparing electrical contacts only on target devices

Substrate removed

Bonding of the substrates

Etching of vias in the integrated devices and filling them with conductive material

(b) Via last

Figure 12. Illustration of the two approaches for electrical via fabrication: (a) the via first approach, where the connections are fabricated prior to integration and (b) the via last approach, where the connections are fabricated after integration.

must be processed after the bonding. As an example for the via last approach, the silicon micromirrors in the mirror arrays (figure 9b) are electrically connected by vias etched through the silicon and the sacrificial layer to the electrical contact pads on the IC substrate. These vias are filled with metal to connect the mirrors to the driving circuitry and allow for electrostatic actuation of the mirrors.

3.2.3 Wafer-bonding techniques

A key technology of heterogeneous integration is the bonding of wafers to each other. The following brief descriptions are based on wafer bonding review papers [68, 69]. In principle, all the mentioned bonding methods are suitable for heterogeneous integration.

In solder bonding [70, 71, 72], layers of metal or metal-alloy based solders are used to bond two wafers. The metal layers are usually deposited on both wafers, which are joined and heated to the melting temperature of the solder. The solder refloWS and wets both wafer surfaces, causing intimate contact and bonding of the surfaces. Example solder materials are lead-tin (Pb–Sn), gold-tin (Au–Sn) and tin-copper (Sn–Cu) solders. Oxides at the metal surfaces can result in poor bonding and therefore most solder bonding processes use flux to remove the oxides. To some extent, solder bonding tolerates particles and structures at the wafer surfaces. The method provides hermetic bonding/package. Furthermore, it allows for combined bonding and vertical electrical interconnection, making it very interesting for heterogeneous integration.

Eutectic bonding [73, 74, 75, 76, 77] is a variation of solder bonding, allowing to join
two wafers with dissimilar surface materials which form a eutectic mixture at temperatures much lower than their melting temperatures. The most common material combination is silicon (Si) and gold (Au) with a eutectic temperature of 363 °C. Eutectic bonding can result in strong and hermetic bonds at relatively low temperatures and is therefore often used for the hermetic sealing of micromachined transducers. Furthermore, the method is interesting for heterogeneous integration because it allows for vertical electrical interconnection.

In adhesive bonding [69, 78, 79, 80], an intermediate adhesive layer creates a bond between two surfaces. Most commonly, a polymer adhesive is applied and the wafers are pressed together. Then, the polymer adhesive is hard-cured, typically by exposing to heat or ultraviolet (UV) light. The main advantages include the relatively low bonding temperatures between room temperature and 450 °C (depending on the polymer material), the insensitivity (to some extent) to the topology or particles on the wafer surfaces, the compatibility with standard complementary metal-oxide (CMOS) semiconductor wafers and the ability to join practically any wafer materials. While adhesive wafer bonding is a comparably simple, robust and low-cost process, concerns such as limited temperature stability and limited data about the longterm stability of many polymer adhesives in demanding environments need to be considered. Also, adhesive wafer bonding does not provide hermetically sealed bonds towards gasses and moisture. The method does not provide electrical interconnection.

In direct or fusion bonding [81, 82, 83], two wafers are contacted without significant pressure, electrical fields or intermediate layers. For reliable bonding, this method requires very flat and very clean wafer surfaces, room temperature contacting of the wafers and an annealing step (typically between 600 and 1200 °C) to increase the bond strength. This method results in strong and hermetic bonds and is therefore of interest if the integration method should also provide hermetic packaging. The method does not provide electrical interconnection.

Anodic or field assisted bonding [84, 85] is based on joining an electron conducting material such as silicon and a material with ion conductivity such as alkali-containing glass. Heating to temperatures of 180–500 °C mobilizes the ions and an applied voltage of 200–1500 V creates a large electric field that pulls the wafer surfaces into intimate contact and fuses them together. Anodic bonding is more tolerant to surface roughness than direct bonding and usually leads to strong and hermetic bonds. The method is interesting if hermetic packaging is required, however, the large voltages might damage IC devices on the substrates. The method does not provide electrical interconnection.

Thermocompression bonding, metal-to-metal direct bonding, and ultrasonic bonding [86, 87, 88, 89] are related bonding schemes in which two surfaces are pressed together and heated. Typically at least one of the surfaces consists of a metal. The surfaces plastically deform and fuse together. Instead of heating, the energy can also be supplied by ultrasonic energy (ultrasonic bonding), with the advantage of breaking through native oxides, particles and surface nonuniformities at the bond interface. Common bonding surface materials are gold to gold, copper to copper, aluminum to gold, and aluminum to glass. The disadvantage of thermocompression and ultrasonic bonding is that large net forces are required when bonding larger wafer areas. Thus, thermocompression bonding, metal-to-metal direct bonding and ultrasonic bonding
Wafer-level heterogeneous integration of MEMS actuators are mainly used in wire bonding schemes and in bump bonding schemes. However, these methods provide hermetic bonding/packaging and the possibility for vertical electrical interconnection, making it very interesting for heterogeneous integration.

In low-temperature melting glass bonding [90] an inorganic low-temperature melting glass or glass frit layer forms the intermediate bonding material and is deposited on one or both of the wafers. The wafers are joined and heated, causing the glass to deform or reflow and bonding the wafers. Two different types of glasses are available; devitrifying glasses, of which the melting point is permanently increased after the curing and vitreous glasses, which always melt at the same temperature. This method allows to hermetically bond various wafer materials at relatively low bonding temperatures and tolerates to some extent particles and structures at the wafer surfaces. The method does not provide electrical interconnection.

3.2.4 Releasing structures for actuation

When integrating actuators there are some more issues to consider beside wafer bonding and vertical electrical interconnection. Actuators imply moving structures which must be detached from their underlying bonding layer to allow their movement. For structures fabricated using wafer-to-wafer bonding, the techniques to detach them from their underlying substrate can be summarized in two approaches. The first method is the localized bonding of areas to be affixed while avoiding the bonding of the structures to be detached. The second method is a bond-and-release approach, in which all structures are bonded to the substrate, followed by removing the bond interface material underneath the structures to be detached.

Localized bonding (illustrated in figure 13a) between two substrates can be obtained using two different principles. The first principle is to modify the interface material prior to bonding, defining bonding and non-bonding areas. Examples of patterned bond interface layers include adhesive layers applied only on areas where bonding is desired [80] and bond blocking layers such as gold or platinum defining local non-bonding areas in anodic bonding [91]. The second localized bonding principle is to use heat triggered bonding methods and to localize the heat to the desired areas of the bond interface. Examples of this approach include integrated heaters for both localized eutectic and silicon fusion bonding [92], localized soldering using inductive heating [93] as well as local heating using lasers [94].

In localized bonding, the non-bonded parts are either fallout-structures or they must remain mechanically connected to the bonded parts by mechanical supports to prevent them from falling out during the remaining process steps. The removal of mechanical support structures through dicing or through controlled fracture has been shown [95, 96]. However, such break-away structures limit the design freedom and potentially increase the footprint area of the MEMS device. Furthermore, the moving structures could be damaged while removing the support structures.

The most common technique for releasing bonded structures is the bond-and-release approach based on sacrificial underetching (illustrated in figure 13b). This technique requires the fabrication of the structures on top of a 'sacrificial' layer, which can be etched with a high selectivity. This approach is common in surface
micromachining [97], where the layers are stacked upon each other. In the crossbar switches presented later in this thesis, the actuators are fabricated using surface micromachining and released prior to integration with the target substrate. A wide variety of sacrificial materials have been demonstrated, such as silicon dioxide [98], polymers [99,100] and metals [101]. In structures fabricated by wafer-bonding, sacrificial underetching is based on wafer-bonding methods with intermediate bonding layers that can be sacrificially etched with a high selectivity to release the attached structures. Examples of such intermediate bonding materials are silicon dioxide [102] and polymers [69, 103]. It should be noted that processes using the buried oxide in silicon-on-insulator (SOI) wafers as sacrificial layer can be considered as such a bond-and-release technology.

A challenge in sacrificial underetching is to provide the selectivity between structures to be detached and structures to remain bonded. If the whole sacrificial layer is removed, there is no selectivity and all structures are detached. One solution for this issue is to affix the structures not to be detached via a second clamping material, which is not attacked when etching the sacrificial layer. An example for this strategy are again the silicon micromirror arrays: the silicon is transfer integrated using adhesive polymer bonding onto a polymer sacrificial layer. Then, metal vias which provide both electrical and mechanical interconnection from the silicon to the IC substrate are fabricated (see figure 9b). Finally, all polymer is removed but the mirrors are still clamped by the metal vias, which are not attacked during the polymer ashing.

Another approach which does not require a second clamping, is to provide the
selectivity by integrating vertical etch holes in the structures to be detached but not in the substrates to remain bonded. These etch holes drastically minimize the distance to underetch as compared to structures without etch holes. Thus, the structures with etch holes are detached while the structures without etch holes are only partially underetched at their edges (see figure 13b).

