Doctoral Thesis

Systems and methods for microfluidic mediated self-assembly of hybrid MEMS devices

Author(s): Goldowsky, Jonas

Publication Date: 2013

Permanent Link: https://doi.org/10.3929/ethz-a-010050190

Rights / License: In Copyright - Non-Commercial Use Permitted

This page was generated automatically upon download from the ETH Zurich Research Collection. For more information please consult the Terms of use.
Systems and methods for microfluidic mediated self-assembly of hybrid MEMS devices

A dissertation submitted to
ETH ZURICH

for the degree of
Doctor of Sciences

presented by
JONAS GOLDSWOKY
Dipl.-Ing., RWTH Aachen University, Germany
born 16 March 1984
citizen of Germany

accepted on the recommendation of
Prof. Dr. B. J. Nelson, examiner
Dr. H. F. Knapp, co-examiner

2013
Preface

Parts of this work have been published or are submitted for publication in the following manuscripts:

  With little reformulations this publication is entirely reprinted in section 4.3.

  For clarity this publication is split and reprinted in section 2.2, section 3.1 and section 5.2.

  This publication is reprinted with some additional information and reformulations in section 5.3.
Acknowledgments

First of all I would like to thank Dr. Helmut F. Knapp, head of the section microfluidics and liquid handling of CSEM for offering me the opportunity to conduct my PhD work in his group and with the great team of CSEM. The freedom of working independently and therefore highly creative gave me the opportunity to create new ideas and concepts of which some have become essential for the thesis presented here. Still, his guidance kept me focused on the most relevant topics of research giving me the opportunity to finish my thesis within desirable time.

Secondly, my thanks goes to Professor Bradley Nelson of the Institute of Robotics and Intelligent Systems (IRIS), who enabled my PhD candidacy by agreeing to be my supervisor at ETH Zurich. I also thank him for always being available for discussions on publications, the dissertation or administrative questions.

I also want to express my gratefulness to the whole team of CSEM Central Switzerland for teaching me so many details on fluidics, simulations, electronics, prototyping and other fields, that it is impossible to announce each and every person in this acknowledgments. However, I would like to emphasize the input of Julian Kaufmann, who has been always available for discussions on simulations and physical models, Stefan Berchthold, who taught me a lot of the laboratory work which has been conducted within this thesis, Dr. Janko Auerswald, who has been more than helpful and encouraging in discussions of research and private topics, and finally Dr. Siegfried Graf, who has been helpful in discussions on research, guided me through the administrative procedures of a PhD candidacy and highlighted significant milestones within this procedure for me.

Additionally I would like to thank Dr. Massimo Mastrangeli for many fruitful discussions, great help on the testing and improvement of the introduced microfluidic chamber for agitation of MEMS for self-assembly and the procurement of parylene coating possibilities within EPFL laboratories. Further I would like to thank him for assisting me in the procedure of publication of my first paper. With his assistance I could improve my writing a lot and I thank him for his patience.
Further I would like to thank Dr. Loïc Jacot-Descombes and Dr. Maurizio Gullo at the Microsystems Laboratory at EPF Lausanne of Prof. Jürgen Brugger for fabricating the MEMS components that have been used for evaluation of the systems in this thesis and for initiating the SelfSys project.

During the period of my PhD thesis at CSEM SA I had the opportunity to supervise Ching-Yu Yuan as a master student for his project and I would like to emphasis that his great work on the sorting of MEMS building blocks has become the basis for the results of the sorting device presented in this PhD thesis.

However, my greatest thanks goes to my wife who spared so much of our time and took over many family responsibilities which I have been failing to fulfill. Especially in the final phase of the work conducted for this thesis, her support was irreplaceable.
Abstract

Research on hybrid MEMS is gaining momentum. Often incompatible fabrication steps of functional blocks of MEMS devices give rise to the need for heterogeneous systems, separating incompatible processes. This separation, however, leads to the need of an assembly step in the line of production. Assembly of hybrid MEMS remains costly and time intensive, as mostly done in serial robotic or manual processes. A vital factor for the success of hybrid designed MEMS are therefore efficient assembly strategies reducing the assembly effort to a minimum.

A promising approach is the parallel stochastic assembly (self-assembly) of hybrid MEMS building blocks into the complete systems envisioned. By designing the building blocks to have a minimum of free energy in their assembly state and supplying sufficient random energy to enable the building blocks overcome potential energy barriers, a massively parallel assembly can be achieved. This self-assembly procedure is particularly interesting when performed in bulk liquids, as for instance surface interactions are better controlled in liquid than in gas phase, the bulk liquid can be used for contactless handling of the entities and hydrophobic interactions are available as a driving potential of self-assembly.

By means of a generic MEMS design three major fluidic systems are determined that are needed to guide the self-assembly of the building blocks from their release to their assembled state. Namely these units are preparation, assembly assistance (within a reaction chamber) and sorting, which are sub-units of a complete microfluidic system, assisting self-assembly (in the following called µFluiSA).

For preparation of the entities for fluidic mediated self-assembly, a transfer from storing liquid (storage is preferably done in apolar liquids to suppress uncontrolled clustering of the components) into a functional liquid is required. Based on gravitational and hydrodynamic effects a simple preparation unit is introduced, which enables not only the transfer of MEMS building blocks from a carrier into a receiving liquid, but offers additionally the possibility to determine a cut-off size of the particles to be transfered. By that fragments of SU-8 can be filtered out of the system, increasing the yield of the subsequent self-assembly
process.

To introduce a sufficient amount of random energy into the system, reduce sticking of
the building blocks on the ground of the reaction chamber and aggregate or disperse the
particles during their assembly procedure, an acousto-fluidic assembly chamber has been
designed, relying on the strong secondary streaming phenomena around oscillating bub-
bles. Two main driving modes of the reaction chamber could be identified, of which one
is aggregating the building blocks in the middle of the chamber, enhancing their assembly
and the other is dispersing the components, braking their connections close to the oscil-
lating bubble surfaces. Assembly yields of approximately 50% could be achieved in spite
of the minimalist component design and the absence of additional surface functionaliza-
tions which could enhance yields by increasing the contrast of the free energies of different
assembly configurations.

As an enabling technology, a detailed investigation of thin membrane PDMS valves, re-
garding their permeability to gases, sealing capabilities and lifetime is conducted within
this work. It is found that for longer closing times, gas bubbles are created inside the fluidic of such valves, which cause problems during the operation of the assembly chamber.

By adding a barrier between pressurized air, used for the actuation of the PDMS valves,
and the valve membrane, the intrusion of gas could be successfully suppressed.

Due to the stochastic nature of self-assembly processes a sorting unit is required for a
complete processing of hybrid MEMS. Here a system is introduced, facilitating dielec-

trophoretic, gravitational and hydrodynamic effects for the separation of the entities in
question. By correcting inaccuracies of the conventional equations for the estimation of
dielectrophoretic forces – originating from the highly non-uniform fields and large particle
sizes of interest – by two dimensionless factors, good predictions of the separation behavior
could be achieved. Separation yields of 90% could be achieved which can be improved by
a systematic redesign of the unit.

Finally, as an outlook, the first concept of the µFluiSA is extended and discussed in detail,
taking the results of the individual sub-units into account. By that a system is proposed,
enabling the guidance of MEMS building blocks along their assembly procedure in an automated manner.
Zusammenfassung


Ein möglicher Ansatz zur Reduktion des Montageaufwands auf ein Minimum, ist die sogenannte Selbst-Montage der Mikrobauteile zu einem Komplett-System. Hierfür werden die Komponenten so ausgelegt, dass ihr Montagezustand einem Zustand der minimalen freien Energie entspricht. Zusätzlich muss auf geeignetem Wege Energie in das System geführt werden um eventuelle Energiebarrieren zu überwinden und so einen Montageprozess der Einzelkomponenten zu einem Komplettsystem zu ermöglichen. Besonders interessant sind solche Selbst-Montage-Prozesse, wenn sie in Flüssigkeiten ausgeführt werden, da dadurch a) Oberflächenkräfte reduziert werden können, b) die Flüssigkeit zum Transport der Bauteile eingesetzt werden kann und c) hydrophobe Wechselwirkungen zwischen den Bauteilen als treibende Kraft für die Selbst-Montage zur Verfügung stehen.

Durch die Betrachtung generischer Beispielkomponenten werden drei Systemkomponenten definiert, die eine komplett, massiv parallele Selbst-Montage der Bauteile ermöglichen. Hierfür werden ein Aufbereitungs-, ein Montage- und ein Separationsystem entwickelt, aus welchen ein komplettes System zur Montage der betrachteten Bauteile (im Weiteren µFluiSA genannt) zusammengefügt werden kann.

Da die Bauteile bevorzugt in nicht-polaren Flüssigkeiten aufbewahrt werden, um eine spontane und unkontrollierte Aggregation zu unterdrücken, liegt die Hauptaufgabe der Preparations- einheit in dem Transfer der Bauteile von ihrer Lagerungssuspension, zur Flüssigkeit,


Da die Selbst-Montage ein stochastischer Prozess ist und immer von Erfolgsquoten unter 100% ausgegangen werden muss, ist die Komplettierung des Systems mit einer Sortiereinheit unabhängig. Hierfür wurde ein System entwickelt, welches basierend auf hydrodynamischen, dielektrophoretischen und Gravitationseffekten die Separation der exemplarisch gewählten Mikrobauteile ermöglicht. Da stark inhomogene elektrische Felder und relative große Komponenten betrachtet werden, sind die herkömmlichen Formeln zur Bestimmung dielektrophoretischer Kräfte ungenau. Daher wurden hier zwei dimensionslose Faktoren eingeführt, welche die Korrektur der konventionellen Gleichungen für solche Fälle ermöglichen. Bei Anwendung dieser erweiterten Gleichung zeigen experimentelle Versuche gute Übereinstimmung zu den theoretischen Voraussagen. Etwa 90% der Zielkomponenten konnten hier richtig sortiert werden, was durch ein gezieltes Redesign der Einheit weiter
verbessert werden kann.

Weiterhin wird basierend auf den Ergebnissen der µFluiSA Subkomponenten das erste Konzept für ein vollständiges System überarbeitet und es werden Richtlinien für die Umsetzung eines solchen Systems mit den hier eingeführten Methoden aufgeführt.
Contents

Preface iii
Acknowledgments v
Abstract vii
Zusammenfassung ix
Abbreviations xvii
Symbols xix

1 Introduction and motivation 1

2 State of the art 3
  2.1 Micro-electro-mechanical systems (MEMS) 3
  2.2 Micro-assembly 5
  2.3 Fluidic mediated self-assembly 9

3 Application and a first concept of a µFluiSA system 11
  3.1 Application 11
  3.2 A first concept of a µFluiSA system 16

4 Enabling technologies 19
  4.1 Technology Overview 19
A Supplementary figures 103

B Derivation of terminal velocity for particle sedimentation 107

C Details of DEP force factor derivations 119
   C.1 Dipole Matching .......................................................... 119
   C.2 Program for calculation of the dimensionless factors .......... 120

D Custom designed power amplifier 125

List of Tables I

List of Figures V

Bibliography XIX

List of publications XXII
**Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>µFluiSA</td>
<td>Complete microfluidic system for the assistance of self-assembly</td>
</tr>
<tr>
<td>AC</td>
<td>Alternating current</td>
</tr>
<tr>
<td>APTES</td>
<td>(3-Aminopropyl)triethoxysilane</td>
</tr>
<tr>
<td>CA</td>
<td>Contact angle</td>
</tr>
<tr>
<td>CSEM</td>
<td>Swiss center for electronics and microtechnology</td>
</tr>
<tr>
<td>DC</td>
<td>Direct current</td>
</tr>
<tr>
<td>DI</td>
<td>Deionized</td>
</tr>
<tr>
<td>DRIE</td>
<td>Deep reactive ion etching (Bosch process)</td>
</tr>
<tr>
<td>FFF</td>
<td>Field Flow Fractionation</td>
</tr>
<tr>
<td>FSA</td>
<td>Fluidic (mediated) self-assembly</td>
</tr>
<tr>
<td>IPA</td>
<td>Isopropanol, Isopropyl alcohol or 2-Propanol</td>
</tr>
<tr>
<td>MA</td>
<td>Micro-assembly</td>
</tr>
<tr>
<td>MEMS</td>
<td>Micro-electro-mechanical systems</td>
</tr>
<tr>
<td>MESA</td>
<td>Mesoscale self-assembly</td>
</tr>
<tr>
<td>NBR</td>
<td>Nitril Butadiene Rubber</td>
</tr>
<tr>
<td>nDEP</td>
<td>Negative DEP, particles are repelled from high field gradients</td>
</tr>
<tr>
<td>PAT</td>
<td>Process analytical technologies</td>
</tr>
<tr>
<td>PC</td>
<td>Polycarbonate</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
</tr>
<tr>
<td>pDEP</td>
<td>Positive DEP, particles are attracted by high field gradients</td>
</tr>
<tr>
<td>PDMS</td>
<td>Poly(dimethylsiloxane)</td>
</tr>
<tr>
<td>PMMA</td>
<td>Poly(methyl methacrylate)</td>
</tr>
<tr>
<td>RIE</td>
<td>Reactive ion etching</td>
</tr>
<tr>
<td>SA</td>
<td>Self-assembly</td>
</tr>
<tr>
<td>SAM</td>
<td>Self-assembled monolayer</td>
</tr>
<tr>
<td>Silane</td>
<td>Organofunctional alkoxy silane molecules</td>
</tr>
<tr>
<td>SPLITT</td>
<td>Split-flow thin fractionation</td>
</tr>
<tr>
<td>USW</td>
<td>Ultrasonic standing wave</td>
</tr>
</tbody>
</table>
Symbols

**Greek Letters**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>Angle of dielectrophoretic force</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Angle of dielectrophoretic electrode</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>Difference</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>Bubble amplitude factor</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Relative permittivity</td>
</tr>
<tr>
<td>$\epsilon^*$</td>
<td>Complex dielectric constant</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Ratio of specific heats</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Dynamic viscosity</td>
</tr>
<tr>
<td>$\nabla$</td>
<td>Nabla operator</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>Angle of widening channel</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Angular velocity</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>Phase of oscillation</td>
</tr>
<tr>
<td>$\Psi_{Wall}^2$</td>
<td>Far-field streamline around a bubble in close proximity of a wall</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density</td>
</tr>
<tr>
<td>$\rho_m$</td>
<td>Medium density</td>
</tr>
<tr>
<td>$\rho_p$</td>
<td>Particle density</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Electric conductivity</td>
</tr>
<tr>
<td>$\sigma_{int}$</td>
<td>Bulk or internal electric conductivity</td>
</tr>
<tr>
<td>$\vartheta$</td>
<td>Poisson’s ratio</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Shear stress</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Polar coordinate</td>
</tr>
<tr>
<td>$\xi$</td>
<td>Amplitude of bubble oscillation</td>
</tr>
</tbody>
</table>