Etch holes are commonly included in sacrificial underetching to minimize the time the whole substrate is exposed to the etchant or the etch process environment, which may result in device destruction if other materials than the sacrificial layer are attacked. Yet, beside the advantages there are also some challenges to consider. Etch holes potentially decrease the mechanical stability and the performance of the structures to be released. Furthermore, the fabrication of such etch holes is feasible only for structures consisting of thin layers, such as the thin silicon layers of micromirror arrays. If the structures are hundreds of micrometers thick, etch holes are difficult to fabricate with the required aspect ratio. Even if such deep and thin vertical etch holes could be fabricated, the etching of the underlying layers would presumably be very slow due to poor mass transport and depletion of the etchant in the etch holes.

An alternative, which allows for the area-independent release of bonded structures without additional etch holes and harsh chemical environments, is the localized removal of the intermediate bonding layers (illustrated in figure 13c). An example of localized removal is the localized laser ablation of a polymer bonding layer [66]. Another example is based on the electrochemical etching of metal sacrificial layers in a neutral salt solution. This principle has been shown for detaching surface micromachined structures [104], which were deposited onto aluminum as sacrificial layer. In this thesis, this method was adapted to release eutectically bonded silicon microstructures to allow for their manipulation by heterogeneously integrated SMA actuators. Further information about this release etch technique can be found in the attached paper 4.
4 Knife gate microvalves with bulk SMA microactuators

This chapter introduces methods for wafer-level integrating the shape memory alloy Titanium-Nickel (TiNi) and their combination with knife gate microvalves which are a new tool for controlling large gas flows. First experiments proof the great promise of the knife gate valve concept, however, the thermal bimorph actuator of the first test devices proved not robust enough and bulk TiNi material was identified as a promising replacement. There were no reported methods to wafer-level integrate bulk TiNi actuators with silicon structures and, thus, no methods for combining bulk TiNi with the knife gate microvalve concept. TiNi is difficult to integrate with conventional methods and therefore large parts of this thesis deal with developing methods for heterogeneous integration of bulk TiNi material with silicon structures and methods for cold-state reset and concepts for thermal energy supply.

The following sections will briefly introduce the challenges of integrating TiNi material with silicon structures and the concept of knife gate microvalves. Finally, first concepts to integrate bulk TiNi sheets and wires for actuating the valves will be presented, together with initial measurements indicating an outstanding performance of the TiNi actuated knife gate microvalves.

4.1 Integration of Titanium-Nickel shape memory alloy

Despite the advantages, the shape memory alloy Titanium-Nickel (TiNi) is not yet a standard MEMS actuator material, partially due to the difficulties to integrate TiNi with silicon structures. So far, TiNi is integrated either monolithically or in a hybrid fashion.

In monolithic integration, the TiNi is deposited directly onto the silicon structures using metal deposition techniques such as evaporation or sputtering. After deposition, the film is amorphous, i.e. it displays no shape memory effect (SME) and is compressively stressed. To functionalize the layer, the film is crystallized in an annealing step, which involves heating the film to typically above 535 °C [105]. The annealing can even be performed by heating the substrate during deposition [106,13]. During crystallization the stress in the film relaxes and after subsequent cooling the film is under tensile stress, which can be utilized to form a bimorph actuator. In the cold state, the silicon structure (typically a cantilever) is stiff enough to overcome the tensile stress and remains flat, thereby deforming the TiNi and providing the cold-state
reset. Upon heating, the TiNi film contracts and forces the silicon cantilever to bend. Upon cooling the silicon cantilever flattens the bimorph again. A well known example for this technique is the microgripper [21, 107], which is shown in figure 14. In the bimorph approach, the cold-state reset is provided by the built-in stress between the TiNi and the silicon, thus, the cold-state reset is integrated monolithically with the TiNi.

Another approach is to remove the silicon underneath the TiNi, which results in a free standing TiNi film. This method requires additional elements to provide the cold-state reset. Commonly, such additional elements include a bias spring and a mechanical spacer, with the spacer placed in between the bias spring and the TiNi film. During the assembly of the parts, the bias spring deflects the TiNi via the spacer. When heated, the TiNi flattens and deflects the bias spring via the spacer. These elements are integrated either on wafer-level by bonding of other wafers containing the cold-state reset elements or on device-level in a hybrid fashion. Figure 15 shows examples for both cases [108, 1].

Monolithic integration comes with several advantages, such as the wafer-level integration of the material and the possibility of a built-in cold-state reset when using the bimorph approach. However, monolithic integration of TiNi also comes with some major challenges [21]. The transformation temperature of TiNi is very sensitive to variations of Ti or Ni content. An increase in the atomic percentage of nickel by 1% from an equi-atomic ratio of Ti:Ni lowers the martensitic start temperature from 50 °C to -100 °C. Therefore the deposition technique must provide precise and reliable control of the deposition rate of the two different metals, which is difficult to achieve. Even if a film has a proper global composition, local inhomogeneities result in the nucleation and growth of precipitates that inhibit shape memory behavior. The purity of the TiNi targets and high deposition vacuum are essential to limit impurities in the deposited film, which also potentially inhibit the SME. The high temperature annealing step causes compatibility problems with other materials and requires additional layers to avoid unwanted interdiffusion between TiNi and silicon. Also, the large
thermal stresses after deposition and during annealing could cause delamination or cracking of the films. Furthermore, the thicknesses of the films are limited to approximately 20 μm [5] and a recent report states that TiNi-based film sputtering is mostly feasible for thicknesses up to 10 μm only [109], potentially resulting in limited mechanical robustness of structures actuated by TiNi films. For completeness it should be mentioned that in a recent report [110] a 30 μm thick film of a ternary TiNi based alloy was achieved by flash-evaporating TiNiCu onto copper substrates, however, the issues of complicated processing and high post-deposition annealing temperatures are still not overcome.

One method to address these issues is the hybrid integration, where the TiNi is fabricated separately in dedicated factories and pick-and-place integrated as bulk material on device level. Bulk TiNi is commercially available in different shapes and dimensions, for example wires with diameters starting from 18 μm and thin sheets starting from 20 μm (even thicknesses down to 5 μm have been reported [5]). Similar to the free-standing thin TiNi film approach, the cold-state reset is provided by additional elements, which are pick-and-place integrated on device level. As an example, figure 16 shows a schematic drawing [111, 5] illustrating the principle of hybrid TiNi integration for microvalves.

Hybrid integration of bulk TiNi comes with several advantages. The material is produced with standard metalworking techniques in dedicated factories, resulting in specified and reproducible material properties and thereby addressing the sensitivity to variations of Ti and Ni content in the alloy. However, the pick-and-place integration of the TiNi in combination with the pick-and-place integration of the cold-state reset elements is difficult for microdevices and potentially results in large fabrication costs for larger volume production.
Figure 16. Schematic illustration of hybrid integration of TiNi to fabricate a microvalve [111, 5]. The bulk TiNi element is patterned and pick-and-place integrated with the other parts, including the spacer for the cold-state reset. An applied pressure pushes the membrane up, which via the spacer deforms the TiNi element. When heating, the TiNi pushes the membrane down to the flow orifice, thereby closing the valve.

Heterogeneous integration methods allow for the combination of the two methods by integrating bulk TiNi material and providing a cold-state reset on wafer-level. There is one report on heterogeneous TiNi integration [67], in which a SMA sheet was patterned on wafer-scale and the elements were selectively transferred to single plastic microvalves using the selective transfer integration approach of IBM [66] mentioned above. However, the cold-state reset was provided by a spacer between the microvalve and the SMA element, which again requires pick and place assembly. Large parts of this thesis deal with wafer-level integration of both TiNi and the cold-state reset.

4.2 Gas microvalves

4.2.1 Background

A valve is a device that regulates the flow of gas or liquids. In this thesis, the focus lies on millimeter sized valves for gas flow regulation. It would go beyond the scope of this thesis to review all the research efforts into microvalves, therefore the interested reader is referred to review papers [112, 113] for a more detailed overview.

Most of the active microvalves use mechanical moving parts which are coupled to integrated actuators. Depending on the flow control principle, these microvalves can be divided into diaphragm/seat type valves and gate type valves. Diaphragm/seat type valves comprise a boss (most common is a flexible diaphragm) which moves in parallel to the gas flow (see figure 17a) and which is coupled to an actuator. In the closed state, the boss completely closes the orifice and the actuator must overcome the pneumatic pressure, thus, a strong actuator is necessary for controlling high pressure. To allow for a large flow in the open state, the distance and thereby the flow channel between the seat and the boss should be maximized, thus, the actuator must provide a large stroke [114].
Figure 17. Illustration of: (a) seat valve with the flow regulating boss moving in parallel to the gas flow, requiring a strong and large-stroke actuator; (b) gate valve with the flow regulating gate moving perpendicular to the flow, reducing the requirements on the actuator.

In contrast to seat valves, the gas flow in gate valves is regulated by a gate which moves perpendicular to the gas flow (see figure 17b). In the ideal case, when fully opening the valve the gate is completely retracted out of the flow channel and there is no obstruction in the flow path, resulting in higher flow rates compared to a similar sized diaphragm/seat type valve. When moving the gate to close the flow path, the pneumatic pressure is counteracted by the mechanical guidance of the gate and in the ideal case the actuator is only moving the gate and must not counteract the pneumatic pressure. However, the limited actuation energy available in microsystems does not allow friction between sliding structures and therefore requires spacing between flow orifice and gate, which results in leak flow in the closed valve state. Fortunately, many valve applications tolerate leak flow.

Previously published work in the field of gate microvalves always featured gates that move in the wafer plane [115, 116, 117, 118, 119]. Figure 18 [1] shows schematic drawings of a sliding plate gate valve [115], which is currently commercialized by the company Microstax [120, 121, 122]. Yet, to allow the gate to move in the wafer-plane requires extra footprint area and increases the footprint-related costs.

The silicon footprint consumed by the valve is a good cost indicator and when comparing microvalves to each other not only the performance in terms of controlled flow and pressure should be considered, but also the performance obtained per consumed footprint area. Therefore, in this thesis the comparison figure ‘controlled flow/pressure drop/footprint’ is suggested with the unit [sccm/kPa/mm²]. Table 4 shows the performance per footprint of different microvalves and the numbers indicate, that gate microvalves typically have a much larger performance than diaphragm/seat microvalves.

Microvalves should be fabricated cost-efficiently to allow them to be successful outside the specific niche markets they currently focus on. This thesis presents the knife gate microvalve concept, in which the gate moves out of the wafer plane to minimize the chip footprint area and the footprint-related cost.
Figure 18. Schematic drawings of the sliding gate microvalve introduced by Williams et al [115], showing (a) a cross-section and (b) a three-dimensional drawing of the three silicon wafers, which are assembled to form a pressure-balanced microvalve. The figure is copied from [1].
Table 4. Comparison of different valves in terms pneumatic performance relative to their consumed footprint area. It should be noted, that not all of the listed valves are silicon valves, however, they are all microvalves. The performance comparison is related to the knife gate valve presented in this work.

<table>
<thead>
<tr>
<th>Reference and actuation method</th>
<th>Q (sccm)</th>
<th>P (kPa)</th>
<th>w (mm)</th>
<th>l (mm)</th>
<th>Q/P/A</th>
<th>related to valve in the attached paper 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>this work, knife gate microvalves</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>thermal bimorph, attached paper 1, externally actuated</td>
<td>3400</td>
<td>95</td>
<td>2.3</td>
<td>2.3</td>
<td>4.21</td>
<td>100%</td>
</tr>
<tr>
<td>SMA (TiNi sheet) actuation</td>
<td>1000</td>
<td>8</td>
<td>6.5</td>
<td>6.5</td>
<td>2.95</td>
<td>70%</td>
</tr>
<tr>
<td>SMA (TiNi wire) actuation</td>
<td>3800</td>
<td>50</td>
<td>2.0</td>
<td>4.5</td>
<td>8.44</td>
<td>200%</td>
</tr>
<tr>
<td><em>other gate microvalves</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[115], thermal</td>
<td>6700</td>
<td>1000</td>
<td>2.5</td>
<td>5.0</td>
<td>0.54</td>
<td>13%</td>
</tr>
<tr>
<td>[116], thermal</td>
<td>5000</td>
<td>100</td>
<td>4.0</td>
<td>4.0</td>
<td>3.13</td>
<td>74%</td>
</tr>
<tr>
<td>[119], externally magnetic</td>
<td>500</td>
<td>40</td>
<td>1.4</td>
<td>1.4</td>
<td>6.17</td>
<td>147%</td>
</tr>
<tr>
<td><em>seat microvalves</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zdeblitz et al [123], phase change, ('FLUISTOR' valve)</td>
<td>5000</td>
<td>140</td>
<td>6.0</td>
<td>6.0</td>
<td>0.99</td>
<td>23.59%</td>
</tr>
<tr>
<td>TiNi Alloy company, SMA (TiNi), figure 15, [1]</td>
<td>1000</td>
<td>690</td>
<td>8.0</td>
<td>5.0</td>
<td>0.04</td>
<td>0.86%</td>
</tr>
<tr>
<td>Messner et al [124], thermal bimorph</td>
<td>1150</td>
<td>800</td>
<td>4.0</td>
<td>4.9</td>
<td>0.09</td>
<td>2.14%</td>
</tr>
<tr>
<td>Jerman [125], thermal bimorph</td>
<td>100</td>
<td>170</td>
<td>2.5</td>
<td>2.5</td>
<td>0.09</td>
<td>2.24%</td>
</tr>
<tr>
<td>Fu et al [126], magnetic</td>
<td>2000</td>
<td>200</td>
<td>10.0</td>
<td>10.0</td>
<td>0.10</td>
<td>2.38%</td>
</tr>
<tr>
<td>Yang et al [127], electrostatic</td>
<td>45</td>
<td>900</td>
<td>1.64</td>
<td>1.64</td>
<td>0.02</td>
<td>0.44%</td>
</tr>
<tr>
<td>Li et al [128], PZT</td>
<td>39</td>
<td>210</td>
<td>20.0</td>
<td>20.0</td>
<td>0.00</td>
<td>0.01%</td>
</tr>
<tr>
<td>Yang et al [129], PZT</td>
<td>52</td>
<td>2070</td>
<td>8.4</td>
<td>5.0</td>
<td>0.00</td>
<td>0.01%</td>
</tr>
<tr>
<td>Shao et al [130], PZT</td>
<td>70</td>
<td>50</td>
<td>13.0</td>
<td>13.0</td>
<td>0.01</td>
<td>0.20%</td>
</tr>
<tr>
<td>Huff et al [131], electrostatic</td>
<td>800</td>
<td>550</td>
<td>3.6</td>
<td>3.6</td>
<td>0.11</td>
<td>2.67%</td>
</tr>
<tr>
<td>Barth et al [132], thermal bimorph</td>
<td>1000</td>
<td>344</td>
<td>8.8</td>
<td>8.8</td>
<td>0.04</td>
<td>0.89%</td>
</tr>
<tr>
<td>Yang et al [133], thermopneumatic</td>
<td>1000</td>
<td>228</td>
<td>8.0</td>
<td>8.0</td>
<td>0.07</td>
<td>1.63%</td>
</tr>
<tr>
<td>Bosch et al [134], magnetic + electrostatic</td>
<td>3</td>
<td>16</td>
<td>3.0</td>
<td>8.0</td>
<td>0.01</td>
<td>0.19%</td>
</tr>
<tr>
<td>Kohl et al [135, 5], SMA (TiNi)</td>
<td>1600</td>
<td>120</td>
<td>20.0</td>
<td>11.0</td>
<td>0.06</td>
<td>1.44%</td>
</tr>
<tr>
<td>Kohl et al [136, 5], SMA (TiNi)</td>
<td>470</td>
<td>500</td>
<td>6.0</td>
<td>6.0</td>
<td>0.03</td>
<td>0.74%</td>
</tr>
<tr>
<td>Kohl et al [137, 5], SMA (TiNi)</td>
<td>180</td>
<td>210</td>
<td>6.0</td>
<td>11.0</td>
<td>0.01</td>
<td>0.31%</td>
</tr>
<tr>
<td>Kohl et al [137, 5], SMA (TiNiPd)</td>
<td>360</td>
<td>250</td>
<td>6.0</td>
<td>11.0</td>
<td>0.02</td>
<td>0.52%</td>
</tr>
<tr>
<td>Kohl et al [138, 5], SMA (TiNiCu)</td>
<td>360</td>
<td>300</td>
<td>6.0</td>
<td>11.0</td>
<td>0.02</td>
<td>0.43%</td>
</tr>
<tr>
<td>Kohl [5], SMA (TiNi)</td>
<td>280</td>
<td>200</td>
<td>6.0</td>
<td>6.0</td>
<td>0.04</td>
<td>0.92%</td>
</tr>
<tr>
<td>Kohl et al [139, 5], SMA (TiNi)</td>
<td>460</td>
<td>800</td>
<td>6.0</td>
<td>6.0</td>
<td>0.02</td>
<td>0.38%</td>
</tr>
</tbody>
</table>

Q = flow in sccm; P = pressure in kPa; w,l = width, length in mm; A = w×l = footprint in mm²
Q/P/A = performance per footprint in sccm/kPa/mm²
4.2.2 Knife gate microvalves

This thesis presents the knife gate microvalve concept, in which the gate moves out of the wafer plane to minimize the chip footprint area and the footprint-related costs. Figure 19 illustrates the three different designs of microvalves with the gate moving out-of-plane. The gate is coupled to a monolithically integrated thermal silicon/aluminum bimorph actuator and moves out-of-plane to regulate an in-plane flow. The valve concept is explained in detail in the attached paper 1.

Figure 20 confirms the valve’s potential for controlling large flows: an active chip area of only $2.3 \times 3.7 \text{ mm}^2$ allows for a flow change of $\Delta Q = 3400$ standard cubic centimeters per minute (sccm) at a pressure difference of 95 kPa.

Table 4 lists the performance per footprint of different microvalves. For simpler comparison the presented knife gate micro valve is chosen as reference and all the other microvalves are compared to it. The comparison shows that the knife gate microvalve provides the highest performance per footprint, only outperformed by a recently published rotary gate valve and the TiNi wire actuated knife gate microvalve. The rotary valve is electromagnetically actuated using an external magnetic field and belongs therefore to another class of microvalves with external actuation mechanisms.