**Roman Letters**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Area</td>
</tr>
<tr>
<td>$a$</td>
<td>Bubble radius</td>
</tr>
<tr>
<td>Symbol</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td>$A_H$</td>
<td>[J]</td>
</tr>
<tr>
<td>$C_i$</td>
<td>[m]</td>
</tr>
<tr>
<td>$D$</td>
<td>[m]</td>
</tr>
<tr>
<td>$d$</td>
<td>[m]</td>
</tr>
<tr>
<td>$De$</td>
<td></td>
</tr>
<tr>
<td>$d_e$</td>
<td>[m]</td>
</tr>
<tr>
<td>$E$</td>
<td>[N m$^{-2}$]</td>
</tr>
<tr>
<td>$E_{0d}$</td>
<td>[V m$^{-1}$]</td>
</tr>
<tr>
<td>$F$</td>
<td>[N]</td>
</tr>
<tr>
<td>$g$</td>
<td>[m s$^{-2}$]</td>
</tr>
<tr>
<td>$h$</td>
<td>[m]</td>
</tr>
<tr>
<td>$h_0$</td>
<td>[m]</td>
</tr>
<tr>
<td>$h_c$</td>
<td>[m]</td>
</tr>
<tr>
<td>$H_{in}$</td>
<td>[m]</td>
</tr>
<tr>
<td>$h_{lev}$</td>
<td>[m]</td>
</tr>
<tr>
<td>$h_{osp}$</td>
<td>[m]</td>
</tr>
<tr>
<td>$j$</td>
<td></td>
</tr>
<tr>
<td>$K$</td>
<td>[S]</td>
</tr>
<tr>
<td>$k_d$</td>
<td></td>
</tr>
<tr>
<td>$k_{nl}$</td>
<td></td>
</tr>
<tr>
<td>$L$</td>
<td>[m]</td>
</tr>
<tr>
<td>$L_s$</td>
<td>[m]</td>
</tr>
<tr>
<td>$P$</td>
<td>[Barrer]</td>
</tr>
<tr>
<td>$p$</td>
<td>[N m$^{-2}$]</td>
</tr>
<tr>
<td>$p_c$</td>
<td>[N m$^{-2}$]</td>
</tr>
<tr>
<td>$p_{eff}$</td>
<td>[C m]</td>
</tr>
<tr>
<td>$p_l$</td>
<td>[N m$^{-2}$]</td>
</tr>
<tr>
<td>$Q'$</td>
<td>[m$^2$ s$^{-1}$]</td>
</tr>
<tr>
<td>$q$</td>
<td>[m$^3$ s$^{-1}$]</td>
</tr>
<tr>
<td>$q_c$</td>
<td>[C]</td>
</tr>
<tr>
<td>$R$</td>
<td>[m]</td>
</tr>
<tr>
<td>$r$</td>
<td></td>
</tr>
<tr>
<td>$r$</td>
<td>[m]</td>
</tr>
<tr>
<td>$R_0$</td>
<td>[m]</td>
</tr>
<tr>
<td>$Re$</td>
<td></td>
</tr>
<tr>
<td>$R_{ih}$</td>
<td>[Pa s m$^{-3}$]</td>
</tr>
<tr>
<td>Symbol</td>
<td>Unit</td>
</tr>
<tr>
<td>----------</td>
<td>------</td>
</tr>
<tr>
<td>$R_m$</td>
<td>[m]</td>
</tr>
<tr>
<td>$R_v$</td>
<td>[m]</td>
</tr>
<tr>
<td>$t$</td>
<td>[m]</td>
</tr>
<tr>
<td>$t_c$</td>
<td>[m]</td>
</tr>
<tr>
<td>$t_{ch}$</td>
<td>[m]</td>
</tr>
<tr>
<td>$t_m$</td>
<td>[m]</td>
</tr>
<tr>
<td>$u$</td>
<td>[m s$^{-1}$]</td>
</tr>
<tr>
<td>$u_{mean}$</td>
<td>[m s$^{-1}$]</td>
</tr>
<tr>
<td>$v_0$</td>
<td>[m]</td>
</tr>
<tr>
<td>$v_{lev}$</td>
<td>[m s$^{-1}$]</td>
</tr>
<tr>
<td>$W_{hyd,i}$</td>
<td>[J]</td>
</tr>
<tr>
<td>$W_{VdW,i}$</td>
<td>[J]</td>
</tr>
<tr>
<td>$x_b'$</td>
<td>[m]</td>
</tr>
<tr>
<td>$y_s$</td>
<td>[m]</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction and motivation

During the last years a multitude of micro-electro-mechanical systems (MEMS) entered into our every day life. Miniature sensors are integrated in cars, smart-phones, entertainment electronics and laboratory equipment, where they measure acceleration, yaw and pressures. Actuators are integrated in ink-jet printers or are enabling modern optical data transmission.

Many of the currently available MEMS are fabricated monolithically. Monolithically fabricated systems have advantages in terms of size, parasitics and signal quality\[4\]. The increasing functionality of MEMS leads, however, to a demand of a variety of fabrication steps and materials which are not always compatible. These incompatibilities create the need for heterogeneous MEMS design and fabrication.

A key factor for the success of such heterogeneous designed systems are cost-efficient assembly strategies and handling methods. Conventional pick-and-place approaches reach their limits in terms of throughput, when dealing with a large number of individual building blocks, as processes are serial and can only be made semi-parallel by installing multiple lines for assembly (grippers, stations, etc.). Additionally, caused by the small sizes of the building blocks, difficulties arise during conventional pick-and-place processes. In microrobotics, sticking effects, surface charges and surface properties have a significant influence on the available assembly techniques\[5\].

As individual MEMS building blocks are fabricated in parallel, it is essential to retain parallelism during assembly\[6\]. A massively parallel approach is parallel stochastic assembly, also called self-assembly (SA). While conventional methods are adapted from large scales, SA is well known on molecular scales (e.g. the formation of crystals\[7\] or self-assembled monolayers\[8\]) and can be scaled up to mesoscale self-assembly (MESA) \[9\].

MESA can be particularly advantageous when performed in bulk liquids, as the liquid can
be used for mass transport and contact-less handling of the building blocks and surface interactions can be better controlled in liquid than in gas phase. As MESA is a stochastic process which needs the input of random energy\cite{10}, methods are needed to drive the assembly of the building blocks into the state envisioned. Besides the design considerations for the individual building blocks, which are essential to enable self-assembly, advanced handling methods such as mixing, concentration and separation can enhance the yield and decrease the time to assembly significantly.

The work presented here will therefore introduce microfluidic systems and methods assisting the self-assembly of hybrid MEMS. These systems are designed as sub-units of a complete system guiding MEMS building blocks from their release to the fully assembled state and is referred to as µFluiSA in the following. The µFluiSA includes three major components – for preparation, assembly and sorting – all keeping up the parallel characteristics of the manufacturing process of the individual building blocks and thereby enabling high throughput SA of MEMS.
Chapter 2

State of the art

2.1 Micro-electro-mechanical systems (MEMS)

Miniaturized mechanical systems have been intriguing and stimulating for the creativity of mankind already before they actually could be fabricated. While Science-Fiction literature – such as "The Invincible" by Stanislaw Lem – speculated about the danger of autonomous, self-replicating machines in 1960s, scientists developed the first micro-electro-mechanical systems (MEMS) like pressure sensors\cite{11, 12} based on piezoresistive effects of silicon, which has been reported by Smith in 1954\cite{13}. However, due to the lack of suited fabrication methods these systems have been, both in terms of miniaturization and functionality, far off the imaginations of science-fiction literature.

Developments in micro-fabrication created advancing processes for MEMS fabrication, leading to decreasing dimensions and increasing functionality of available systems. Important fabrication technologies like contact aligners by Colvin and Kulick \cite{14}, reactive ion etching (RIE) patented by Ephrath \cite{15} and deep reactive ion etching (DRIE) patented by Laermer and Schilp \cite{16}, have turned out to be driving developments in MEMS technologies. An overview of such developments is given in figure 2.1. Starting from the first pressure sensors from the early 1960s, devices such as microphones, accelerometers, miniature strain gauges, gyro-meters and yaw-rate sensors have been developed, which find their application in cellphones, automotive control, medical, aerospace, automation and biotechnologies\cite{17}. These systems are usually fabricated from crystalline structures, such as silicon and metals, which have to be put under harsh environmental conditions (such as used for RIE and DRIE processes) to create the envisioned structures from bulk material. Especially in BioMEMS applications, these conditions are incompatible to biological entities such as DNA and proteins, as they are highly sensible. Hence, devices
Figure 2.1 Time-line for major events in micro-fabrication and MEMS technology, which are displayed on top and bottom of the time-line, respectively.

have to be designed modular, in order to decouple incompatible processes. This type of design is called hybrid MEMS design. Besides BioMEMS, for which the need for separated fabrication techniques is fundamental, also other devices such as MEMS-waveguides and chromatographs are no longer designed only monolithically.

Developments in MEMS sensing devices can be described as "more of the same", which means that little new devices are developed, but existing devices are improved and used in greater numbers. A reason for this development is that conventional monolithic devices – and their fabrication processes – reach their limits in terms of complexity. Hybrid MEMS technology is gaining momentum but a lack of generic assembly approaches prevents hybrid systems from being competitive.

Hybrid MEMS

With hybrid designed and fabricated MEMS the complexity of fabrication of individual building blocks processes can be decreased drastically as individual process parameters can be used for the fabrication of each entity. Additionally, hybrid approaches allow the reuse of well known subsystems which can be combined to a system of higher complexity and functionality. This is realized for a "first generation hybrid MEMS chromatograph" designed by Lu et al., which is built from seven submodules. Another advantage of hybrid designs is that individual building blocks of hybrid MEMS devices can be tested independently before they are assembled to the final product. By that nonfunctional
building blocks can be identified and replaced before assembly.

Hybrid systems can suffer for instance from performance degradation due to parasitics introduced at the interconnections of the individual building blocks. Another drawback of heterogeneous system designs is an increased overall system size. Due to the individual packaging of the building blocks, additional space is required. However, as dimensions of available monolithic MEMS are continuously decreasing, this fact is getting less important for applications where size is not the most critical design parameter. Besides this, the – maybe most important – challenge of hybrid designed MEMS is the final assembly of the individual building blocks, which is nowadays often done manually or with pick-and-place robots. It is therefore, that the assembly of the miniature building blocks is expensive, especially when dealing with components in micrometer-size. Hence, a key factor for the success of hybrid designed MEMS is the availability of suited, low-cost assembly strategies.

2.2 Micro-assembly

Micro-assembly (MA) is defined as assembly of components with sizes between one millimeter and one micrometer, framed by conventional assembly for larger components and nano-assembly for components with dimensions less than a micrometer. Although conventional assembly systems are well known for macro dimensions, transfer of this knowledge to micro dimensional systems is difficult. Significant differences can be found, e.g. in the needed accuracy of MA systems and in the physical behavior of the handled parts (e.g. the decreased influence of gravity in micro domain). Robots for the MA of MEMS are often custom designed for specific applications, as grippers, feeders and machines have to be adapted e.g. to the shape of the assembly parts or to the needed accuracy. Most processes of robotic MA are serial, i.e. one component can be handled and assembled at a time.

Generally MA can be divided into two major fields, serial and parallel MA, which is illustrated in figure 2.2. Robotic assembly of micro components can be classified as serial MA. Research in serial robotic MA is growing constantly and a manifold of examples for designed machines, feeders and grippers can be found. Generally, processes used for robotic assembly of micro-components are analog to processes from the macroscopic world. The component to be assembled is fed to a positioning system (with a high demand of accuracy), which is gripping (with usually adopted methods), transferring (with high accuracy) and placing the components on its desired assembly position. Even though principles for accurate positioning, gripping and feeding need to be developed for microscopic assembly chains, the process flow can be adapted from macroscopic, well known systems. Serial
Figure 2.2  Classification of micro assembly strategies and concepts, including stochastic parallel assembly also known as *self-assembly*.

Robotic microassembly techniques are well-established; yet, they reach their limits in terms of throughput and accuracy when dealing with a multitude of micrometer-sized components \[27\], as sticking effects make contact handling of microcomponents problematic \[5\], \[28\]. Research on massively parallel microassembly techniques is therefore gaining momentum.

Such parallel approaches to MA can be divided into deterministic and stochastic approaches. Examples for deterministic parallel assembly are wafer-to-wafer bonding \[24\] and arrayed manipulation systems, such as arrayed grippers \[29\], for which the location of the building blocks are known in advance \[26\]. Deterministic parallel approaches can have an outcome of 100% yield, when process parameters are well known. Thousands of components can be assembled at a time. However, the predefined location of components can be of disadvantage when receptors with low density of components features are needed. For example for the integration of GaAs optoelectronics on Si substrates, approximately one hundred devices are needed on a two inch wafer, so that – even tough many more GaAs devices would fit its wafer (about 2 million) – the high pitch on the target wafer has to be matched and material is wasted \[30\].

**Self-assembly**

In stochastic parallel MA, also referred to as *self-assembly*, the locations of the individual building blocks are unknown. SA is the spontaneous coordination of systems of functionalized (e.g., chemically-treated, shape-matching) components into ordered aggregates.
achieved through the minimization of the system’s free energy \[31\].

Molecular and nanoscale SA are ubiquitous in chemistry, biology and material science \[32\]. Hence, microscale self-assembly processes are adapted from the molecular domain, where efficient self-assembly processes can be found e.g. in crystal growth and antibody-antigen recognition \[10\]. The SA of micron- to millimeter-sized building blocks is rapidly establishing altogether as a field of high technological relevance \[9, 33, 34\]. A well known example of self-assembly on molecular scale can be found in self-assembled monolayers (SAMs), which refers to a chemical deposition of a monolayer (e.g. a silane) for a surface modification of the substrate. Even though this technique is frequently used in micro-technology, its process is on molecular scale. However, the basic physical principles of self-assembly are valid for all scales and can be used to engineer hybrid MEMS owning the ability to self-assemble into a desired assembly state.Upscaling the SA approach, from molecular to micro domain, leads to a shift in dominating physical effects, which has to be taken into account when systems are designed for SA. For advantageous component designs, three main criteria are to be fulfilled, allowing the overall system to self-assemble into the envisioned organization. Those criteria are summarized by Cohn et al. \[10\] to:

1. The assembly state of the system has to be a state of minimum potential energy.
2. Energy barriers which have to be overcome, approaching the assembly state, must be small in comparison to the driving potential.
3. The system has to be driven by a sufficient amount of random energy.

For more details on the principle of self-assembly, energy barriers and random energy refer to Cohn et al. \[10\]. During the deposition of SAMs, energy minimization is caused by chemical bond formation of the monolayer molecules with the surface and intermolecular interactions \[35\]. Random energy is brought into the system in form of heat. Increased brownian motion causes the spontaneous reaction at the surface of the target. On atomic and molecular scales, brownian motion is sufficient to drive self-assembly as particles are small and randomly distributed in liquid or gas phase of the system. As long as the chemical solution is not contaminated, there are little energy barriers to overcome as the exposed surfaces are the only place the monolayer molecules can bind to.