![Figure 19](image1.png)

**Figure 19.** Illustration of the three different knife gate microvalve designs introduced in detail in the attached paper 1.

![Figure 20](image2.png)

**Figure 20.** Measured pressure-flow characteristics of a back-gate microvalve. The dashed line indicates the expected leak caused by imperfect assembly.
Figure 21. Cross-sectional drawing of the first design of a TiNi sheet actuated knife gate valve showing (a) a back gate valve bonded to a carrier substrate and the TiNi sheet prior to integration; (b) the adhesive bonding of the TiNi sheet onto the valve and (c) releasing the flow regulating gate to allow for its manipulation by the actuator.

The TiNi wire actuated knife gate microvalve is a successor of the thermal bimorph knife gate microvalve and will be discussed below.

However, it should be noted that while the experiments indicate the excellent capabilities of the knife gate microvalve concept, the thermal bimorph actuator failed for several reasons. First, the bimorph beam was not strong enough to withstand the vibration and torsional forces caused by the flow. Second, improper thermal design caused improper heating and actuation of the beam. Bulk TiNi actuators were identified as a promising replacement, however, concepts for integrating bulk TiNi materials had to be developed first.

4.3 TiNi sheet actuated knife gate valves

4.3.1 Design

In a first, yet unpublished design to integrate TiNi sheets onto silicon knife gate microvalves, the TiNi is integrated with a back gate valve (back gate valve see figure 19c). Figure 21 shows the design, in which the back-gate valve is bonded onto a carrier substrate with a vertically through-etched hole, providing an enclosed flow channel which is expected to simplify the pneumatic connection. The TiNi is bonded onto the valve: one end of the TiNi is bonded to the flow channel forming the base for the cantilever and the other end is bonded onto the flow-regulating gate.

4.3.2 Fabrication - Integration of TiNi sheets

A method was investigated to adhesively bond TiNi sheets onto silicon structures, together with methods for the cold-state reset and thermal energy supply. The attached paper 2 contains a detailed description of these methods.

The concept to integrate TiNi sheets onto silicon structures is illustrated in figure 22a. The TiNi sheet is patterned to form the actuator structures, using flexure interconnections to hold them together. The patterning is performed prior to integration to avoid the exposure of the silicon target structures to the very aggressive TiNi etchant. The bonding adhesive is stamped onto the surface of the patterned target.
wafer-level heterogeneous integration of MEMS actuators

(a) TiNi sheet integration concept

(b) trimorph actuator concept

Figure 22. Illustration of (a) final bulk TiNi sheet integration concept and (b) trimorph actuator concept, as developed in paper Nr. 2.

wafer, which was a 'dummy' wafer with etched holes to allow the TiNi actuators to deflect freely. The stamping method is specially developed in this thesis and based on standard dicing blue tape. Then, the TiNi sheet is aligned and bonded onto the target wafer. For developing this integration method, the target wafer was a 'dummy' wafer with etched holes, which allow the TiNi actuators to deflect freely.

After the TiNi material is integrated, the cold-state reset and thermal energy supply must be provided for actuation. In this work, these elements are integrated monolithically with the TiNi sheet in form of three functional layers. Figure 22b illustrates the actuation concept. The first functional layer is the core actuation layer formed by bulk TiNi material. The second functional layer is a stressed film which deforms the actuator in the cold-state. This film is deposited onto the TiNi and eliminates the need for pick-and-place integration of an additional bias spring. The third functional layer is a heating layer to supply thermal energy to the actuator via an indirect heating scheme and to avoid the complicated electrical contacting of the TiNi alloy.

In the valve design shown in figure 21, the TiNi sheet is bonded onto the gate, which itself is bonded to another silicon wafer. To allow the gate to be manipulated for controlling the flow, its underlying bonding layer must be removed without removing the bonding layers underneath the other silicon structures. Section 3.2.4 presents some methods for the localized release of structures while keeping other structures bonded,
however, most of them require underetching of the structures to be released, including exposure of the whole device to harsh environments and etching of all bonding layers. To avoid these issues, a new bond-and-release method was developed: The valve and the carrier substrate are bonded together using eutectic Au-Si bonding, followed by localized removal of the eutectic bonding layer. For a detailed description and investigation of this method, the reader is referred to the attached paper 4.

4.3.3 Results

Figure 23 shows first results of the flow performance of a gate microvalve with TiNi sheet actuation. An active chip area of only $6.5 \times 6.5 \text{ mm}^2$ allows for a flow change of $\Delta Q \approx 1000 \text{ sccm}$ at a pressure difference of 8 kPa. These numbers result in a flow performance per footprint (see Table 4) of about 70% of the first knife gate valve with the non-functional thermal bimorph actuators. However, in contrast to the first knife gate valve, the TiNi sheet actuated valve was actuated with the integrated actuator and did not require any external actuation. Furthermore, the tested TiNi sheet knife gate valve is an early prototype with room for optimization.

4.3.4 Discussion

The TiNi sheets are integrated directly onto the silicon structures, without any intermediate carrier or transfer substrate. Since the sheet is patterned prior to integration, it has to be aligned to the target wafer. Both alignment and placing onto the adhesive layer were performed manually. However, the patterned TiNi sheet was fragile and very easily deformable, which complicated the handling. The alignment of the sheet was enabled only by a high ambient temperature caused by a hotplate underneath the target wafer, which triggered the stiff hot state of the sheet. To allow for an alignment and bonding using a standard wafer alignment and bonding tool, future designs should aim for a transfer integration method, in which the SMA sheet is preprocessed on an intermediate carrier substrate and then transfer bonded from the carrier substrate onto the target wafer.
Wafer-level heterogeneous integration of MEMS actuators

Figure 24. (a) Photographs of a eutectically bonded TiNi cantilever which was severely plastically deformed by manual pulling with a tweezer without breaking the bond, thereby illustrating the extreme bond strength. (b) Picture of a eutectically bonded TiNi trimorph actuator with a resistive heater.

The sheets are affixed onto the silicon structures using adhesive polymer bonding. The adhesion strength looks promising, however, more tests are necessary to verify the bond stability, especially for long-term cycling of the actuator. An alternative method could be the one used for the micromirror arrays presented in section 3: the adhesive bonding could serve as temporary mechanical fixation and electroplated metal vias through the TiNi sheets could provide both electrical interconnection and permanent mechanical fixation. Yet another alternative is to use a different bonding method which allows for direct mechanical fixation. Figure 24a shows non-published pictures of first experiments testing the eutectic bonding of TiNi to silicon and illustrating the extreme bond strength: a eutectically bonded TiNi cantilever was severely plastically deformed by manual pulling with a tweezer without breaking the bond.

At this stage, an electrical interconnection between the TiNi and the silicon structures is not necessary, since any scheme for electrical contacting of the actuator would most likely involve wire bonding directly to the metal heater on top of the TiNi trimorph actuators. Since the work in the attached paper 2 was focused on integration and cold-state reset, the test structures did not contain a metal heater. Figure 24b shows a photograph of a yet unpublished complete trimorph actuator containing a resistive metal heater, which is eutectically bonded to silicon. The heater was contacted using probe needles and consumed approximately 100 mW to trigger the TiNi hot state.

4.4 TiNi wire actuated knife gate valves

4.4.1 Concept

Figure 25 shows a first, yet unpublished design to integrate TiNi wires with the knife gate valve concept. The wires are integrated with a front gate valve (front gate valve see figure 19c).
4 KNIFE GATE MICROVALVES WITH BULK SMA MICROACTUATORS

4.4.2 Fabrication - Integration of TiNi wires

For the SMA wire actuators, the integration concept is derived from the actuation concept, which is illustrated in figure 26a. TiNi wires are strained by pulling them prior to integration. Then, the strained wires are integrated with silicon cantilevers by anchoring one end of the wires to the base of the silicon cantilever and the other end of the wire to the moveable end of the cantilever. Upon heating, the TiNi wires recover the strain, i.e. they contract and thereby force the silicon cantilever to bend out of plane. In the cold state, the silicon cantilevers act as cold-state reset, recovering their flat shape by stretching the TiNi wires.

Figure 26b illustrates the resulting wafer-level integration concept. The wires are oriented and placed on a dedicated tensioning frame, which is used to strain the wires. Then, the wafer and the wires are aligned to each other and put in contact. Finally, the wires are anchored for each actuator and the tensioning frame is removed. After integration, the wires are diced together with the silicon chips. For a detailed investigation including the proof of concept by fabricating first test structures the reader is referred to the attached paper 3. The fabricated test devices showed strokes of up to 396 μm for a cantilever length of 3 mm, which is among the highest values in comparison to different microactuators reported in a recent review paper [6]. Since the work in this paper was focused on integration and cold-state reset, no heating concept is presented.

4.4.3 Results

Figure 27 shows first results of the flow performance of a knife gate microvalve with TiNi wire actuation. An active chip area of only $2 \times 4.5 \text{ mm}^2$ allows for a flow change of $\Delta Q \approx 3800 \text{ sccm}$ at a pressure change of 50 kPa. These numbers result in a flow performance per footprint (see Table 4) of about 200% of the first knife gate valve with non-functional thermal bimorph actuators. In contrast to the first knife gate valve, the TiNi wire valve is actuated with the integrated actuator. The flow performance per consumed footprint area is a world record compared to the other valves and clearly demonstrates the promise of TiNi actuated knife gate microvalves.

4.4.4 Discussion

The TiNi wires are transfer-integrated, using a dedicated tensioning frame as temporary carrier. For the first test devices, the alignment was performed manually and the wires were placed onto the adhesive anchors using a dedicated lift stage. This process
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![Diagram of actuator concept and wafer-level integration concept](image)

(a) actuator concept

(b) wafer-level integration concept

**Figure 26.** Illustration of (a) the actuation concept using TiNi wires on silicon cantilevers and (b) concept for wafer-level integration of the wires, as developed in the attached paper 3.

![Graph of pressure-flow characteristics](image)

**Figure 27.** First measurements of the pressure-flow characteristics of a yet unpublished TiNi-wire actuated knife gate microvalve.
could be adapted to implement a high precision (x,y,z) stage, thus, the process looks promising for the wafer-level integration of wires. However, prior to integration the wires need to be placed onto the tensioning frame with the correct orientation and pitch, which was performed manually in this work. Future work should verify that the wires can be placed onto the tensioning frame using automated methods.

The wires are attached to the silicon cantilevers using anchors made of SU-8, which is locally cured with UV light. However, the area underneath the wires is shadowed by the wires and therefore not fully cured. Future work should implement reflective patterns in the silicon underneath the wires to reflect the UV light into the SU-8 volume underneath the wires. Alternatively, the wires could be anchored using metal clamping via electroplating metallic connections between the silicon and the wires.

4.5 Outlook

The work presented above is a big step towards a microvalve with potential for commercial application. However, a fully integrated TiNi actuated valve with integrated heaters has not been shown so far. All necessary elements have been discussed and future work will focus on combining all elements to show a fully functional TiNi actuated microvalve.

For commercialization the valve must be packaged. Figure 28 shows the suggested packaging concept, which is inspired by the packaging of several commercial pressure sensors. The valve is glued onto the pneumatic connector tube of a TO8-housing, thereby pneumatically interconnecting the valve to an inlet pressure. The outlet of the flow can be provided by a hole in the lid of the TO8-housing. The electrical interconnection to the actuator on the valve is provided by wirebonding to the electrical interconnection pins of the TO8-housing.
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5 Automated main distributing frames with S-shaped actuator switches

This chapter presents a MEMS crossbar switch as the core unit to automate main distributing frames, in which the parties in copper-wire telecommunication networks are cross-connected. The crossbar switch consists of an array of MEMS switches which are individually addressable and allow to interconnect a number of input lines to a number of output lines in any combination desired. In this work, the switches are based on the electrostatic S-shaped actuator described earlier in section 2.3.2. Each of the switches in the array is individually addressable using a row/column addressing method, avoiding a complicated CMOS circuitry as utilized in micromirror arrays. The fabrication concept of the crossbar switch is based on the basic concept of heterogeneous integration, which involves the separate fabrication of parts followed by their assembly to a device.

The following subsections briefly introduce automated main distributing frames, followed by a description of the S-shaped actuator switch. Finally, the MEMS crossbar switch and the concept of individual switch addressing are presented.

5.1 Switch units in automated main distributing frames

The current telecommunication networks evolved from the original telephone networks and they are for the most part still based on copper-wire networks. Within these networks, the main distributing frame (MDF) is the center of cross-connecting equipment of service providers to their customers and it is located both in large central offices and remote street cabinets. The MDF still relies upon the same routines and equipment it did 50 years ago. Hence, whenever a cross-connection must be changed, this re-configuration must be carried out manually by technicians physically changing the interconnection wires (jumpering) in the MDF. Before the deregulation of the telecommunication markets the customers only rarely changed their services and there were no or little economical incentives to automate the jumpering. Nowadays, however, the customers are highly flexible and there is a growing need to adapt quickly to new telecommunication services. Due to the increased labor-intensive manual jumpering the network maintaining costs are drastically rising and thereby creating a clear incentive to automate the jumpering using an automated MDF (AMDF).

The core element of the AMDF is a crossbar switch. Originally, the term "crossbar
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Figure 29. Electrical and hierarchical schematic diagrams: (a) switch unit, consisting of an array of 3 × 3 double switches; (b) arrangement of switch units on higher hierarchical layers using the Clos method to minimize the necessary amount of switches.

Switch" relates to a grid of metal bars crossing each other without touching each other and which are electrically interconnected or isolated by switches in their crosspoints. In a AMDF, the metal bars are formed by signal channels, with a set of input channels and a set of output channels. A channel consists of a signal line pair and switching the signal line pair simultaneously requires a double-pole single-throw (DPST) switch in each cross-point. Typically, the cross-bar switches are symmetrical, with N inputs and N outputs resulting in N^2 crosspoints. Figure 29a shows an electrical schematic of the signal circuit for a simplified crossbar switch with N=3. A typical AMDF connects tens of thousands of channels and it is not feasible to provide this amount of crosspoints in a single crossbar switch since it is difficult to fabricate such large arrays with an acceptable yield. Furthermore, each bar or channel can only be connected in one crosspoint while the other crosspoints remain unused and therefore large parts of the crossbar switch are not utilized. A solution is to fabricate small crossbar switch units with a low N and interconnect several of them to a bigger crossbar switch unit, which itself again forms a switch unit in a bigger crossbar switch. In 1953, Charles Clos at Bell labs developed the 'minimal spanning switch' method [140] to interconnect the small crossbar switch units in a way to reduce the total number of switches and interconnections, but still allowing for a non-blocking network which always provides one route to interconnect an input to an output. In this method, the switch units are arranged in three stages with each the same number of switch units and each switch unit sharing only one connection with a switch unit in another stage, as illustrated in figure 29b. If a path is blocked, the connections can be rerouted via other switch units to open a new path. When scaling up the resulting crossbar switch, Clos' interconnection method reduces the amount of crosspoints from the quadratically scaling N^2 to the more favorable 3×√N×√N×√N = 3×N^{1.5}, thereby drastically minimizing the number of switches and the related costs. As an example, a conventional crossbar switch with N = 100 would require N^2= 10000 crosspoint switches, whereas a Clos crossbar switch requires 10 switch units à 10×10 crosspoints...
in three stages, which results in $10 \times 10 \times 10 \times 3 = 3000$ crosspoint switches, only.

It would go beyond the scope of this thesis to extend this introduction, therefore the interested reader is referred to literature such as [140, 141, 142, 143, 144].

A crossbar switch unit comprises three basic elements. The first element is the routing network with input and output signal channels crossing each other without touching each other. The second element are switches needed for interconnecting the signal channels in their crosspoints. The third element is controlling of the switches: each switch must be individually addressable to allow for the interconnection of any of the N input lines to any of the N output lines in any configuration desired.

To ensure the highest flexibility when connecting new services and new technological equipment to the customers, the signal path should ideally act like a copper-wire cable which requires ohmic mechanical switching with metal contacts and excludes solid-state relay based crossbar switching. Previous attempts to provide a switch unit for a Clos network in an automated MDF consist of robots [145, 146, 147] or electromagnetic relays [148, 149].

Figure 30 [145] exemplarily illustrates the robot approach: the routing network is formed by a matrix board and the switches are metal pins, which are inserted/extracted in the crosspoints of the signal channels using a robot. The addressing is provided by moving the robot to the addressed crosspoint using a xy-stage with a laser for fine alignment. In the electromagnetic relay approach, the crossbar switching is performed by an array of electromagnetic relays on printed circuit boards. These arrays include control circuits with diodes and transistors to allow for a row/column addressing. The attached paper 5 contains a short comparison of the technologies, which did not provide solutions with the desired performance at acceptable costs.

Nowadays, MEMS technology offers the possibility to integrate a large number of micro-switches on a single chip and utilizes high-volume semiconductor manufactur-
Wafer-level heterogeneous integration of MEMS actuators

Figure 31. Illustration of a conventional cantilever-type electrostatic MEMS switch. The figure is modified from [37].

Figure 31. Illustration of a conventional cantilever-type electrostatic MEMS switch. The figure is modified from [37].

MEMS switches have been investigated extensively during the last decade for many applications requiring high quality signal switching [150,151,152]. They fill the gap between solid-state relays (SSR) and electromagnetic relays (EMR) by offering true ohmic switching, high miniaturization and integration and very good signal properties over a large bandwidth. To the authors’ knowledge, there are no scientific reports on MEMS crossbar switches or switch arrays for the described application. However, there are a few reports on small-scaled and unpackaged metal-contact MEMS switch arrays for other applications [153,154,155,156,157,158].

5.2 MEMS switches

5.2.1 Background

MEMS switches are devices that mechanically open or short-circuit a transmission line. They are of submillimeter size and they outperform semiconductor switches in terms of power consumption, on-state resistance, cut-off frequency, isolation and signal insertion loss [150,151,152]. There are two basic types of MEMS switches: capacitive switches and metal-contact switches. Capacitive switches are typically used as shunt switches between the signal line and the ground line while metal-contact switches are used as series switches between two transmission lines, opening or closing the signal path. In metal-contact switches, the signal is conducted through metal contacts and in capacitive switches, the contact is made between the metal and dielectric material. The application in automated MDF’s described above requires ohmic switching of signals from DC to max. 50 MHz, therefore only metal contact series switches are of interest in this work.