In micro domain, Cohn, Kim, and Pisano \[36\] made first experiments ordering hexagons on a slightly concave diaphragm. This curvature of the diaphragm in combination with gravity is the driving potential, for self-assembly. In order to bring random energy into the system, the diaphragm is moved vibrational to overcome sticking of the hexagons on the diaphragm surface (i.e. an energy barrier). These physical principals are applicable for all
self-assembly experiments, regardless the size of the assembled components. An overview of reported assembly strategies is given in table 2.1, showing the method of energy input, SA driving force and dimensional characteristics of the process.

<table>
<thead>
<tr>
<th>Application</th>
<th>Random energy</th>
<th>Driving force</th>
<th>Dimension</th>
<th>Year</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hexagon alignment</td>
<td>Vibration</td>
<td>Gravity, curved diaphragm</td>
<td>2D</td>
<td>1991</td>
<td>Cohn, Kim, and Pisano</td>
</tr>
<tr>
<td>GaAs LED alignment</td>
<td>Fluid motion</td>
<td>Gravity, pinholes</td>
<td>2D</td>
<td>1994</td>
<td>Yeh and Smith</td>
</tr>
<tr>
<td>Dummy part alignment</td>
<td>Vibration</td>
<td>Electrostatic fields</td>
<td>2D</td>
<td>1998</td>
<td>Bohringer et al.</td>
</tr>
<tr>
<td>Dummy parts assembly</td>
<td>Orbital motion</td>
<td>Capillary (liquid)</td>
<td>2D</td>
<td>1999</td>
<td>Bowden et al.</td>
</tr>
<tr>
<td>LED packaging</td>
<td>Pulsating flow</td>
<td>Capillary (solder)</td>
<td>3D</td>
<td>2005</td>
<td>Zheng and Jacobs</td>
</tr>
<tr>
<td>Micropump assembly</td>
<td>Fluidic Flow</td>
<td>Magnetics</td>
<td>2D</td>
<td>2006</td>
<td>Bleil, Marr, and Bechinger</td>
</tr>
</tbody>
</table>

Table 2.1  Principles of MESA from different sources ordered by date of publication. Listed is the method of random energy input into the system, the driving force of SA, the binding force and dimensional characteristic of the assembled structures.

Whereas first MESA experiments in the 1990s demonstrate the feasibility of the principle using dummy building blocks, later publications focus on applications such as LED packaging or micropump assembly. Common sources for random energy are vibration and liquid flows, enabling the self-assembly due to gravity, electrostatic forces, capillary forces or magnetic forces, to name only the mostly used principles. A recent breakthrough in MEMS packaging had a templated target substrate slid through an interface between immiscible fluids to obtain unprecedented yield and throughput for SA of microcomponents [40]. A more detailed overview of MESA principles is given by Mastrangeli et al. [33]. Importantly, working with bulk liquids brings along significant advantages: a) a bulk liquid can be used as carrier for mass transport and contactless handling of microcomponents; b) surface interactions can be better controlled in the liquid than in the gas phase, and sticking issues can be reduced or avoided due to electrostatic screening effects [28]; and c) drag from flow fields can induce the relative motion and mixing of the components [38].
2.3 Fluidic mediated self-assembly

Fluidic (mediated) self-assembly is the self-assembly of components either at a liquid-gas, liquid-liquid interface or in bulk liquid. Placing micro-components on a liquid-gas or liquid-liquid interface reduces the assembly to a 2D problem, as components – when the liquids are chosen accordingly – are floating at the interface of the fluids. This pre-orientation reduces the complexity of the assembly system drastically. As described by Hosokawa, Shimoyama, and Miura [41], surface tension at the fluid interface might drive the self-assembly when the components to be assembled are designed accordingly. A challenge for the 2D interface assembly is the proper component handling in pre and post-assembly steps.

Utilizing 2D characteristics and combining it with the advantages of bulk liquid component handling, Chung et al. [42] introduced the concept of railed fluidic self-assembly of microstructures. In this approach the microcomponents are fabricated from an ultraviolet-curable oligomer solution, by illuminating the solution within the rail system. By this, a fin with an exact fit to the rail is formed and developed structures can be moved along the predefined rails by fluid flow. In this way it is impressively demonstrated that complex structures, such as a miniaturized Eifel-tower or a micro version of a human skeleton, can be assembled. However, fabrication techniques inside the rail system are limited, so that most conventional microfabrication processes cannot be used. Fabricating the components outside the rail system leads to the challenge of introducing the pre-fabricated building blocks into the rail system. Besides these limitations, railed fluidic micro-assembly is not a true self-assembly process, as the system is deterministic, the assembly state does not have to be a minimum state of energy and the process is serial. Railed fluidic microassembly is therefore highly suitable for low and medium lot sizes but will face – similar to conventional robotic approaches – problems when dealing with lot sizes produced in batch fabrication of MEMS technology.

When components are assembled in bulk liquid, the complexity of the assembly is much higher than for 2D assembly approaches as components can move and rotate in three dimensional space. One of the greatest advantages of bulk liquid self-assembly approaches is that components can be easily suspended in a bulk liquid after their fabrication. For instance components that are released by wet-etching processes are stored in a liquid by default and can be kept there for bulk liquid self-assembly. Early experiments were conducted by Yeh and Smith [30] (see also table 2.1) assembling GaAs LEDs in bulk liquid on a target wafer. Further examples are micro-pump assembly [39], the assembly of silicon resistors on a binding site [43] or 3D electrical networks [44].
Recent publications are focusing on fluidic self-assembly processes and little is reported on supplementary handling techniques of MEMS components for preparation and post-processing. However, for cost efficient assembly strategies it is necessary that the advantages of massively parallel batch fabrication of the individual building blocks is kept throughout the complete assembly process. Hence, an asset of MESA in bulk liquids is the availability of liquid handling methods for component preparation and post-assembly processes.

To summarize, assets of FSA compared to conventional, serial approaches are:

- handling of microcomponents in liquid domain reduces surface charges and therefore unwanted electrostatic interactions,
- manipulation of microcomponents by fluid drag avoids high precision pick-and-place operations,
- liquid manipulation is parallel and many components can be handled simultaneously.

Additionally assets compared to deterministic parallel approaches (wafer-to-wafer bonding) are:

- fabrication of building blocks is allowed to have large differences in spacial density, as the components are released before assembly,
- 3D structures can be assembled, as binding sides can be located on any surface of the device, not only on top, as for wafer-to-wafer processes.
Chapter 3

Application and a first concept of a µFluiSA system

3.1 Application

The strengths of fluidic self-assembly of MEMS take effect when large numbers of two component systems with large variation on the density on a wafer are assembled, more than two components should be assembled or the geometrical demands of the assembly make wafer-to-wafer bonding impossible (section 2.3). When a functional liquid should be encapsulated, a working self-assembly process can be more efficient than wafer-to-wafer bonding processes, as the release of the components is done in a pre-assembly process. This release might be problematic for the assembled components.

In the following, an application of fluidic self-assembled MEMS systems and thereafter a first concept of µFluiSA assisting the assembly of these units is introduced. The application is leading the design of the µFluiSA and its subunits. Furthermore the systems and methods are validated with respect to the introduced MEMS design.

A target application of MEMS, which are beneficially assembled in bulk liquid, can be found in process analytical technologies (PAT), where spatial fixed sensors are used to determine process parameters within closed reaction tanks of processes to be controlled. Immersed MEMS sensors within the liquids of the process can be used to sense for instance temperature or PH values in higher spacial resolution, enabling the detection of local extrema. For this, large numbers of miniature sensors have to be produced in a competitive manner. Such sensing devices can be built by encapsulation of a functional (e.g. thermo sensitive) liquid into hollow MEMS structures. The main focus here is the liquid encapsulating self-assembly of hollow cylindrical bodies within a functional liquid (figure 3.1).
Chapter 3. Application and a first concept of a µFluiSA system

The low geometric complexity of such a design simplifies the theoretical evaluation of the physics of the µFluiSA sub units.

The target application is one of the case studies of the SelfSys project of the NanoTera.ch program by which this work was partially founded. Other fields of research in the framework of the SelfSys project are MEMS fabrication technologies, physical investigations on the binding interactions of hydrophobic entities in water, surface fictionalization and research on material properties.

Miniaturized cylinders for temperature sensing in PAT require small sensor outlines to suppress sedimentation by given streaming within the process tanks, keeping the sensors well distributed inside the process liquid. As the gravitational force on the sensors is proportional to its mass and therefore volume, it is essential to keep the sensor as small as possible. Yet it has to be guaranteed that the cavity of the cylinder is filled during SA. Furthermore sufficient binding forces are required, which scale with binding area. Hence, down-sizing of the sensors is limited. A good compromise for swimming sensors with a cavity filled by a functional liquid can therefore be seen in sub-millimeter sized components. Here effects of gravity are small, yet the cavity can be filled by the liquid, and fabrication methods are reasonably complex. As shown in figure 3.1 a cylindrical

Figure 3.1 A micro-assembled design composed of two hollow cylinders, which encapsulate the liquid they are immersed in during the self-assembly process.

setup with a diameter and height of 100 µm is used. In the cavity within the cylinder the functional liquid can be encapsulated for later sensing applications. A standard material for the fabrication of MEMS is the photoresist SU-8, for which process parameters are well known. The natural water contact angle (CA) of SU-8 lies between 74° and 90°.
SU-8 is therefore of hydrophobic character\textsuperscript{48}, so that no additional surface modification is needed to enable hydrophobic interactions as a driving force for self-assembly processes. Hence, the micro-assembled design used in this work is fabricated from SU-8 photoresist.

To demonstrate the functionality of the μFluiSA components, a simplified cylinder design without cavity is utilized. Reasons for this are ease of fabrication and stronger interaction forces of such dummy components, caused by larger contact areas. The cylinders are fabricated from SU-8 spun over a flat substrate and patterned by a single-step photolithographical process. No surface chemical treatment is applied afterwards. The MEMS components used in the work presented here are fabricated by EPFL LMIS1 group by fabrication strategies developed by Jacot-Descombes et al. \textsuperscript{45}.

To develop a basic model of the SA process, three main geometrical configurations of microcylinders appearing during the experiments are considered: facing (\(C_1\)), parallel (\(C_2\)) and orthogonal (\(C_3\)), as shown in figure \ref{fig:configurations}. These configurations correspond to area-, line- and point-contact conditions. Other undesired though possible configurations, such as skew configurations, are neglected as they are intermediate levels with free energies between those main configurations (as shown in the following).

The binding interaction of hydrophobic particles in aqueous solutions are caused by hydrophobic and van der Waals interactions, whereupon hydrophobic interaction energies exceed van der Waals interactions by an order of magnitude \textsuperscript{49}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{configurations.png}
\caption{Facing (\(C_1\)), parallel (\(C_2\)) and orthogonal (\(C_3\)) configurations of cylinders (a) as schematic drawing, (b) in experimental results and (c) as overlaid image enhancing the visibility of the configurations in the experimental representation. Cylinders that have a configuration \(C_1\) are framed with a solid line and such having configuration \(C_2\) are marked with a dashed line.}
\end{figure}
Hydrophobic effect

In spite of being investigated since 1937, the physics underlying hydrophobic interactions are still being discussed.

For short range effects (particle distances < 100 Å) a commonly accepted explanation can be found by a thermodynamic consideration of the system. Apolar entities immersed in water cause the polar water molecules to form a net-like structure around the contaminants. The formation of net-like structures around contaminants is energetically unfavorable as the entropy of the system is decreased (see figure 3.3 top). This leads to the fact, that clusters of hydrophobic contaminants are energetically more favorable than single distributed entities (see figure 3.3 bottom). Hence, such systems, i.e. oil-water emulsions, are evolving towards –macroscopically– higher ordered states, by increasing their entropy on molecular dimensions.

![Figure 3.3](image-url)  

**Figure 3.3** Schematic drawing explaining the hydrophobic effect. The polar water molecules form a net-like structure around the apolar bodies. Two bodies in contact lead to fewer water molecules that are forced into this net-like structure. Hence, the overall entropy is increased during the assembly of two components.

Long range effects, that have been reported for distances up to 3000 Å, are not fully understood\(^50\). Especially nano-bubbles and surface charges of the particles are discussed to cause such long range effects\(^50\). Recent findings on the hydrophobic interactions for in liquid self-assembly of micron-sized functional building blocks are described by Gullo et al. \(^46\).

Given the yet unresolved complexity of the physics of the hydrophobic effect, the forces for
the configurations \((C_1,C_2\text{ and } C_3)\) caused by the hydrophobic interaction can be hardly estimated. However, it is generally accepted that the forces caused by hydrophobic interaction scale with contact area\(^{51, 52}\). Hence it can be stated, that for the hydrophobic part of the free energy the relation \(W_{\text{hyd},1} < W_{\text{hyd},2} < W_{\text{hyd},3}\) holds, as the contact area for \(C_1\) (surface) is bigger than for \(C_2\) (line) than for \(C_3\) (point).

### Van der Waals interaction

The fraction of the binding interaction caused by van der Waals interactions can be estimated by the non-retarded van der Waals interaction free energies \(W_i\) between two surfaces, according to Isrealachvili \(^{53}\). The equations can be simplified with respect to the configurations \(C_i\) for \(i = 1, 2, 3\) assuming equal radii for all cylinders \((R_1 = R_2 = R)\):

\[
W_{VdW,1} = -\frac{A_H R^2}{12D^2} \quad (3.1)
\]

\[
W_{VdW,2} = -\frac{A_H L}{12\sqrt{2}D^2} \sqrt{\frac{R}{2}} \quad (3.2)
\]

\[
W_{VdW,3} = -\frac{A_H R}{6D} \quad (3.3)
\]

where \(A_H\) is the Hamaker constant defining the interaction between two components suspended in an aqueous liquid, \(D\) the distance between the two approaching surfaces and \(L\) the length of the cylinders (see also figure \(3.2a\)). All other possible geometrical configurations, such as skew configurations, have energy levels between those of \(W_{VdW,3}\) and \(W_{VdW,1}\). The previous equations obey the relationship:

\[
-\frac{A_H R^2}{12D^2} < -\frac{A_H L\sqrt{R}}{24D^{\frac{3}{2}}} < -\frac{A_H R}{6D} \quad (3.4)
\]

that is, \(W_{VdW,1} < W_{VdW,2} < W_{VdW,3}\). As expected, out of all considered configurations the assembly configuration \(C_1\) has the lowest free energy, while single components immersed in water have the highest. equation \((3.4)\) shows that van der Waals interactions are scaling with contact area. This interaction is additive and does not oppose the hydrophobic interaction. To summarize: hydrophobic and van der Waals interactions scale with contact area, so that the \(C_1\) \((assembly)\) configuration has lowest free energy by having the largest contact area between two components.
3.2 A first concept of a µFluiSA system

Wet-etch processes and ultrasonic agitation\[43\] are two of the default release mechanisms used to remove MEMS from their support structure they have been fabricated on. Utilizing these processes, building blocks are by default immersed in a liquid solution (section \[2.3\]), which offers the possibility of keeping the MEMS building blocks inside liquid solutions throughout the complete assembly process. The goal of this thesis is to provide liquid handling modules fitting the demands of self-assembly processes. These modules should guide MEMS building blocks from their release solution all the way to their final assembled state. Meaning the parallel nature of assembly processes has to be maintained throughout all subunits of the system.

A first concept of a µFluiSA is given in figure 3.4. The introduced system is composed of three main units enabling preparation, controlled assembly and sorting of the MEMS building blocks in a parallel manner. Starting from a tank storing the MEMS building blocks after their release, a pump is generating fluid flow enabling transportation of the building blocks by drag forces. These drag forces carry the individual building blocks within their supply liquid into the preparation unit, where they are transferred into a functional liquid, in which assembly should and can take place. This is targeted to be a temperature sensitive liquid for the application introduced here. Once transfer is done, the building blocks are leaving the preparation unit within the functional liquid in which they are transferred into a reaction chamber, that assists the self-assembly of the MEMS components. Assistance is given by agitation of liquid and building blocks, enabling the evolution of multiple individual building blocks into envisioned systems (here configuration $C_1$). However, as described earlier, the self-assembly process is a stochastic process which is likely to have yields far below 100%. It is likely that components will remain unassembled or clusters of components might be created. Due to this, a sorting unit is needed, post-processing the assembled, non-assembled and over assembled components present after assembly.

Those challenges – namely mixing, sorting and particle transfer from a carrier to a receiving liquid – are reoccurring problems in microfluidic and liquid handling applications and are therefore not only interesting in the context of this work but also in fields such as microbiology (e.g. cell-washing applications\[54\]), biomedicine (e.g. microfluidic liquid solution mixing on DNA biochips\[55\]) and for instance blood cell separation in Point-Of-Care diagnostics\[56\].
3.2. A first concept of a µFluiSA system

Figure 3.4 System concept with separated supply fluid cycle (yellow) and functional fluid cycle (blue). The system includes a preparation unit, a reaction chamber and a sorting unit for the assistance of self-assembly.
Chapter 3. Application and a first concept of a μFluSA system
Chapter 4

Enabling technologies

For implementation of the introduced system several technologies are used and developed to enable the production and/or increase functionality of the sub-units of the µFluiSA system. As reoccurring requirements for the design, fabrication and application of the final units, those technologies are introduced here and referred to in the following. First a summary of well known and yet for the implementation of the µFluiSA system outstanding technologies are described. Thereafter modified technologies, customized and improved to meet the challenges of the implementation of the specific µFluiSA components are introduced.

4.1 Technology Overview

4.1.1 Fabrication Technologies

Micro-milling

For fabrication of all units described in the following, micro-milling is used in one or more production step, either directly for the production of parts, or indirectly for the production of molds or holders. Especially for prototyping, micro-milling is a fast, inexpensive and versatile tool, enabling multiple iterations of system fabrication, testing and redesign within a day. For milling tasks preformed in this thesis a StepFour from Laumat GmbH, Switzerland is used. Tool sizes down to 50 µm diameter and a precision of 20 µm allow the production of a large variety of microfluidic setups.
Laser structuring

If higher precision is required or applicable micro-milling tool sizes exceed feature sizes of the components to be fabricated, laser structuring is a complementary approach of fabrication. With spot diameters and scanner precision of a few micrometer, much smaller features can be fabricated. Additionally, a wider range of materials can be machined, such as glass, silicon, ceramics and rubber. Especially glass and rubber are often used in microfluidic setups and are almost impossible to machine with conventional methods. The price of high precision and material compatibility is paid with decreased ablation rates and hence longer processing times. CSEM provides two UV laser machines supporting the prototyping of microfluidic systems, a nano second (TruMark) and a pico second (TruMicro 5000) laser, Trumpf AG. Both lasers have been used for the production of components which are essential for the functionality of the µFluiSA.

PDMS molding

Poly(dimethylsiloxane) (PDMS) is widely used for the production of microfluidic setups, as PDMS has a number of advantageous properties. Features on micron scale can be reproduced by replica molding, it is optically transparent, it cures at low temperatures, it is non-toxic, it has high flexibility, it seals reversible or irreversible to many surfaces, its surface chemistry can be controlled with well-developed techniques and it is elastomeric\[57\]. To create PDMS layers, including microfluidic channels and features, molds are produced from photoresist or structured silicon, usually in cleanroom procedures with mask aligners or etching strategies. An interesting, less laborious method was introduced by Duffy et al. \[58\]. They propose a method printing a design onto a transparency with the help of a high resolution printer and use this transparency for photolithography of a photoresist.

Here we micro-mill molds of desired PDMS gaskets into Poly(methyl methacrylate) (PMMA), which is comparably fast and precise as the introduced printing method. Drawback of micro-milled molds is an increase in surface roughness of the machined surfaces resulting in decreased sealing capabilities of PDMS gaskets. This can be compensated by a double replica molding process as discussed in section 4.2.

For production of the final PDMS gasket, the created mold is closed with the help of additional PMMA support structures, screws and clamps (see also figure 4.1). PDMS (Dow Corning, Sylgard 184) is mixed with a weight ratio 10:1 of base material to curing agent. Subsequently, the mixture is kept in vacuum (200 mbar) for degassing for one hour, to avoid the formation of bubbles within the PDMS layer during the casting process. Finally the PDMS is casted, manually with the help of a syringe, into the mold. Then the
4.1. Technology Overview

Figure 4.1  Mold for PDMS casting, closed by screws on its sides and additionally pressed together with a screw clamp.

PDMS is cured at 65° for 6 hours.

Self-Assembled Monolayer

For many applications surface properties of microfluidic systems have to be controlled in terms of hydrophobicity, biological conformance or bonding capabilities. For this purpose self-assembled monolayers can be applied to define the surface properties needed for such specialized applications. Self-assembled monolayers can render targeted surfaces hydrophilic or hydrophobic\cite{59}, can enhance\cite{60} or suppress bonding\cite{61}. When organofunctional alkoxysilane molecules (silanes) are used as self-assembled monolayers the self-assembly process is also called silanization.

For vapor phase deposition, sample and silane are placed inside a vacuum bell jar and pressure is reduced to 100 mbar, causing the silane to evaporate. While keeping the pressure low for 2 hours, the silane (gas phase) is forming a self-assembled monolayer on all exposed surfaces of the sample, accessing even small cavities. Caution is demanded as silanes are usually highly reactive and such vapors are difficult to handle.

For liquid phase deposition the samples are inserted into a mixture of liquid silane and solvent. Surface tensions of the solvents (here aqueous solutions) are causing an increase of the minimal cavity size that can be accessed by liquid phase depositions. However, liquid solutions are easier to handle than transparent, vapors, so that liquid deposition in general is safer than vapor phase deposition.
Bonding

Due to ease of manufacturing, most microfluidic systems are composed of two or more layers. At least one layer implementing the fluidic channels, a second layer sealing the chip against leakage. Essential for the functionality of microfluidic chips is therefore an adequate bonding between the different layers. Commonly used bonding techniques are adhesive tapes, hot-bonding, plasma activated bonding and silane activated bonding.

**Plasma activated bonding** is available for PDMS, glass, silicon, silicon oxide and oxidized polystyrene material combinations\cite{58} and is used for many microfluidic chips\cite{62}. It is widely believed that, exposed to a reactive plasma, methyl groups (Si–CH\(_3\)) located at the PDMS surface are substituted by silanol groups (Si–OH) which then form covalent (Si–O–Si) bonds with the second activated layer of the structure\cite{57} e.g. glass\cite{63}. It should be noted that the surface qualities of both materials are crucial for the quality of the bond. Properties of interest are surface roughness and – when bonded to hard materials such as glass – waviness of the materials. If one of those criteria is insufficient, a partly bonded, leaking fluidic unit can be the result.

**APTES activated bonding** enables bonding of thermoplastic entities and PDMS gaskets and is therefore of high interest in applications of disposable microfluidic chips. (3-Aminopropyl)triethoxysilane (APTES) is an aminosilane which can be used for the surface modification of thermoplastic entities to enable irreversible bonding to PDMS layers\cite{60}. For bonding, the PDMS surface needs to be activated by an oxygen or air plasma. An plasma activation of the thermoplastic surface, however, does not lead to silanol groups at the surface of the thermoplast. Therefore, surfaces of thermoplasts are modified by self-assembled monolayers of APTES (liquid deposition, see above), which makes covalent bonding of thermoplast to silane and silane to PDMS possible. By that bonds with tensile strengths of approximately 400 kPa can be formed\cite{60}. For more details refer to Sunkara et al. \cite{60}, from which processes and process parameters are adopted for the applications of this thesis.

### 4.1.2 Fluidic technologies

**Particle storage and filtering**

For particle storage and filtration standard laboratory glass vials are utilized. Making use of the effects of gravity onto particles in question, no additional filtering is required.
as for other systems reported in literature (such as particle concentrators with upstream ultrafiltration\cite{64}). For fabrication of a particle storage device, two holes are drilled into the cap and the sealing of the vial, of diameters slightly smaller than the outer dimensions of the tubing to be used. Through these holes tubings are inserted into the vial. By this a closed volume reservoir is created and the inflow through the first tubing is compensated by an outflow through the second tubing (assuming incompressible liquids and fully filled reservoirs). Figure 4.2 shows an image of a fabricated reservoir (a) and the schematic representation that will be used in the following (b). Particles that are entering the vial through the first tubing sedimenting to the bottom of the vial and are thereby removed from the liquid stream.

![Figure 4.2](image)

**Figure 4.2** Particle storage device as image and schematic representation used throughout the thesis.

**Particle supply**

Based on the particle storage and filtration principle MEMS can be supplied to the µFluiSA by storing them in a laboratory vial. For a supply unit one of the tubings is extended further into the vial, such that particles that are not sedimented to the bottom of the vial are dragged into this tubing when a sufficient flow through the closed volume reservoir is applied. Distributing the building blocks homogeneously within the vial by activating an attached test tube shaker (Heidolph Reax top) leads to a constant particle stream leaving the supply storage reservoir. In opposite, when the shaker is turned of, particles are sedimenting and the stream through the vial is not loaded with building blocks. By that, it can be easily controlled whether the stream contains particles or not. Additionally automation of this supply unit is straight forward.
4.2 Double Replica Molding

As described in section 4.1.1, surface properties of surfaces which are to be bonded by plasma or APTES activated bonding are crucial for the success of the bonding process. Micro-milled mold forms are discussed to have high surface roughness, which is reproduced during the PDMS molding process. Resulting surface roughnesses of the PDMS gaskets make proper sealing to the opposing surface difficult. Especially when machining the negative of a microfluidic gasket, large surfaces – which are responsible for bonding later on – are milled into the raw material. When those surfaces are to be used for bonding or sealing later on, the device might malfunction due to insufficient sealing of the rough PDMS gasket. Still, micro-milling is advantageous as prototypes can be produced fast and without the need for cleanroom infrastructure.

![Process flow diagram for double replica molding](image)

**Figure 4.3** Process flow for double replica molding. The decreased surface quality after milling is represented by dots on the corresponding surfaces. These surface roughnesses are reproduced by PDMS casts and therefore existing also on the final PDMS gasket.

Thermoplastic raw materials for milling are fabricated by continuous casting processes
resulting in higher surface qualities than standard milling processes. Hence it is advantageous to machine the positive of microfluidic systems and utilize a double replica molding process for the fabrication of the final PDMS gaskets. While channel side and bottom wall roughnesses are increased by the milling process, roughnesses of sealing surfaces are retained with raw material surface quality as they are not machined.

Zhuang and Kutter [61] introduce a double replica molding process in which SU-8 or PMMA master are replicated by a first mold. Thereafter a self-assembled monolayer of 1H,1H,2H,2H-Perfluorooctyltriethoxysilane is vapor-deposited on the PDMS master to decrease adhesion between PDMS master and PDMS gasket for the second replica molding. Once residual silane is washed off, the second replica molding can be performed, resulting in the targeted PDMS gasket. An image visualizing the process is given in figure 4.3.

Figure 4.4 shows the differences between a single replica process (in which the negative form of the gasket is milled) and a double replica process (where the positive of the gasket is milled). It can be seen that the surface roughness of sealing surfaces is drastically improved by the introduced double replica molding process.

![Figure 4.4](image)

**Figure 4.4** Comparison of single and double replica molding process outcomes. (a) Single replica molding of micro-milled negative mold form results in high surface roughness. (b) Double replica molding results in higher surface roughness within the machined channels, sealing areas have improved surface roughness properties.

Utilizing a simple double replica molding process enables micro-milling as a fast production method for PDMS mold forms. It should be noted that the increase of surface quality on sealing surfaces is opposed by decreased surface qualities within the channels of the micro-fluidic gasket. However, within the experimental parts of this thesis no constraints caused by the increased roughness of the channel walls could be identified.
4.3 An integrated PDMS valve

For controlling the flows through the µFluiSA as envisioned, valves are required that stay operational, even when used with particle containing streams. Most commercially available valves require filtration as the small gaps inside the valves otherwise get clogged by the particles within the stream. An alternative are integrated valves, which allow operation even with flows containing particles of the size of interest here.

Additional advantages of integrated microvalves include small outline, smaller dead volume and shorter switching time\[65\], as well as integration, i.e. short microfluidic channels instead of tubings to combine the valves with other fluidic sub-systems of the overall setup.

As the considerations and results presented in the following are of interest in a broad range of applications, this section has been published in the following manuscript:

The working principle for numerous integrated valves is based on a flexible membrane that is deflected to open or close the valve on demand. These valves can be densely packed on microfluidic chips which is demonstrated by Thorsen et al.\[66\]. Combining advantages such as high flexibility, transparency and low cost, PDMS has proven to be a highly suitable material for such applications.

Supplying enough energy for opening and closing the valves is one of the major challenges in microvalve design\[65\]. One approach is to supply these needed energies in form of pressurized fluids e.g. pneumatic actuation of such thin membrane PDMS valves. This is advantageous, as compressed air can be supplied easily to the system by means of a pump and small pressure tank, high strokes of the valve can be driven and forces are easily controllable. Additionally, when driven by pressurized fluids, the thin membranes of the valve can adopt to inaccuracies of the opposing surface and alignment is less crucial than for mechanically actuated microvalves. Depending on the demands of the valve, pressures as high as 350 kPa\[67\] are used to ensure that no leakage is created in the valve.

However, high operating pressures can be problematic, as PDMS is permeable to gases. Although negligible at short closing times of such valves, gas intrusion can become critical when the valve is closed for longer periods of time, i.e. pressurized, for minutes and gas bubbles are formed inside the fluidic channels of the system. These bubbles cause this method to be unusable for many applications and have to be avoided in any case.