For metal contact switches there are several requirements to consider when designing the switch. In the off-state, the switch should provide a high isolation when applying signals with high voltages, hence, a large distance between the switch contacts is necessary. When the switch is closed, the contact resistance should be as low as possible and the contact should remain stable during the whole ON time. The switch contact resistance and reliability is directly influenced by the contact force and the contact material. The influence of the contact materials is a research field on its own [159,160,161,162] and not touched upon in this work. The contact force should be maximized, however, a strong contact force increases the risk of stiction between
5 AUTOMATED MAIN DISTRIBUTING FRAMES WITH S-SHAPED ACTUATOR SWITCHES

the contacts. Therefore, the forces opening the switch should be strong enough to overcome the adhesion forces between the switch contacts.

Most of the MEMS switches are electrostatically actuated and the conventional and so far most common electrostatically actuated MEMS switch is based on a simple cantilever approach, as illustrated in figure 31. The switch contact bar at the moveable end of the cantilever interconnects two signal lines when the cantilever is pulled down, as illustrated in figure 31b. This configuration is basically a parallel-plate actuator and comes with all the problems mentioned in section 2.3.1, especially in combination with the switch requirements described above: a large distance between the switch contacts for a high OFF state signal isolation results in a large initial electrode gap and thereby in large actuation voltages. To overcome stiction forces when opening the switch, a stiff cantilever is required to provide strong opening forces. As a consequence, increased actuation voltages are necessary to overcome the strong spring force. Figure 32 [37] illustrates all the parameters involved for electrostatically actuated metal contact switches and how they are interconnected.

5.2.2 The S-shaped actuator switch

To overcome the limitations of the conventional cantilever type switch, an alternative approach was developed based on the S-shaped film actuator described in section 2.3.2 [35,36,37]. The assembly concept of the S-shaped actuator highlights this actuator for the heterogeneous integration with other structures. One substrate contains all the moveable parts of the actuator, while the target substrate provides an actuation electrode and a spacer to provide the gap in which the membrane moves up and down. Figure 33 illustrates the basic concept of the S-shaped film actuator.
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switch. The switch substrate contains the flexible membrane with a switch contact and the target substrate contains the signal lines which are to be interconnected by the switch (figure 33a). The distance $d$ between the switch contacts in the OFF state (figure 33b) can be tuned and a large distance allows to obtain a high off-state isolation. In the ON state (figure 33c), the signal lines are interconnected by the switch contact on the membrane. The switch contact area is surrounded by the actuation electrode, resulting in a more homogeneous contact force.

If the spring force of the thin rolling membrane is not strong enough to open the switch, the upper zipper-actuator provides an active opening capability.

5.3 The MEMS crossbar switch

The following subsections introduce the MEMS crossbar switches developed in this thesis. These crossbar switches are fully fabricated using standard MEMS technologies and materials. Thus, strictly speaking no heterogeneous integration is applied since heterogeneous integration refers to the integration of different technologies or materials. However, the development of the MEMS crossbar switch is based on the basic concept of heterogeneous integration; the device is divided into substructures, which are fabricated separately and finally integrated with each other.

For the MEMS crossbar switch, the elements to integrate are a signal channel routing network, switches to interconnect the signal channels in their crosspoints and a control line network for the individual addressing of single switches. The following sections briefly introduce the routing network, the switches and their integration to a crossbar switch. Finally the addressing concept will be presented. A detailed description of the concept and the fabrication can be found in the attached paper 5 and 6.

5.3.1 The routing network

Figure 34 (bottom part) illustrates the signal line routing network. The signal lines are fabricated in two different metal layers, which are isolated from each other by an intermediate polymer layer. The input lines are in the lower metal layer and the output lines are in the upper metal layer, crossing the input lines. In each crosspoint the input lines are connected to the upper metal layer by vertical metal vias through the
Figure 34. Three-dimensional drawing showing the concept of the KTH MEMS crossbar switch, simplified to a $2 \times 2$ array. Some components of the bottom part have been removed to reveal details. The bottom part contains the signal-routing network on two metal layers and the bottom electrodes for the switch actuation. Furthermore, the picture shows the two BCB layers for isolating the metal layers of the routing network from each other and for creating the encapsulating spacer ring between the top and the bottom part. The top part contains the moving part of the S-shaped film actuator switches with the switch contacts to interconnect the signal lines in their crosspoints.
intermediate polymer layer. The upper metal layer also contains actuation electrodes (bottom electrodes) to actuate the switches later on.

5.3.2 The crosspoint switches

Figure 34 (top part) illustrates the switching part of the crossbar switch, which allows to interconnect the signal lines in each crosspoint. The switches are S-shaped actuator switches as introduced above. As illustrated in the electrical schematic of the signal circuit in figure 29a, the signal lines are paired to channels, consisting of a signal+ and a signal− line. To switch both lines simultaneously, each membrane contains two separate switch contacts to allow for the parallel switching of two line pairs in the target substrate.

5.3.3 The integration

Finally, the top part with the switches is placed onto the bottom part with the signal channels. The spacing between the two parts is provided by a polymer ring (figure 34, spacer ring) around the crosspoints. Besides spacing, the polymer ring is also designed to provide the mechanical fixation of the two parts. The polymer ring is patterned prior to the assembly, but not fully cured. After the assembly, the polymer is cured and thereby the two parts are adhesively bonded. Furthermore, the switches are encapsulated/packaged by the polymer ring, based on the encapsulation/packaging concept illustrated in figure 10.

5.3.4 Individual switch addressing

There are several possibilities for the individual addressing of the switches. The conventional approach would be to connect each switch with an individual control wire. However, the number of switches and thereby the number of control wires scale quadratically with the size of the matrix, making this conventional approach feasible only for very small arrays with a small number of elements. Another approach is to integrate a CMOS addressing circuitry as shown earlier for micromirror arrays, which allows for the analog control of the actuators in the array as well as for high addressing frequencies [50]. The presented fabrication concept of the MEMS crossbar switch would allow for the heterogeneous integration of the switches with a CMOS wafer, however, the AMDF application requires only digital mode addressing with low addressing frequencies and does not justify the integration of high-cost CMOS circuits.

The addressing approach developed for the MEMS crossbar switch utilizes the hysteresis behavior of the actuation voltages of electrostatic actuators, which was explained in section 2.3.1 and illustrated in figure 3c. Applying a set voltage $V_{set}$ which is larger than the pull-in voltage always pulls in the moveable plate and the switch is ON: $V_{set} \geq V_{pull-in}$. Reducing the applied voltage to a hold voltage $V_{hold}$ within the hysteresis range between the pull-in and the pull-out voltage holds the moveable plate in the current position, i.e. either in the ON or in the OFF state:
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V_{pull-out} < V_{hold} < V_{pull-in}. To open the switch, the applied voltage is reduced to the reset voltage $V_{reset}$, which is smaller than the pull-out voltage: $V_{reset} \leq V_{pull-out}$.

For the addressing scheme to work, the electrodes of the fixed plates are interconnected in each respective column, whereas the electrodes of the moveable plates are interconnected in each respective row. This arrangement allows to provide the required potential differences in the crosspoints of the electrodes and the number of necessary control lines is reduced from the quadratically scaling $N^2$ to the linear scaling complexity of $2N$. As an example, with the conventional addressing approach a crossbar switch with $N = 20$ would require 400 control lines, while the presented row/column approach requires only $2N = 40$ control wires.

The individual pull-in is illustrated in figure 35. If all columns are fed with the hold voltage $V_{hold}$ and all rows are on ground potential, all switches maintain their current states (figure 35a). To set the actuator at the address (2,1), the potential difference between the electrodes must exceed the pull-in voltage $V_{pull-in}$. Therefore, a voltage level of $V_{hold} + V_{set+}$ is applied at the 2nd row, and a negative voltage level of $V_{set-}$ is applied at the 3rd column (figure 35b). After the individual pull-in the voltages $\Delta V_{set+}$ and $\Delta V_{set-}$ are removed and the columns are connected to the hold voltage $V_{hold}$, maintaining the current state of all switches as illustrated in figure 35c.

The individual pull-out is illustrated in figure 36. All columns are fed with the hold voltage $V_{hold}$ and all rows are on ground potential, all switches maintain their current states (figure 36a). To reset the actuator at the address (2,1), the potential difference between the electrodes must be below the pull-out voltage $V_{pull-out}$. Therefore, a positive voltage level of $V_{reset}$ is applied at the 3rd column and thereby subtracted.
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Figure 36. Schematic drawings illustrating the individual resetting of cell (2,1) in a 3×3 array and the voltages involved. (a) Hold state. Each actuator maintains its current state. (b) Pull-out of the actuator by applying the addressing voltages at the respective rows and columns. (c) Return to hold state. Maintaining the programmed states of all cells.

from \( V_{\text{hold}} \). To avoid resetting all the switches in the 3rd column, \( V_{\text{reset}} \) must be added to \( V_{\text{hold}} \) at the other rows (figure 36b). Finally, all columns are connected to the hold voltage \( V_{\text{hold}} \), maintaining the current state of all switches as illustrated in figure 36c. Another simpler method for the resetting is to connect all electrodes to ground and set a new pattern as described above.