Here two different approaches to avoid gas intrusion into the fluidics are investigated. The
4.3. An integrated PDMS valve

First approach is a parylene layer which is deposited on the surface of the PDMS valve membrane, introducing a barrier suppressing the gas flow through the thin membrane of the valve. The impermeability of parylene coated PDMS – even in dead-end channels – is investigated and described in detail by Flueckiger et al.\[68\]. The second approach is an oil droplet which is placed in front of the membrane on the pressurized side of the valve, as well building a barrier between the pressurized gas and the permeable PDMS membrane. This approach can be seen as an intermediate solution between pneumatic and hydraulic actuation of such valves, keeping the simplicity of air pressure preparation.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
No. & Design principal & Reference & Pressure [kPa] & Unactivated State & Fluid Path \\
\hline
1 & & Zhang et al. (2009) & -60 & 25 & closed & 3D \\
& & Grover et al. (2006) & -85 & 40/0 & & \\
& & Thuillier et al. (2005) & - & - & & \\
2 & & Baek et al. (2005) & -2 & 40 & closed & 3D \\
3 & & Go et al. (2004) & 0 & 10 & open & in-plane \\
& & Unger et al. (2000) & 0 & 100 & & \\
\hline
\end{tabular}
\caption{Recent valve designs from literature ordered by principal and year of occurrence. The marking L stands for liquid channel, P is for pressure, indicating the volume where the pressure for opening or closing is applied, cross-hatch is a PDMS layer, diagonal-hatch glass or thermoplastic layers. The pressures used by the authors are listed. Additionally it is specified if the valve is normally opened or closed and whether the design is an in-plane design or a rectangular design.}
\end{table}

An overview of PDMS valve principles is given in table 4.1 specifying opening and closing pressures used in the publications cited. Further it is summarized whether the valve design is normally closed or opened and whether the fluid is passing the valve in plane or is redirected into a second plane (3D). A simple design allowing high density valve placement is given when two crossing channels of which one is pressurized to close the other (table 1, no. 3) are implemented. For full sealing rounded fluidic channels are required, which is challenging in microproduction technology. To avoid the need for rounded channels more complicated valves have been designed. However, these valves are more complex and require additional material layers (no. 2). Recently improved designs were published with reduced complexity and number of layers (no. 1). These designs need structuring of the top and bottom material of the valve, which is usually glass or silicon, and is therefore time and
cost intensive. Zhang et al. \[69\] introduced a valve composed of a PMMA/PDMS/PMMA sandwich, making its fabrication easier and therefore cheaper. By combining advantages of the different designs given in table \ref{tab:valve-designs}, a simple valve design is introduced, by which the required machining can be reduced to a minimum. This valve design is evaluated with respect to gas intrusion, sealing capabilities, hydraulic resistance and lifetime.

### 4.3.1 Valve design and fabrication

Moving the valve (principle based on table \ref{tab:valve-designs} no. 2) to an inlet of the microfluidic chip reduces the required machining of the top layer to simple drilling. Also the bottom layer of the valve can be fabricated by drilling with two different diameters and is therefore easier than for table \ref{tab:valve-designs} no. 1. By that, full closure can be reached by only three layers of material with minimal machining required. The valve design introduced here is a three dimensional approach (figure \ref{fig:valve-design}). A thin, circular PDMS membrane is placed at the inlet or outlet of the microfluidic chip which can be deformed by applying a pressure in the dead end pressure channel (marked as P in the figure). When pressure is applied the membrane is pressed against the (circular) opening of the top Polycarbonate (PC) layer and the valve is closed, see also figure \ref{fig:valve}. Releasing the pressure (to ambient pressure) lets the membrane relax and the valve is opened. Therefore, the valve is normally opened. Two valves are connected through a fluidic channel in the test setup used here.

For the investigations a valve with $R_v=400 \ \mu m$, $R_m=875 \ \mu m$, $t_c=100 \ \mu m$ and $t_m=100 \ \mu m$ (see also figure \ref{fig:valve-design}) is fabricated and should be considered in the following. The inset of figure \ref{fig:valve} shows the valve from top, exposing its fluidic connectors. Pressure connectors are located at the bottom of the valve assembly. An estimation of the pressure difference over the valve, needed in order to completely close it, can be given with the help of the membrane deflection curve\[75\]

$$w(r) = w_0 \left(1 - \frac{r^2}{R_m}\right)^2, \text{ with } w(R_v) = t_c$$

and the corresponding pressure approximation\[75\], resulting in the valve specific equation

$$\Delta p_{\text{min}} = \frac{16}{3} \frac{t_m^3}{R_m^4} \frac{E_m}{(1 - \vartheta_m)} \left(1 - \frac{R_v^2}{R_m^2}\right)^2$$

\[4.2\]

with the definition

$$\Delta p = p_l - p_c$$

\[4.3\]

where $t_m$ is the membrane thickness, $t_c$ the valve thickness (distance for membrane to close), $R_m$ and $R_v$ the radii of membrane and inlet respectively, $E_m$ and $\vartheta_m$ are the
4.3. An integrated PDMS valve

Figure 4.5  Symbolic drawing of the thin membrane PDMS valve with fluidic (solid) and pressure (dashed) connections. The thin membrane valve is controlled by a 3/2-way control valve switching between a defined closing pressure $p_c$ and atmospheric pressure $p_{atm}$. In detail, sectional views of the valve in opened and closed state are given. The marking L stands for liquid channel, P for pressure channel. Here a valve with $R_v = 400 \, \mu m$, $R_m = 875 \, \mu m$, $t_c = 100 \, \mu m$ and $t_m = 100 \, \mu m$ is considered.

Young’s modulus and Poisson’s ratio of the membrane material, respectively and $p_l$, $p_c$ the liquid and closing pressure applied at the valve, respectively (refer to figure 4.5). For the valve dimensions specified above the needed pressure difference $\Delta p$ can be calculated to be approximately -1 kPa. Taking a misalignment of the membrane (100 µm) into account this value is increased to be approx. -1.5 kPa. At this pressure difference it is calculated that the membrane is touching the edges of the inlet channel with radius $R_v$ on a circular line contact. Due to imperfections in the drilling process, resulting in oval shaped holes or scratches on the contact area this pressure might not be sufficient to seal the valve, so that a safety factor of 10 is proposed to guarantee appropriate closure of the valve. This leads to a pressure difference of $\Delta p \leq -15 \, kPa$ for proper operation.

For fabrication of the valve the PDMS is mixed at a weight ratio of 10:1 base to catalyst, pressed into a previously produced cast form and cured for 6 h at 65°C (for details see section 4.1.1 and section 4.2). Subsequently, the PDMS gasket is removed from the cast form with the help of isopropanol – reducing the adhesion force between mold and gasket – to protect the fine features of the gasket from damage. The polycarbonate top and
Figure 4.6  Images of the valve setup in top view and cross section. In the inset fluidic connectors are on top of the assembly, the pressure connectors are below the assembly. The fluidic channel between in and outlet has 800 µm width and 100 µm depth. The main image shows a cross section of a pressurized (closed) valve. The membrane is deflected towards the liquid channel and pressed against the valve seat, thus closing the fluidic channel (top).

bottom layer are micro-milled and washed in soap water and isopropanol for cleaning. Subsequently they are exposed to a 13,56 MHz air-plasma for 120 s at 50 W for surface activation and then silanized for 30 min inside a 2% v/v APTES - DI-water solution. After silanization the polycarbonate samples are washed in DI-water and dried in a stream of air for further use. The PDMS gaskets are activated by the same plasma as the polycarbonate parts for 60 s and subsequently put into conformal contact for 30 min for bonding. For details on this bonding procedure see section 4.1.1.

Air pressure for the control of the PDMS valve is supplied by a membrane gas pump (KNF, NMP850), filling a 0.1 liter pressure reservoir. As shown in figure 4.5 a 3/2-way control valve (LHDA0531515H, The Lee Co), is connected to the pressurized reservoir and its common port is connected to the dead-end channel of the thin membrane PDMS valve. The third port of the control valve is left open, i.e. is at ambient pressure, which defines the opening pressure of the PDMS valve. An additional valve is needed to enable reliable starting of the membrane pump, as it might be choked when starting against already high pressures in the pressure reservoir. For security reasons a pressure release valve is integrated in the system to avoid overpressure.
4.3.2 Permeability

First experiments regarding the permeabilities of organic membranes were carried out by Barrer and Rideal in 1939 [76]. Later a relation between the permeability coefficient \( P \), the volumetric flow rate \( q \), the material thickness \( t \), area \( A \) and the pressure difference \( \Delta p \) was established and can be reformulated for the circular valve with radius \( R_m \) to [77]:

\[
q = \frac{A \Delta p}{\Delta t} P = \frac{\pi R_m^2 \Delta p}{\Delta t} P. \tag{4.4}
\]

From equation (4.4) it can be seen that the volumetric flow \( q \) through the membrane is reciprocally proportional to the thickness \( t \) and therefore gets relevant for small material thicknesses. As flexibility is highly important and highly dependent on material thickness, small thicknesses are crucial for valve functionality. For commonly used valve thicknesses the volumetric flow due to permeability gets non-negligible even for small valve areas \( A \).

Values for permeability coefficients of untreated PDMS can be found in literature to be approximately 600 Barrer [78, 79]. However, due to the fabrication steps of the valve introduced here, an oxygen plasma treatment is needed for bonding of PDMS and Polycarbonate support structures. Houston [78] characterized PDMS with and without plasma treatment concerning their permeability coefficients and found an average value for PDMS after argon plasma treatment of 260 Barrer. Taking the dimensions of the specific valve into account a prediction of the flow rate \( q \) can be given, as shown in figure 4.7 (dashed line).

Inserting a diffusion barrier, that separates pressurized gas and thin PDMS membrane, can suppress the permeability of the system. One approach is a pinhole free parylene coating on the PDMS surface as reported by Shin et al. [80]. Another approach is the separation of pressurized air and membrane by placing an oil droplet in the dead end channel of the valve.

Experiments

To verify the permeability effects described above, experiments are conducted. The detection of flows in the range predicted by equation (4.4) for the test valve (\( \sim 10\text{–}100 \text{ nl min}^{-1} \)) is extremely challenging with commercial available flow sensors. Hence an alternative approach is used for the measurement of the permeability volume flow \( q \). For this approach the fluidic channels of the valve setup and the attached tubings are filled with water. Subsequently the valve is closed with a defined closing pressure \( p_c \). In this state the gas is pressed through the thin PDMS membrane into the channel inside the valve and into the outlet/inlet which is closed by the membrane. The tubing attached to this outlet,
as well as the fluidics of the valve, are slowly filled by gas diffusing through the PDMS membrane. At a distance of 30 mm a sensor is placed around the tubing, which detects the approaching water/gas interface by a change of the diffraction index (see figure 4.8). The inner diameter of the used tubing is 0.51 mm, leading to a volume of 6.13 mm$^3$, which is filled during the experiment. By measuring the time between closure of the valve and arrival of the water/gas interface at the sensor, the average volume flow can be calculated.

This experimental procedure is executed for multiple closing pressures $p_c$ and valves. It is tested for valves without and with parylene coating of 2 µm and 5 µm and oil droplets as diffusion barrier.

Results and Discussion

For investigation of the effects of PDMS permeability for the introduced valve design and consequences for all pneumatically driven PDMS valves experiments are conducted. Those experiments are carried out with uncoated valves, without oil barriers that would suppress gas intrusion into fluidic channels of the test system. Figure 4.7 shows the results of these initial experiments, where the dashed line is the calculated curve (from equation (4.4)). Single measurements are marked with the number of the specific valve tested, the solid line is the calculated linear regression for all measurements. The resulting gas flow is proportional to the applied closing pressure (as predicted by equation (4.4)) and the linear regression leads to a line almost parallel to the calculated values. However, it can be seen that the measurement values are mostly located below the theoretical curve, resulting in a permeability coefficient of approximately 202 Barrer. Variations of the membrane thickness caused by inaccuracies during fabrication can account for the offset to values from literature\cite{78}. Additionally, plasma activation process parameters, utilized for the APTES bonding process, deviate from parameters used for measurements by Houston, Weinkauf, and Stewart \cite{78}. Most notably differences between the treatment with inert Argon plasma and highly reactive Oxygen plasma could contribute to those differences.

From the experimental results, however, it can be seen that the measurements confirm the theoretical considerations. Hence, pneumatically driven thin membrane PDMS valves are found to introduce gas into the microfluidic setup in which they are implemented. For closing periods longer than a few seconds the introduced gas forms bubbles which are unwanted in most microfluidic setups.

Parylene coatings of 2 µm and 5 µm thickness are applied to suppress the introduction of gas into the fluidic system through the thin membrane PDMS valve. The
4.3. An integrated PDMS valve

Figure 4.7  Permeability measurement of the introduced valve. Measurements are performed for four valves (numbering 1-4) and a linear best fit is calculated. Even though the resulting permeability of 202 Barrer varies slightly from values from literature\cite{78} – due to fabrication differences – the results confirm that the pneumatically driven thin membrane PDMS valves are responsible for gas intrusion into the microfluidic system.

experiments described above are conducted on each valve type. For both coating thicknesses experiments show that no gas gets into the measurement channel even when the valve is pressurized for one day. So that a pinhole free, perfectly sealed membrane can be assumed. However, inside the channel of the PDMS gasket gas bubbles are slowly forming and approaching the second outlet of the valve. This behavior is observed for all valves of both coating thicknesses.

An explanation might be found in a small lift off of the PDMS layer from the Polycarbonate substrate once the valve is pressurized (see figure 4.8). Resulting in an uncoated area of the valve which is exposed to the pressurized air and through which the gas can permeate into the channel of the valve, but not into the closed outlet of the valve as here the coating stays intact.

Due to the coating the flexibility of the membrane is decreased\cite{81}, which leads to the need of higher closing pressures in comparison to uncoated valves. This behavior is observed in valve characterization experiments with the coated valves conducted as described in section 4.3.3 (see also figure 4.9).

Even though it is shown that the parylene coating sufficiently suppresses the permeation
Chapter 4. Enabling technologies

Coating defect
Optical sensor
Water / gas interface

Figure 4.8  Sectional view of the thin membrane PDMS valve in closed state with coating defect. By the applied pressure an area of the PDMS membrane is lifted off from the Polycarbonate substrate and an area which has not been coated by the Parylene is exposed to the pressurized air. While the gas flow $q_1$ stays zero, a small flow $q_2$ can be observed.

of gas where a proper coating is reached, this approach does not completely eliminate the gas bubble creation inside the valve. Additionally, the performance of the valve is decreased and the coating process needs special machinery. This can be a hurdle for the implementation of such valves when the equipment is not accessible.

Oil droplets placed in the dead-end pressurized channel of the valve provide an alternative approach. This approach needs no special machinery and can be done easily by the operator. It is, however, more labor intensive when the valve is implemented in a disposable chip, as it has to be done manually for every valve used. Experiments show that the diffusion of gas into the valve can be completely eliminated by this method. No influence on performance and lifetime is to be expected. However, the oil droplet has to be placed on the membrane itself and no residual air must remain on the membrane. Either the oil is placed at the membrane with the help of a capillary (e.g. Eppendorf Microloader) which is inserted into the dead-end channel of the valve, or the system needs a priming time. During this priming time the residual gas is pressed into the channel and out of the dead-end of the valve. Long term tests showed that small oil droplets are fractured when a large number of switching events occur, so that pressurized gas and membrane are no longer fully separated by the droplet. Using larger droplets reaching into the tubing
4.3. An integrated PDMS valve

Figure 4.9 Maximum liquid pressure $p_l$ as a function of valve closing pressure $p_c$ for investigation of parylene coating influence on valve performance. Measurement points of an uncoated valve (circle), 2 $\mu$m parylene C coating thickness (triangle) and 5 $\mu$m parylene C coating thickness (cross) including their linear regression are visualized. With constant closing pressures lower liquid pressures are acceptable with parylene coated valves, indicating a performance loss. The coating thickness does not have an influence on the valve performance for the two valves tested.

connected to the pressurized channel of the valve suppresses the fracturing of the droplet inside the valve, so that proper operation can be guaranteed.