This addressing scheme has been reported before for micromirror arrays [163,164,165,166,167] and programmable capacitor banks [168]. Neither of these reports, however, discusses any design requirements or considerations on the operational robustness of the addressing scheme. This thesis contains a full investigation for determining the operational reliability of the addressing scheme and to optimize the addressing voltage levels, taking into account the statistical deviations of the actuation voltages both for a single actuator as well as across the array. The attached journal paper 6 extensively investigates this issue and presents methods to choose actuation voltages which result in a statistical certainty of better than 99.9% for the addressing to work.

5.4 Discussion

The routing network and the switches are integrated directly, without any intermediate carrier or transfer substrate. The mechanical fixation of the two substrates is designed as adhesive bonding via the patterned adhesive spacer ring. In this design, the polymer spacer ring not only provides spacing and mechanical fixation, but also an encapsulation and thereby packaging of the crosspoints. However, it should be noted here, that even though the mechanical fixation of the two substrates is designed as a wafer-level process, the first test structures were assembled manually on
chip-level using epoxy droplets in the corners for mechanical fixation. This issue will be addressed in more detail below.

Usually, a controlled atmosphere inside the packaged volume is desired and therefore hermetic sealing of the encapsulation would be the optimum. The polymer based sealing of the presented crossbar switches does not provide hermetic sealing even if the chosen polymer, Bencyclobutene (BCB) from the Dow Chemical Company, is often referred to as "near-hermetic" packaging [169]. A full hermetic packaging is obtained using a metallic bonding scheme, however, at the cost of the relatively non-complicated method to provide the spacing between the substrates using a polymer ring.

The two substrates interact with each other both electrically and mechanically. Yet, there are no vertical electrical interconnection vias which allow to access the switch control electrodes on the switch substrate via the network substrate. The lack of this vias is the main reason, why the first test structures were assembled manually on chip-level: both the switch substrate (top part) and the network substrate (bottom part) contain switch electrodes with contact pads. For the assembly the switch substrate is flipped over and placed onto the spacer on the network substrate. Now the electrode contact pads of the switch substrate cannot be accessed from the top anymore and so far there are no vertical electrical interconnection vias allowing to link the electrodes on the switch substrate to contact pads on the network substrate. The chosen contacting method is illustrated in figure 37: the device is assembled on chip-level with an overlap between the rims of the two substrates and the contact pads are accessed from the top and from the bottom using probe needles. For the early prototypes, this method was sufficient to evaluate the feasibility of the crossbar switches, but future devices should contain vertical electrical interconnections.
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Figure 38. Picture showing a MEMS crossbar switch after the assembly. A weight was necessary to force down the top part, counteracting the spring forces of the membranes, as illustrated in the left-hand inset. Then, the top part with the switches was aligned to the bottom part and finally the two substrates were fixated with epoxy droplets in the corners.

The moveable parts of the switches are released prior to integration: the membranes are fabricated by plasma enhanced chemical vapor deposition (PECVD) of silicon nitride on a polymer sacrificial layer. Assisted by etch holes in the membrane, the polymer was removed in a plasma ashing step. As a consequence, the thin membranes are not mechanically supported during the integration of the switch substrate, potentially damaging the membranes. However, the manual assembly has shown that the membranes of the switches are surprisingly mechanically robust. As an example: during the manual assembly, the top part with 400 silicon nitride membranes with a thickness of 1 μm was placed on the bottom part. Because of large stress gradients in the membranes the deflection of the free ends were much larger than the thickness of the spacer ring and the top part had to be forced down onto the spacer ring using a weight as shown in figure 38. In this state, the switches were manually aligned (alignment accuracy ±5 μm), with considerable friction between the tips of the strained membranes and the surface of the bottom part. Despite the friction and the resulting strains and stresses, in most cases all the membranes survived the procedure.

The stress gradients in the membranes are high, resulting in high actuation voltages especially for the 20×20 array (≈95 V) with shorter membranes and smaller electrode area. Therefore the PECVD process should be optimized to allow for more control over the stress gradients in the deposited films. Furthermore, when depositing the metal film for the membrane electrode additional stresses are induced between the metal and the membrane. Also, the devices got very hot during the removal of the sacrificial layer underneath the membranes in an oxygen plasma. The combination of heat and plasma influences the stresses in the silicon nitride membranes [170,171,172], which issues should be further investigated.

Most of the switches failed to provide a good ohmic contact. Assumed reasons are
that the contact force was not high enough and the surfaces of the switch contacts were contaminated since the switch was not assembled in a cleanroom environment. In future devices, the contact force can be increased by lowering the stress-gradient in the membrane and by local stiffening of the membrane to improve the transfer of the electrostatic force between the surrounding electrodes to the switch contacts. To avoid contamination, future devices should be assembled in the cleanroom, ideally on wafer-level and after a short plasma cleaning of the surfaces.

The actuators were very susceptible to stiction, which was most probably caused by electrostatic stiction between the electrodes. In general, electrostatic stiction is an issue for electrostatic actuators where dielectric layers are involved. Charges are injected and trapped in the dielectric layers, thereby causing an electrostatic attraction. In the MEMS crossbar switch, charges can be trapped in the silicon nitride of the membranes and the electrical isolation layers as well as in the large amount of BCB underneath the bottom electrodes. Consequently, in future devices the amount of dielectric materials should be kept at a minimum.

5.5 Outlook

Currently a second generation of MEMS crossbar switches is under development, which features arrays of $20 \times 20$ double-switches on a silicon footprint of only $12 \times 12 \text{ mm}^2$. In the revised fabrication no complicated electroplating of thick metal layers is necessary and the overall stress gradients in the membranes can be controlled using a stress-compensation design. The chip is fully hermetically packaged by metallic wafer-bonding and contains vertical electrical interconnection between the two substrates as well as through-silicon vias through the network substrate to allow for hybrid integration as introduced in section 3. To obtain a more reliable operation of the switches all polymers are removed to reduce the risk of electrostatic stiction caused by trapped charges.
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6 Summaries of the Appended Papers

Paper 1: Out of plane knife gate microvalves for controlling large gas flow
This paper considers design issues for microvalves for large gas flow control. It introduces out-of-plane knife-gate microvalves as a novel design concept and a proportional microvalve concept for pressure control applications. The design of three different actuator-gate configurations and first prototypes are presented. The first valve prototypes feature thermal silicon–aluminum bimorph actuators and the pressure-flow performance per chip area of the demonstrator valve presented is greatly increased using out-of-plane actuation and an out-of-plane orifice. The characterization of the actuators and of the pressure-flow performance is presented.

Paper 2: Wafer-scale manufacturing of bulk shape memory alloy microactuators based on adhesive bonding of Titanium-Nickel sheets to structured silicon wafers
This paper presents a concept for the wafer-scale manufacturing of microactuators based on the adhesive bonding of bulk shape memory alloy (SMA) sheets to silicon microstructures. Wafer-scale integration of a cold-state deformation mechanism is provided by the deposition of stressed films onto the SMA sheet. A concept for heating of the SMA by Joule heating through a resistive heater layer is presented. Critical fabrication issues were investigated, including the cold-state deformation, the bonding scheme and related stresses and the Titanium-Nickel (TiNi) sheet patterning. Novel methods for the transfer stamping of adhesive and for the handling of the thin TiNi sheets were developed, based on the use of standard dicing blue tape. First demonstrator TiNi cantilevers, wafer-level adhesively bonded on a microstructured silicon substrate, were successfully fabricated and evaluated. Intrinsically stressed silicon dioxide and silicon nitride were deposited to deform the cantilevers in the cold state and the resulting tip deflections were evaluated.

Paper 3: Design and wafer-level fabrication of SMA wire microactuators on silicon
This paper reports on the fabrication of micro actuators through wafer-level integration of pre-strained SMA wires to silicon structures. In contrast to previous work, the wires are strained under pure tension, and the cold state reset is provided by single crystalline silicon cantilevers. The fabrication is based on standard MEMS manufacturing technologies and enables an actuation scheme featuring high work densities. A mathematical model is discussed, which
Wafer-level heterogeneous integration of MEMS actuators provides a useful approximation for practical designs and allows analyzing the actuators performance. Prototypes have been tested and the influence of constructive variations on the actuator behavior is theoretically and experimentally evaluated. The test results are in close agreement with the calculated values, and show that the actuators feature displacements among the highest reported.

**Paper 4: Localized removal of the Au-Si eutectic bonding layer for the selective release of microstructures**

This paper presents and investigates a novel technique for the footprint and thickness-independent selective release of Au–Si eutectically bonded microstructures through the localized removal of their eutectic bond interface. The technique is based on the electrochemical removal of the gold in the eutectic layer and the selectivity is provided by patterning the eutectic layer and by proper electrical connection or isolation of the areas to be etched or removed, respectively. The gold removal results in a porous silicon layer, acting similar to standard etch holes in a subsequent sacrificial release etching. The paper presents the principle and the design requirements of the technique. First test devices were fabricated and the method successfully demonstrated. Furthermore, the paper investigates the release mechanism and the effects of different gold layouts on both the eutectic bonding and the release procedure.