4.3.3 Valve characterization

Understanding the valve characteristics of thin membrane PDMS valves is essential to establish their usage in commercial applications. Especially sealing capabilities, hydraulic resistance, lifetime, internal- and dead-volume are values which are crucial when choosing a
valve for a certain application. Whereas internal- and dead-volume can be calculated from design parameters, sealing capabilities, hydraulic resistance and lifetime are experimentally determined for the introduced valve and described in the following.

Volume

With the dimensions specified in section 4.3.1 internal volume and dead volume can be calculated to be approximately 1.4 µl and 0.24 µl, respectively, which to our knowledge is factor 10 less than the smallest available solenoid valves (e.g. 3000 Series, The Lee Co or Series 282, Asco). It should be noted here, that the dimensions used are not critical in the fabrication process and hence can be decreased when needed. Channel height, diameter of the connector and by that the size of the needed membrane diameter can be further reduced in order to optimize internal and dead volume of the valve.

Sealing

For the estimation of the sealing capabilities of the introduced thin membrane PDMS valve, an experimental setup is used in which a syringe pump (KD scientific Legato 110) is set to pump liquid at a flow rate of \( q_{\text{in}} = 0.5 \text{ ml min}^{-1} \) into a closed volume reservoir. This reservoir encapsulates a certain air volume and is connected through a tubing to the PDMS valve that should be tested. The pressure \( p_l \) within this reservoir is measured while the pump is compressing the air volume inside the reservoir (the valve is assumed to be fully closed). A characteristic measurement curve of the pressure difference between reservoir \( p_l \) and valve closure pressure \( p_c \) is given in figure 4.11. Point 1 in the graph marks the starting point of the experiment at which the pump is running and the gas volume in the reservoir gets compressed. In the first section (to point 2) it is expected that the valve is perfectly sealed as the pressure difference is sufficient for sealing (\( \Delta p \leq \Delta p_{\text{min}} \), see also equation (4.2) and the following explanation). At point 3 liquid pressure and closing pressure at the valve are equal and the valve starts to leak, as it can be seen in the volume flow curve (middle) of figure 4.11. Even though the valve starts leaking the flow through the valve is much smaller than the flow of the syringe pump, so that the liquid pressure is still increasing, until point 4 is reached. Here the valve is opening rapidly so that \( q_{\text{in}} = q_{\text{out}} \) is fulfilled, keeping the pressure in the reservoir constant. Point 5 marks the time at which the syringe pump is stopped (\( V_{\text{in, total}} = 15 \text{ ml} \)) and thus relaxation of the pressure in the reservoir starts.

Interestingly, as can be seen from figure 4.11, the leakage of the valve is small until a threshold of approximately 1.5 times the closing pressure (see also figure A.1), which is
Figure 4.10  Symbolic drawing of the experimental setup for the estimation of the sealing capabilities of the introduced thin membrane PDMS valve. A syringe pump is facilitated to pump water into a reservoir closed by the thin membrane PDMS valve, compressing an initial gas volume \(V_{\text{gas}}\). By measuring the pressure \(p_l\) the leakage flow \(q_{out}\) through the valve can be calculated.

in accordance with values reported by Zhang et al.\(^{[69]}\). Even though it is expected that the resilience of the PDMS layer cause the valve to open at values of \(\Delta p \leq -15\) kPa (see equation (4.2) and explanation thereby), it can seal reasonably for liquid pressures higher than its closing pressure.

By calculating the forces resulting from liquid \((p_l)\) and closing \((p_c)\) pressures on the part of the membrane which is blocking the channel \((A = \pi R^2)\), one can conclude that an additional opening force (for the case shown in figure 4.11 \(\Delta F_{\text{open}} = 25mN\)) is acting on the membrane. This must be compensated by a force resulting from the contact area between membrane and valve seat, where (a) the closing pressure is pressing the membrane against the PC material and \(p_l\) is not opposing this pressure and (b) surface forces create adhesion between membrane and valve seat. Such surface adhesion forces can be suspected to be caused by hydrophobic and/or van der Waals interactions. Estimating the magnitude of the non-retarded van der Waals interaction forces with the help of equation\(^{[53]}\)

\[
p_{\text{vaw}} = \frac{A_H}{12\pi D^3}
\]  

\(^{(4.5)}\)

a Hamaker constant \(A_H\) of approximately \(1e^{-20}\) J\(^{[53]}\) and a distance \(D\) in the range of surface roughnesses of the materials of 3 nm, surface adhesion force per contact area can be
Figure 4.11  (Top) Pressure curve $\Delta p = p_1 - p_c$ for a closed system with a compressible air encapsulation sealed by a thin membrane PDMS valve with closing pressure $p_c=100$ kPa and an input pumping rate of $q_{in}=0.5$ ml min$^{-1}$, until point 5, at which the pump is switched off. Between points 1 and 2 the encapsulated air is compressed while the valve is tightly sealed so that $p_1$ increases. Point 3 marks the point where $p_c = p_1$ and leakage can be expected. Beginning from point 4 a stable state is reached where the leakage $q_{out}$ is as big as the input flow rate $q_{in}$, until the pump is stopped at 5 and relaxation of the gas volume takes place. (Middle) Corresponding volume flow through the thin membrane PDMS valve calculated from the pressure curve above. (Bottom) Corresponding graph of volume flow as a function of $\Delta p$ resulting in a hysteresis following the points of the pressure curve above. The experiment is carried out with DI-water.

estimated to be approximately 10 kPa. When assuming a contact ring between membrane and valve seat, calculations show that the additional opening force can be compensated by both pressure $p_c$ and surface forces acting on a ring of 270 $\mu$m width, which seems
reasonable for the given valve design. Experiments carried out with Isopropanol show comparable results (figure A.2). Slightly higher leakage at lower pressures (see example measurement given in figure A.3) can be explained by the missing hydrophobic interactions between PDMS and polycarbonate layer.

Plotting leakage flow as a function of the pressure difference $\Delta p$ a hysteresis can be found (see figure 4.11 (bottom)). Assuming a contact ring on which pressure $p_l$ and surface forces are acting in absence of the opposing liquid pressure $p_l$ an explanation for this hysteresis can be found in the following:

The valve is closed at low liquid pressure and is pressed into conformal contact, creating good sealing and a surface area (ring) where only pressure $p_c$ is acting upon. Additionally, the distance $D$ between the two surfaces is reduced to a minimum and adhesion forces get non-negligible. Once leakage of the valve can be observed the distance between the surfaces is increased. Which gives rise to that pressure $p_l$ is acting on this surface area and the adhesion force is, locally, significantly decreased. Even though the pressure is dropping the gap in the valve is maintained. However, while the liquid pressure is continuously dropping, material internal strains and adhesion forces at the borders of the gap are starting to close the defect again. Hence, the gap of the valve is finally fully closed again, even though the liquid pressure is still exceeding the closing pressure. These closing forces are smaller than the forces of the already fully closed valve, which is giving rise to the hysteresis found in the measurements.

Hydraulic resistance

Values for the hydraulic resistance of the valve can be concluded from the sealing experiments described above. In those experiments the valve is opened when the pressure reaches $\Delta p=0$ (i.e. $p_l = p_c$). Hence the flow through the opened valve can be measured for $p_l$ at this distinct moment. The hydraulic resistance $R_{\text{hyd}}$ is defined as

$$R_{\text{hyd}} = \frac{(\Delta p)_{\text{liquid}}}{q}$$

where $q$ the flow through the valve and $(\Delta p)_{\text{liquid}}$ is the pressure drop in the liquid channels of the valve, not the difference between closing and liquid pressure. Knowing the pressure and pressure drop when the valve is opened one can calculate the flow through the system. The tubings integrated in the setup are chosen to have a much greater diameter than the critical dimensions in the valve, so that the pressure drop due to the flow in the tubings can be neglected. Figure 4.12 shows the measurement results including a linear regression leading to a hydraulic resistance $R_{\text{hyd}} \approx 1 \cdot 10^{10}$ Pa s m$^{-3}$ for water at 20°C. It should be
Figure 4.12 Maximum flow through thin membrane PDMS valve as a function of applied liquid pressure across the valve. Maximum flow detected is more than 18 ml min$^{-1}$ and a hydraulic resistance of $R_{\text{hyd}} \approx 1 \cdot 10^{10}$ Pa s m$^{-3}$ can be calculated for water at 20°C.

Lifet ime

Lifet ime experiments are conducted with a similar setup as the sealing experiments, but instead of a syringe pump a peristaltic pump is used, as the maximum volume for syringe pumps is limited. When pumping liquid into a reservoir, closed by the thin membrane PDMS valve, the pressure rises slowly. When the valve is opened the pressure drops due to the high flow rate through the valve. In the lifetime experiments the valve is toggled.
4.3. An integrated PDMS valve

open/close at a constant period of 500 ms and the flow rate of the pump is chosen such, that the pressure is oscillating approx. between 22 kPa (closed valve) and 20 kPa (opened valve). The valve is operated at a closing pressure of 100 kPa. After one thousand alternations the cycle is stopped for 2 min with the valve closed and the pressure drop over this time is measured. If this pressure drop is greater than a threshold, the valve is leaking and therefore defective.

Running this procedure for 72 h the valve showed no sign of leakage, whereas the tubing used in the peristaltic pump was worn down, so that the test was ended after over 250000 switching (open and close) operations of the thin membrane PDMS valve without failure.

4.3.4 Conclusions

The effects of the permeability of PDMS on the application of pneumatically driven thin membrane PDMS valves are investigated. It is shown that the permeability of PDMS is responsible for gas intrusion into the fluidics of pneumatically driven thin membrane PDMS valves. Especially for long switching times and high pressures the intrusion gets non-negligible. A simple, straight forward solution for this problem is proposed involving separation of the pressurized gas from the PDMS membrane by means of an oil droplet placed in the dead end channel of the valve. Whereas the parylene coating of the valve could not prove to suppress the intrusion of gas into the valve completely. This is assigned to a damaged bonding between PDMS and Polycarbonate, which exposes small uncoated areas of PDMS to the pressurized gas. At these areas the gas can permeate into the fluidic channel of the valve. This was investigated for 16 coated valves, so that we suppose an underlying systematical problem.

Deduced from known thin membrane PDMS valves the introduced three layer valve design combines easy fabrication (only drilling) and high misalignment tolerance and is placed preferably at in- or outlets of the microfluidic entity. It has been tested in terms of sealing capabilities, hydraulic resistance and lifetime which are important values when a valve is chosen for commercial applications. The results show that the thin membrane valve can seal up to 180 kPa (with higher closing pressures even higher values should be possible), and allows flows up to 18 ml min$^{-1}$ for water, benefiting from smaller internal and dead volume than commercial available solenoid valves. As it is fabricated from a PC/PDMS/PC sandwich it can be integrated in low-cost, disposable microfluidic chips. Its lifetime has been tested to be more than 250000 switches, which seems appropriate for its target as a disposable microfluidic entity.

Even though the valve has been tested for liquids only, it can be also a viable solution for
microfluidic applications handling gaseous solutions.
For later use within this thesis, a valve with slightly different dimensions is implemented, as particles of 100 µm are required to cross the valve without clogging it. When increasing the closing distance $h_c$ it is beneficial to increase also the membrane radius $R_m$. 
Chapter 5

Major µFluiSA Components

The three main components of the µFluiSA concept given in section 3.1, designed and fabricated with the help of the enabling technologies introduced before, are now being described. Following the path of the MEMS building blocks (see also figure 3.4), preparation, assembly assistance and sorting subunits are discussed with respect to their theoretical background, fabrication and experimental results.

5.1 Preparation

Main goal of the preparation unit is the transfer of MEMS building blocks from their supply into a functional liquid. This procedure is also known for cells as cell washing, which is required in many molecular biology and microbiology protocols. Nowadays these preparations steps often require off-line centrifugation\cite{54}. Already in 1984, Lueptow, Peterson, and Wellesley \cite{82} invented a cell washing apparatus based on centrifugation and separation of entities within the system due to density differences. This system is mainly used in blood processing applications.

Microfluidic approaches imply a number of advantages, enabling the high throughput, continuous particle washing. Due to the laminar behavior of liquids in microfluidic systems, two liquids can be brought into contact for particle transfer and – when the transfer is done – the liquids can be separated, as only diffusional mixing is taking place\cite{83}. Due to the fact that only small displacements are required, usually smaller forces have to be exerted onto the entities of interest, which is especially advantageous for biological entities\cite{54}.

Benefiting from these assets of microfluidic systems, Hawkes et al. \cite{54} and Petersson et al. \cite{84} introduced systems that enable the continuous washing of cells, based on ultrasonic standing wave (USW) manipulation of these entities. However, the setup of USW ma-
nipulation setups needs expertise and special equipment. Additionally a number of error sources, such as proper sonic coupling and an exact channel width, have to be accounted for, during fabrication and system setup. Here a principle is introduced, relying on gravity – which is still reasonable strong for particles in sub-millimeter to micron size – that needs no special actuator. Particles are sedimenting from the carrier liquid into the receiving liquid, in which they are carried out of the unit after transfer.

In parallel to USW washing systems, methods have been developed for continuous separation of particles in so called split-flow thin (SPLITT) devices. For SPLITT fractionation a driving force or gradient is applied across the separation channel perpendicular to the flow axis to send sample components selectively into various lateral positions for separation[85]. For more detailed information in SPLITT fractionation refer to Fuh [85]. Even though separation is not a main goal of the μFluiSA preparation unit, the design of this unit can benefit from the knowledge gained from SPLITT system setups. Additionally the removal of dust or fractions of SU-8, created during release processes, can be separated from intact components by this approach.

By combining advantages of continuous cell washing strategies (USW) and SPLITT fractionation system designs, a controller-less system for the continuous washing of cells or MEMS is introduced in the following.

The storage of SU-8 components in Isopropanol (IPA) is advantageous as hydrophobic effects and thereby uncontrolled self-assembly is suppressed. Hence transfer of MEMS building blocks from IPA to aqueous solutions is the main target application of the preparation unit designed here. The design is made in line with those requirements.

5.1.1 Theory and design considerations

Theoretical background

In principle recently designed split-thin fractionation devices are designed such that particle washing can be directly performed with those devices. From the design proposed by Moon et al. [86], where separation is driven by gravitational force, one can conclude that a transfer from feed stream to carrier stream is already taking place. However, to our knowledge this transfer has not been utilized for particle or cell washing. Huh et al. [87] proposed a method for amplifying sedimentation based differences, by a widening separation channel. This widening channel results in hydrodynamic amplification of the separation distance between differently sized particles.

The governing equation of motion for particles in such a microfluidic sorting device are
defined to\[87]:

\[
\begin{align*}
\frac{dx}{dt} &= \frac{6Q'_f}{(H_{in} + x \tan \Omega)^3} [(H_{in} + x \tan \Omega) y - y^2] \\
\frac{dy}{dt} &= \frac{6Q'_f \tan \Omega}{(H_{in} + x \tan \Omega)^3} [(H_{in} + x \tan \Omega) y^2 - y^3] + \frac{2r^2g\Delta \rho}{9\mu}
\end{align*}
\] (5.1a)

(5.1b)

where \(x\) and \(y\) are the coordinates of the particle in question, \(H_{in}\) is the initial height of the widening channel, \(\Omega\) the widening angle between channel top and bottom walls, \(Q'_f = q_f/\text{tch}\) the flow rate (two dimensional), \(\text{tch}\) the channel thickness, \(r\) the particle radius, \(\mu\) the dynamic viscosity of the medium and \(\Delta \rho = \rho_p - \rho_m\) the difference between the densities of particle and medium, respectively (see also figure 5.1).

Figure 5.1  Schematic drawing of the particle transfer principle for the preparation unit based on SPLITT fractionation devices introduced in literature\[86, 87\].

Figure 5.1 visualizes the working principle of the envisioned particle washing system. The supply liquid, which carries the particles, is fed from the upper left inlet with flow rate \(q_f\) into the device. This inlet channel is widened with an angle \(\Omega\) for amplification of displacement differences due to sedimentation. By gravity and its hydrodynamic amplification larger particles are approaching the liquid-liquid interface earlier (in \(x\) direction) than smaller entities. A characteristic dimension of the device is found in \(H_{in}\), defining the inlet channel height and the corresponding flow profile within the washing unit. Assuming incompressible liquids, flow rates are defined by the relation:

\[
q_c + q_e - q_r - q_t = 0
\] (5.2)

where \(q_c\) is the flow rate of the collector inlet, \(q_e\) and \(q_t\) the flow rates of residual and target outlets, respectively. It follows that when the inlet flows are defined (e.g. by flow rates set at the corresponding pumps) the output flow rates are both defined when one outlet flow rate is controlled. This is of interest, as the height of the outlet splitting plane \(h_{osp}\) is defined by the ratio of collector inlet and target outlet

\[
h_{osp} = \frac{q_c}{q_t} h_c, \text{ with } h_c = \frac{q_c}{q_t + q_c} h,
\] (5.3)
which can therefore be controlled by any of the outlet flow rates. When a particle crosses the outlet splitting plane (OSP), i.e. it is \( y > h - h_{\text{osp}} \), it is successfully transferred. To avoid contamination of functional liquid with supply liquid, the collector inlet flow rate has to exceed the target outlet flow rate and it follows \( h_{\text{osp}} < h_c \).

When calculating the particle path with equation (5.1), results are highly dependent on the starting position \( x_s \) and \( y_s \) (see also figure 5.2). While \( x_s = 0 \) is valid in all cases,

![Figure 5.2](image)

**Figure 5.2** Sedimentation length \( L_s \) as function of starting height \( y_s \) calculated for PS beads of 200 µm diameter.

the position in direction of gravity \( y_s \) is dependent on characteristics of the fluidic setup and particle size. Huh et al. [87] facilitated sheath flows to focus particles in the center of the inlet flow. To suppress impact of gravity during the focusing process this is done in a stream directed parallel to the gravitational field. Subsequently, particles and flow are redirected by a curved channel so that gravity and flow are perpendicular to each other. By this the starting height of a particle is controlled and defined values for its sedimentation length \( L_s \) are achieved.

When the transfer of particles is envisioned from a supply to a receiving liquid of similar properties, such as density and polarity (e.g. two aqueous solutions), results analogous to conventional SPLITT devices are anticipated. However, when different liquids are in question, surface tensions or particle properties (such as hydrophobicity) might prevent the particles from being transferred through the liquid-liquid interface.

**Design considerations**

The design of a particle washing system is highly dependent on the entities to be handled. For preliminary experiments Polystyrene beads of 50 µm, 100 µm and 200 µm diameter
are used. Additionally rod-shaped SU-8 dummy MEMS are used to evaluate the systems capabilities for the handling of such components. As mediums tap water and Isopropanol are investigated.

Knowing the liquids and particles of interest, a first step towards a proper design is the estimation of sedimentation lengths for the targeted particles. To this end sedimentation paths are calculated for the targeted particles as function of feeding velocity $q_f$ (results are displayed in figure 5.3) and a sedimentation length $L_s$ applicable for all particles is chosen (here 15 mm). The sedimentation length $L_s$ is defined as the x position of a particle at which it is touching the imaginary extension of the widening channel wall, i.e. $y > x \tan \Omega - r$.

The collector inlet flow rate is set to be $q_c = 1/3 q_f$. Hence the collector interface height results with equation (5.3) to $h_c = 1/4 h$ to which the collector inlet channel height is approximated. For the absolute height of the preparation device channel it is therefore $h \approx 5/4 L_{s,\text{min}} \tan \Omega \approx 3.3$ mm. By that, the dimensions of a particle washing unit, utilizing gravitational and hydrodynamic effects, are given.

![Figure 5.3](image.png)

**Figure 5.3** Calculated sedimentation lengths $L_s$ for 25 μm, 50 μm and 100 μm radius polystyrene beads in water and IPA as function of feeding flow rate $q_f$. 
5.1.2 Fabrication and setup

The core preparation unit is composed of a PC backplane, a NBR gasket – defining the channel geometry – and a PC cover. PC backplane and cover are micro-milled from 10 mm and 2 mm feedstock, respectively (see also section 4.1). The cover includes a 0.6 mm deep cavity supporting form stability of the NBR gasket and defining the height of the channel system. The gasket is fabricated by nano-second laser structuring of 1 mm thick NBR raw material. Thus, taking cavity depth of the cover and material compression into account the resulting channel height is roughly 300 $\mu$m. The NBR gasket is clamped between cover and backplane of the preparation unit by screws which are located around the channel geometry. By that sealing of the fluidic chamber is achieved.

Figure 5.4 shows a sketch of the experimental setup for evaluation of the designed and fabricated preparation unit. Two peristaltic pumps (Ismatec Reglo Digital MS-4/12) are utilized to create the needed flow rates at feeding inlet $q_f$ and collector inlet $q_c$. For regulation of the complete flow pattern within the unit, the target outlet flow is regulated by a needle valve (see also equation (5.2)). Particles are stored in a closed volume reservoir, which is placed on a test tube shaker (Heidolph Reax top). By activating the shaker, particles are homogeneously distributed in the closed volume reservoir and – if peristaltic pump 1 supplies a sufficient flow rate – the particles can be transported into the preparation unit (see section 4.1). Depending on particle size and experimental settings the targeted particles are transferred to the target particle reservoir, whereas smaller or less dense particles are transferred to the residual particle reservoir. The experimental procedure is captured with a video camera for later assessment.

5.1.3 Results and discussion

In experiments conducted for the verification of the fabricated design, it is assumed that the collector liquid should not be contaminated by the feeding liquid. Hence, as a first step in the experimental procedure the flow pattern within the preparation unit has to be tuned to the state envisioned. This is done by adjusting the needle valve, positioned in the target outlet flow of the system setup (see also figure 5.4).

Aqueous to aqueous solution transfer experiments are carried out in tap water (both for feeding and collector liquids) of which the collector liquid is colored with blue ink. Also experiments for the transfer of particles from IPA to water are performed with colored water as collector liquid. The coloring makes the interface of the two liquids and their separation at residual and target outlet visible in video footage.
Preliminary experiments are conducted with 50 µm, 100 µm and 200 µm diameter Polystyrene beads. Experimentally obtained feeding flow rates for those entities, with a unit design with sedimentation length $L_s=15$ mm are summarized in table 5.1. By comparison of these values and predictions displayed in figure 5.3 one can see considerable differences between theoretical calculations by equation (5.1) and the experimental results. These differences are accounted to the influence of the channel walls of the filter onto the particle paths. The walls are leading to a decreased particle velocity\cite{88} and thereby to a relative velocity between particle and medium. It is assumed that this relative velocity (a) has influence on the particle Reynolds number so that creeping flow regimes are exceeded and (b) lift forces are resulting from the higher flow velocities above than below the particle\cite{89, 90}. A preliminary explanation is derived in section B and a extended calculation is displayed in the figures thereby. While with this approach a better agreement is achieved for particles sedimenting in water, results are worse for particles suspended in IPA. However, measurement points are too few to confirm or refute the underlying theoretical considerations. It could be shown that the particle transfer from feeding to collector liquid is possible both, from aqueous to aqueous solution and from IPA to aqueous solution for Polystyrene beads of sub-millimeter size.

Besides the shown particle transfer, separation of different sized entities is possible with the proposed preparation device. To proof this behavior of the system, two differently sized particles are fed to the unit simultaneously, while the flow rate is set to the optimal transfer flow rate of the larger particle (as found for transfer experiments in table 5.1).
Particle radius [µm] | Feeding flow rate $q_f$ [µl min$^{-1}$] in medium
---|---
25 | 122.4 | 180
50 | 227.4 | 300
100 | 600 | 900

**Table 5.1** Experimentally obtained feeding flow rates for optimal sedimentation and washing in a preparation unit designed for sedimentation length $L_s = 15$ mm with channel thickness $t_{ch}=0.3$ mm for PS beads.

The sedimentation path of the differently sized PS beads is visualized in figure 5.5. Here a feeding flow rate of $q_f = 1.2$ ml min$^{-1}$, a collector flow rate $q_c = 0.25$ ml min$^{-1}$ are applied. The liquid-liquid interface (IPA to colored water) is clearly visible. Furthermore it can be seen that a small portion of the collecting flow is exiting the device through the residuum channel. Thereby, the contaminated surface layer – by diffusional mixing – is transported away from the target outlet and therefore the functional liquid leaving the target outlet is not contaminated. On the video snapshot of figure 5.5, 200 µm particles are located in four main states and are marked by the numbering (1-4). The first state shows a particle in free sedimentation before it touches the channel boundary or is crossing the liquid-liquid interface, i.e. $x < L_s$. In second state the particle is located on the liquid-liquid interface. Depending on liquid and particle properties particles might not be able to cross the interface, e.g. when surface tensions between the liquids are strong or the hydrophobicity of the particles is avoiding its transfer. However, as visible from state three, the hydrophobicity of the used PS beads (CA ≈ 86°) does not lead to such behavior and the particles are fully immersed into the collecting liquid. From there on, the particle has to sediment within the collecting liquid so that $y > h - h_{osp}$ is fulfilled. Only if this condition is true the particle is leaving the unit through the target outlet, which is the case for the particle in state four. Smaller (100 µm sized) particles are crossing the device

**Figure 5.5** Sketch of the experimental setup for evaluation of the designed preparation unit.
5.1. Preparation

with a reasonable distance to the liquid-liquid interface, approaching the outlet separator within the residual stream. Once they get close to the outlet separator, the upward flows are lifting the particles again, transporting them towards the residual outlet. From video footage of the IPA to aqueous solution transfer experiments no small component can be found leaving the target outlet and no big component can be found which is not transferred into the collector liquid. Hence for these experiments a yield of 100% is found.

The major scope of the preparation unit is the transfer of SU-8 cylinders from their storing liquid (i.e. IPA) into the liquid in which assembly should take place. Here no separation is envisioned as only a single type of cylinder (100 µm diameter and length) is entering the preparation unit if particles are unassembled. Experiments with SU-8 cylinders are carried out with the same setup as calculated for PS beads. It is found that transfer of the SU-8 particles is possible at feeding inlet flow rate $q_f = 1113 \mu l \text{ min}^{-1}$ and collector inlet flow rate $q_c = 600 \mu l \text{ min}^{-1}$. The increased collector flow rate is required as SU-8 particles tend to stick to the channel sidewalls for lower flow rates once fully immersed in the aqueous solution. This behavior is accounted to the larger contact area possible for cylindrical shaped objects and flat channel walls. While beads can only have point contact, cylinders can have line or surface contact to the channel walls of the device. Hence, both, hydrophobic effects and VdW forces are increased, leading to stronger adhesion forces between particle and channel wall (for details see section 3.1). This holds true for hydrophobic particles in aqueous solutions.

5.1.4 Conclusions and outlook

To our knowledge for the first time, highly suitable principles of split-flow thin fractionation (SPLITT) systems have been utilized for particle washing applications. Based on gravitational and hydrodynamic effects the introduced design needs minimum control to transfer targeted particles from feeding liquid into collecting liquid. Experiments with PS beads of three different sizes are revealing considerable differences between the expected sedimentations lengths and the experimental results. This is accounted to particle sizes in the range of the units channel depth, giving rise to a relative velocity between particle and fluid, which itself is expected to have influence on the particle Reynolds number and to create lifting forces that act upon the particles. However, the gathered data is insufficient to proof the theoretical considerations made here and is left for further work.

By controlling the flow rates of the inlets and outlets accordingly, not only a selective particle transfer can be achieved, but also the particle concentration per fluid volume

† Video (1) can be requested from the author (gokyjo@gmail.com)
is tunable. Besides the awaited selectivity, it is shown that particles can be transferred through the interface of two unequal liquids such as IPA and water.

From experimental investigations the capability of the device for the preparation, i.e. particle transfer of SU-8 cylinders for the envisioned self-assembly system is shown. By adopting design guidelines of SPLITT devices the introduced system benefits from its separation capabilities, which are gravity driven and hence available without additional control electronics. The separation of SU-8 components from SU-8 fractions, which can be produced during harsh release procedures, can be advantageous for the µFluiSA system setup. Reported problems with sticking of cylinders can be avoided when different materials (e.g. glass) are used for channel sidewalls or PC surfaces are rendered hydrophilic.

As suggested by literature[87] the technique is supposed to be adaptable for smaller particle dimensions with equal density differences between particle materials and liquids. Effects of the curved channel are negligible for flow rates of a few ml min$^{-1}$ and particles smaller than $100\mu$m radius. It is anticipated that the washing of biological entities such as large cells and small cell clusters is possible with the introduced approach.
5.2 Reaction chamber

The second step, after preparation of the MEMS building blocks is their actual assembly. For this purpose, a unit is designed to achieve effective mixing of the building blocks by introducing a sufficient amount of random energy into the system. The functionality of this unit has been published in:


5.2.1 Introduction

Achieving efficient fluid mixing is an important challenge in microfluidic devices, which are typically low Reynolds number (*Re*) systems [91]. This challenge is particularly important for microfluidic SA, where fluid stirring is necessary to promote the effective aggregation of building blocks. As a valid alternative to tumbling [44] and pulsating turbulent flow [38], and in accord with collateral evidence [55, 92, 93], bubble-induced acoustic microstreaming is proposed as a promising agitation technique to address this issue.

Here the theoretical background, design, fabrication and characterization of a microfluidic chamber assisting the SA of MEMS in bulk liquids is presented. Exploiting bubble-induced microstreaming, several robust and competing driving modes are excited inside the chamber by ultrasonic piezoelectric actuation. The chamber functionality is demonstrated through the repeated aggregation and dispersion of pairs of polymeric microcylinders. Discussion of assembly performance as related to design choices and conclusions are finally presented.