**Paper 5: Single-chip MEMS 5×5 and 20×20 double-pole single-throw switch arrays for automating telecommunication networks**

This paper reports on microelectromechanical (MEMS) switch arrays with 5×5 and 20×20 double-pole single-throw (DPST) switches embedded and packaged on a single chip, which are intended for automating main distribution frames in copper-wire telecommunication networks. Whenever a customer requests a change in his telecommunication services, the copper-wire network has to be reconfigured which is currently done manually by a costly physical re-routing of the connections in the main distribution frames. To reduce the costs, new methods for automating the network reconfiguration are sought after by the network providers. The presented devices comprise 5×5 or 20×20 double switches, which allow us to interconnect any of the 5 or 20 input lines to any of the 5 or 20 output lines. The switches are based on an electrostatic S-shaped film actuator with the switch contact on a flexible membrane, moving between a top and a bottom electrode. The devices are fabricated in two parts which are designed to be assembled using selective adhesive wafer bonding, resulting in a wafer-scale package of the switch array. The on-chip routing network consists of thick metal lines for low resistance and is embedded in benocyclobutene (BCB) polymer layers.

**Paper 6: Row/Column addressing scheme for large electrostatic actuator MEMS switch arrays and optimization of the operational reliability by statistical analysis**

This paper investigates the design and optimization of a row/column addressing scheme to individually pull in or pull out single electrostatic actuators in an \( N^2 \) array, utilizing the electromechanical hysteresis behavior of electrostatic
actuators and efficiently reducing the number of necessary control lines from $N^2$ complexity to $2N$. This paper illustrates the principle of the row/column addressing scheme. Furthermore, it investigates the optimal addressing voltages to individually pull in or pull out single actuators with maximum operational reliability, determined by the statistical parameters of the pull-in and pull-out characteristics of the actuators. The investigated addressing scheme is implemented for the individual addressing of cross-connect switches in a microelectromechanical systems $20 \times 20$ switch array, which is utilized for the automated any-to-any interconnection of 20 input signal line pairs to 20 output signal line pairs. The investigated addressing scheme and the presented calculations were successfully tested on electrostatic actuators in a fabricated $20 \times 20$ array. The actuation voltages and their statistical variations were characterized for different subarray cluster sizes. Finally, the addressing voltages were calculated and verified by tests.
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7 Conclusions

This thesis presents methods for the wafer-level integration of TiNi and S-shaped electrostatic actuator switches to functionalize MEMS devices. The integration methods are based on concepts of heterogeneous integration. Using the developed integration methods, TiNi actuators are integrated with a new type of microvalves, drastically improving their performance. The microvalves are knife gate microvalves and introduced in this thesis. The S-shaped actuator switches are arranged in arrays and integrated with a signal line routing network, forming a MEMS crossbar switch.

In more detail, the developed TiNi integration methods:

– allow to wafer-level integrate bulk TiNi sheets and wires, together with mechanisms for the cold-state reset, avoiding the complicated monolithic integration and the pic-and-place hybrid integration. First actuator test structures were fabricated and evaluated, showing promising results. Heating with integrated heaters is shown for the sheet based actuators;

– provide techniques for handling the TiNi prior to integration. The TiNi sheets are patterned prior to integration to avoid exposure of the target structures to the very aggressive TiNi etchant. The thin TiNi wires are oriented and strained before they are transferred to the target substrate.

– are discussed, including initial tests of alternative approaches.

The developed knife gate microvalves:

– feature a gate moving perpendicular to the flow, reducing the demands on the actuator. The gate moves out-of-plane to control an in-plane gas flow, minimizing the required silicon footprint area and the related costs;

– display excellent pneumatic performance in relation to the consumed silicon footprint area, however, the first test structures required external actuation since the integrated actuators failed;
For combining knife gate microvalves and TiNi actuators, the thesis shows:

– first designs for integrating TiNi sheets and wires with silicon knife gate microvalves, including a method for the localized release of eutectically bonded, thick silicon microstructures to allow their manipulation by the integrated actuators;

– first experiments displaying outstanding pneumatic performance of the valve in relation to the consumed silicon footprint area.

– a discussion and outlook on future work, including a scheme for packaging of the valve.

The MEMS crossbar switch:

– is intended as core switch unit for automating parts of copper-wire telecommunication networks;

– consists of two parts, with one part containing signal input and output lines crossing each other and the other part containing an array of S-shaped actuator switches. After integrating the switch array on the signal lines using adhesive bonding, the switches allow to interconnect the input to the output lines in any combination desired;

– features integrated encapsulation of the switch arrays;

– contains up to $20 \times 20 = 400$ crosspoint switches on an area of $12 \times 16 \text{ mm}^2$. First prototypes were fabricated and evaluated, proofing the feasibility of the concept;

– requires a method for the individual addressing of selected switches. The thesis presents the concept of row/column addressing, drastically reducing the necessary amount of control wires. The reliability of the addressing is maximized by determining the addressing voltages based on the statistical deviation of the actuation voltages across the array.

– is discussed and an outlook is given, based on current developments of a second generation of MEMS crossbar switches.
Acknowledgments

This work was financially supported by Pondus Instruments AB, by Network Automation mxc AB, by Vinnova (the Swedish Agency for Innovation Systems) through the Summit and the Forska&Väx framework, and by the European Commission through the sixth framework programme funded project Q2M.

As all big projects, the project 'PhD' requires the support of so many other people. Figure 39 expresses what I want to say to you:

First of all, my principal supervisor Professor Göran Stemme for allowing me to start the PhD-adventure in his group, yet always being there to limit the adventure part and giving advice when needed. I truly appreciate that your door was always open to discuss major and minor issues, not only during my ups but mainly during my downs.

My supervisors Wouter van der Wijngaart and Joachim Oberhammer for showing me how the academic world and research works. Special thanks to Wouter for not only being my supervisor, but for the feeling of being welcome in the early days and for being a great friend who helped during those downs.

Frank Niklaus for sorting out the worst in the integration section of this thesis and for always having an open-minded approach to things.

Björn Samel for being a true friend, the great atmosphere in our 'German office' and for giving me the assurance that I’m not the only German fighting against Swedish windmills. Thank you for our friendship!

Another good friend, Niklas Sandström, for showing me the Swedish way of life and of course for all the wonderful company when sharing hotel rooms (not like it sounds) and when enjoying our 'matlåda' together.

Henrik Gradin for being a great room-mate and for the very fruitful work we did together. You’re a smart one and I hope some of the smartness diffused to my side of the office.

Kjell Norén for his shared interest in everything with motors and wheels and for demonstrating what a real engineer is. Thanks for all your brilliant ideas and prototypes which helped so much.

Petra Palmquist for proofreading this thesis without despairing over it.

Special thanks also to my former professors, Peter Pokrowsky and Patrick Klär for the support in the early days of my PhD adventure and for the remaining good contact.

Of course a big 'thank you’ also to all the other colleagues I had the pleasure
to work with in my projects. Sjoerd Haasl for the guidance and great spirit in my early PhD days. Prof. Manfred Kohl, Dr. Thomas Grund and Johannes Barth from FZK Karlsruhe for our fruitful work in the Q2M project and for the honor of inviting me as speaker to your seminar. Special thanks to Thomas and the ‘Deutsche Eiche’ Johannes for the nice time beside those meetings and conferences. Dr. Jan Peirs and Donato Claudi from KUL Leuven for the fruitful work in the Q2M project. Donato - I am glad I met you and I hope we will remain friends. Thorbjörn Ebefors, Göran Edström, Göran Lindvall and Jochen Walter from Silex Microsystems for the close collaboration when developing the MEMS crossbar switch 2.0. Cecilia Aronsson for introducing me to the cleanroom routines and to the Swedish language. Sveinbjörg Ingvarsdottr, Jutta Müntjes and Gaspard Pardon for enduring my guidance during your master thesis and placements.

Thanks to Erika Appel and Hanne Eklund for paving the way through KTH-bureaucracy and enabling things.

All the work was performed in a great atmosphere, for which I want to thank my colleagues from KTH-MST: Göran, Frank, Joachim, Wouter, Hans, Erika, Kjell, Niclas, Mikael, Mikael, Mikael (yes, it’s a common Swedish name), Niklas, Fredrik and Carl Fredrik, Adit, Farizah, Andreas, Martin, Kristinn, Gaspard, Umer, Zargham, Hitthesh, Henrik, Nutapong, Staffan.

Besides work, there is also a personal life. I would like to thank all my friends who helped me during this time by either distracting me from work or cheering me up in hard times. You know who you are - Thank you!

My family - always there for me. Thank you to my parents Regina and Kurt for demonstrating the values of honesty and reliability and how to be almost perfect parents. I have not forgotten that you should be among the research funders in the first paragraph of the acknowledgments. Thank you to my brother Andreas for being my big brother. Thank you to my niece Charlotte for the smile when I think of you. Last, but not least - the biggest thank you to my Love Juliane for loving me the way I am.

Das war meine Thesis - das Spiel geht weiter ...
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Wafer-level heterogeneous integration of MEMS actuators


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