5.2.2 Theory, design and fabrication

Three main criteria need to be necessarily met to enable efficient and robust SA [94]. First, SA only works for systems that have their minimum of free energy in the assembled state of the components. Second, a significant difference between the energies associated with all non-assembled configurations and the energy of the assembled configuration of components needs to be designed. Finally, sufficient kinetic energy needs to be supplied to the system to ensure effective mixing of components and overcome local energy barriers (see also section 2.2). Jung and Livermore [95] demonstrated how the fluidic forces induced by ultrasonic fields can drive the SA of microspheres into templates by selectively removing
undesired assemblies. Furthermore, ultrasonic agitation enhances mixing of the building blocks, enables parallel control and is easy to tune. Hence, ultrasonic agitation of the entire microfluidic chamber seemed appropriate. Ultrasonic standing wave (USW) particle manipulation was considered. USW is a massively-parallel manipulation method used in applications where many particles have to be controlled, clustered or held in specific positions, such as flow-through filtration and particle trapping[83, 96, 97]. However, the force driving USW particle manipulation depends on the distance of the particles to the closest node(s) in the pressure field, and it reduces to zero for particles at pressure nodes. Additionally, the one-dimensional manipulative characteristic of most known USW setups limits the mixing capabilities of such systems. As promising alternative, we considered bubble-induced acoustic microstreaming.

Theoretical background

Early investigations of particle dynamics close to an oscillating bubble were made by Longuet-Higgins [98, 99]. This secondary streaming phenomenon has been used so far for mixing enhancement [55, 92, 100], sample preparation [101], density-based trapping[102], propulsion of water floating objects[103] and for sorting of particles and cells [93, 104]. In accordance to Marmottant [105], the far-field streamline $\Psi_{2}^{\text{wall}}$ around a bubble oscillating near a wall can be described by:

$$\Psi_{2}^{\text{wall}} = -3\epsilon^2 a^3 \omega \sin (\Delta \Phi) \frac{a}{r} \cos^2 (\theta) \sin^2 (\theta) + O (\epsilon^2 r^{-2})$$

(5.4)

with

$$\epsilon = \frac{\xi}{a} << 1$$

(5.5)

where $\omega$ is the angular frequency of excitation, $a$ the bubble radius, $\xi$ the amplitude of bubble oscillation, $\Delta \Phi$ the phase shift between radial and translational oscillations of the bubble and $r$, $\theta$ polar coordinates with its origin at the bubble center. Velocities can be derived from the streamline equation with

$$u_r = \frac{1}{r} \frac{\delta \Psi}{\delta \theta}, \text{ and } u_\theta = -\frac{\delta \Psi}{\delta r}.$$  

(5.6)

One can see that the components of the flow field ($u_i$ for $i = r, \theta$) induced by the bubble are proportional to the square of the amplitude $\xi$, and that the phase shift $\Delta \Phi$ influences both magnitude and sign of the fluid flow. A typical streamline pattern resulting from a single air bubble oscillating close to a wall inside an acoustic field is illustrated in figure 5.6.
Figure 5.6 Numerically-calculated far-field streamline pattern caused by an air bubble oscillating close to a wall inside a sonic field [105]. The bubble radius $a=50 \mu m$, the amplitude factor $\epsilon = \xi/a = 0.2$, angular frequency $\omega = 2\pi \cdot 60$ kHz and phase shift $\Delta \Phi = 20^\circ$ were chosen according to Marmottant [105]. Due to equation (5.4) the phase shift $\Delta \Phi$ can suppress or reverse the flow pattern (e.g. $\Delta \Phi = -20^\circ$).

Particles immersed in a liquid in proximity of the surface of an oscillating bubble experience two main forces: the drag force, resulting from the ensuing fluid flow, and the secondary radiation force (Bjerknes force), resulting from gradients in the kinetic energy density. For low Reynolds numbers (as in our case, see section 5.2.3) Stokes law can be applied to estimate the drag force on spherical particles as

$$|F_D| = 6\pi \mu \rho |u|$$  \hspace{1cm} (5.7)

where $\mu$ is the dynamic viscosity of the liquid, $r$ the radius of the particle and $|u|$ the absolute value of the relative velocity. The Bjerknes force for spherical particles in proximity of an oscillating bubble is calculated to be [106, 107]

$$F_B = 4\pi \frac{\rho_l - \rho_p}{\rho_l + 2\rho_p} \rho_l a^3 \frac{\rho}{D^5 \omega^2 \xi^2}$$  \hspace{1cm} (5.8)

where $\rho$ is the density and $D$ the center-to-center distance between bubble and particle, and subscripts $l$ and $p$ refer to properties of liquid and particles, respectively. While the direction of the drag force is dependent on the fluid flow and therefore on dynamic properties of the bubble oscillation – namely the phase shift $\Delta \Phi$ – the direction of the secondary radiation force depends on the ratio of densities of particle and surrounding liquid. That is, radiation force direction is constant for defined materials, and only its magnitude can be influenced by the amplitude and frequency of agitation.
Assuming reasonable bubble amplitudes ($\epsilon = 0.2$) drag and Bjerknes force can be estimated to be in the same order of magnitude for thermoplastic particles suspended in water with acoustically-actuated air bubbles [105]. The secondary radiation force is in this case directed away from the oscillating bubble. Assuming a positive phase shift $\Delta \Phi$, drag and radiation force are opposing each other, and from figure 5.7 it is apparent that they give rise to an overall force directed towards the bubble (at 40 kHz and small $\Delta \Phi$) or away from the bubble (at 60 kHz and large $\Delta \Phi$). This is referred to as *thesis 1* in the following. Stokes drag can also toggle by a switch of sign of the flow pattern, and be directed away from or towards the oscillating bubble (at its center, see also figure 5.6). This is referred to as *thesis 2*.

We thus designed a spatial arrangement of a multiplicity of oscillating gas bubbles to obtain a desired force field. A circular arrangement can produce a central field which can be controlled to either focus (i.e. push toward the center) or defocus particles. Focusing increases local particle concentration and therefore enhances the rates of assembly. Defocusing can be advantageous to reconfigure or even disperse unwanted aggregates. Indeed the tension exerted on particles inside the flow field generated by a vibrating bubble within a sound field was calculated as [105]

$$\tau_{\text{max}} \approx \mu G_{\text{max}} r$$

(5.9)

where $\mu$ the dynamic viscosity and $G_{\text{max}}$ the maximum of the rate of strain tensor (defined as $G_{ij} = \partial_i u_j + \partial_j u_i$) [105]. As the rate of strain tensor has its maximum close to the
5.2. Reaction chamber

bubble surface (see also figure 5.6), defocusing the particles (i.e. displacing them towards the bubble surfaces) can break up unwanted configurations.

The resonant frequency of gas bubbles within liquids can be estimated with the help of Minnaert’s equation \[ f_M = \frac{1}{2\pi a_0} \sqrt{\frac{3\gamma p_0}{\rho_l}} \] where \( f_M \) is the linear frequency, \( a_0 \) the bubble’s initial radius, \( \gamma \) the ratio of specific heats of gas, \( p_0 \) the hydrostatic liquid pressure and \( \rho_l \) the density of the liquid.

Design of microchamber and peripherals

The above considerations regarding flow patterns, drag and Bjerknes forces, and bubble resonance frequency led the design of the ultrasonically-driven, bubble-mediated microfluidic self-assembly chamber, shown in figure 5.8. The chamber is built around a core unit composed of two glass slides—making up the top and bottom walls—sandwiching a cen-

![System setup showing the core chamber, illumination, tubings, transducer and its piezo positioning stage. In detail (bottom right) the chamber core consisting of two glass slides and a PDMS gasket is shown. It includes all channels, filters, air encapsulation sockets and valves (which are described in detail in section 4.3) needed to drive the self-assembly in the envisioned manner. For details see also figure 5.9a](image-url)
58 Chapter 5. Major µFluiSA Components

tral, 400 µm-thick PDMS gasket (see figure 5.9a and figure 5.9b for a schematic depiction). The chamber sidewalls, input and output microchannels, lateral sockets hosting air bubbles 93, filters and pneumatic valve structures were patterned within the gasket. The roughly rhomboidal chamber is 5 mm long and 3.5 mm wide, as shown in figure 5.9c. According to equation (5.10), air bubbles in water resonating at the nominal frequency of the piezoelectric transducer (60 kHz) should have a diameter of about 100 µm. To closely match this condition through a simple fabrication, the 500 µm-long lateral air sockets inside the chamber sidewalls were therefore designed to have a cross-section of 100-by-100 µm². 20 of such air sockets were inserted symmetrically along the chamber sidewall. A schematic sketch of the sockets and the resulting flow field in the chamber is given in figure 5.9c. This configuration results in a central force field, generated by Bjerknes and drag forces, having symmetry planes along the main axes of the chamber. Assuming the Bjerknes force predominant (∆Φ → 0, thesis 1) or a reversed flow pattern (∆Φ < 0, thesis 2), the oscillating bubbles generate a focusing force field.

A mechanical filter consisting in a thin lateral channel is located at one sidewall of the chamber. The height of the channel (50 µm) allows only the fluid and not the microcomponents to exit through. By activating the lateral fluid flow (represented by the dashed black arrow in figure 5.9c) by a proper valve configuration, the components are thus led to accumulate at the chamber sidewall (figure 5.10a). To avoid any significant interaction with the hydrophobic surfaces of the microcomponents, top and bottom walls of the chamber were made of glass. Clean glass has a native water contact angle (CA) tending to 0°. It has therefore a strong hydrophilic behavior 110, in contrast to the untreated SU-8 surfaces of the microblocks (see next section), which have a water CA between 74° and 90° 111. PDMS is hydrophobic, as confirmed by a water CA of about 105° 110. While promoting local disaggregation of microcomponents, we also expected the strong bubble-mediated streaming along the chamber perimeter to prevent the microcomponents from sticking to the PDMS sidewalls.

Pioneering works from Liu et al. 92, Lee et al. 101 and Patel et al. 93 were useful references for the design of the setup. For the fabrication of the core unit, a positive of the chamber was milled into a PMMA body (refer also to section 4.2). To fabricate the negative mold form an approximately 5-10 mm-thick layer of PDMS (Dow Corning DC 184) in a 1:10 mixture of base material and curing agent was poured over the milled form and cured for 6 h at 65 °C. This PDMS mold form was then silanized with trichloroperfluorooctylsilane, which promoted the subsequent separation of the secondary mold form from the final PDMS gasket at a later stage. Residual excess silane was washed off with toluene. The final casting of the gasket was performed again with a 1:10 PDMS mixture of Dow Corning
5.2. Reaction chamber

Figure 5.9 Cross-section of reaction chamber setup (a) including chamber core, PMMA holder, integrated illumination, transducer, springs and guide pins (see figure 5.8 for reference). The detailed view in (b) (10:1 scale) shows the filtered lateral outlet of the chamber, which being 50 µm thick prevents the approaching microcomponents from passing through dragged by the fluid flow. The top view (c) sketches the flow field created by encapsulated air bubbles within the chamber core. Loading (dashed black arrow) and clearing (dash-dotted black arrow) paths for the microcomponents are also indicated.
DC 184, cured for 6 h at 65 °C. The top glass slide of the unit was laser-cut from a 1 mm-thick microscope slide (Faust 9.161 130). As bottom chamber wall, a 150 µm-thick round glass coverslip (Faust 9.161 062) was used.

The challenging requirement of keeping the chamber sealed during ultrasonic agitation was met by a plasma-activated irreversible bonding of PDMS gasket and glass slides[62, 63]. This technique avoided the uncontrolled introduction of air bubbles into the system, as well as water leakage out of the system. These advantages justified the complex fabrication of the laser-cut top glass slide, as plasma-activated bonding with PDMS is not possible with most alternative materials. For plasma bonding, the PDMS gasket and the two glass slides were kept in air plasma (5 $\cdot$ 10$^{-2}$ mbar, 5 W) for 4 minutes. After the core unit was assembled, it was kept at 65°C overnight to speed up inter-diffusion and therefore enhance the bonding of the materials. More details on the plasma treatment can be found in the references [112, 113].

Air bubbles were trapped within the lateral sockets while filling the chamber with deionized water. They could remain thereby encapsulated for a long time, although progressively depleting due to air dissolution in water or bubble break-up. Conversely, a degassing unit (BioTech) was included into a closed water recirculation loop. This loop involved both inlet and outlet of the chamber so to avoid the eventual, uncontrolled insertion of air bubbles into the chamber. To avoid release of water upon sonication of the chamber, pneumatic valves in PDMS were included in the core unit (these valves have been described in detail in section 4.3). The valves could be used to shut the inlets and outlets and at the same time to direct the fluid flow during the loading and clearing stages (see next section). By isolating the chamber from the rest of the fluidic setup, the valves also avoided liquid drift during actuation.

The piezoelectric transducer (SMATR10H60x80, Steiner & Martins, Inc., nominal frequency: 60 kHz) that introduces the acoustic energy into the system was attached to the core unit through a spring setup (see also figure 5.9a) and a stepper motor in order to create reproducible contact pressures between the bottom glass and actuator surfaces before actuation. The frequency generator and amplifier driving the transducer between DC, 100 kHz AC and 0 – 150 V$_{pp}$ were custom-designed at EPFL DISAL and CSEM laboratories, respectively. To enhance the acoustic coupling between the transducer and the bottom glass slide, a thin layer of ultrasonic gel was uniformly interposed. The frequency of the first resonance mode of the chamber, featuring a single pressure node at the center of the chamber, was estimated around 42 kHz by FEM simulations.
5.2.3 Results

The first stage of the experiments involved the loading of the SU-8 microcylinders into the chamber. To this end, the PDMS valves were configured to enforce water flow through and accumulate the microcylinders in front of the lateral filter (figure 5.9c, dashed black arrow). The microcomponents could be stored thereby for an arbitrary amount of time before further action (figure 5.10a). Normally several tens of microcylinders were introduced into the chamber for each experiment. Before starting each realization of a SA process, all valves were closed to isolate the chamber. The SA of the microcylinders could then be performed upon ultrasonic actuation. After the conclusion of the assembly experiments, described below, the valves were reconfigured and the microcomponents could be finally unloaded from the chamber by dragging them through the unfiltered outlet of the chamber (figure 5.9c, dash-dotted arrow).

A systematic exploration of the behavior of the chamber according to the available control parameters was experimentally conducted. Frequency sweeps (0 to 80 kHz) at fixed actuation amplitude, and amplitude sweeps (0 to 150 V$_{pp}$) at fixed actuation frequency were carried out.

These experiments evidenced a strong dependency of the microstreaming patterns induced within the chamber on the actuation frequency. Actuation frequencies below 20 kHz did not lead to any significant movement of the microcomponents within the chamber even under actuation amplitudes larger than 140 V$_{pp}$. Conversely, motion of the microcomponents could be incepted for actuation frequencies higher than 20 kHz and for most of the available actuation amplitudes. Moreover, for every effective constant frequency, an increase of the actuation amplitude led to an increase of the mobility of the microcomponents inside the chamber. Remarkably, four different and reproducible actuation configurations (or modes in the following) could be identified. These modes could then be pre-programmed, and effective strategies to direct the assembly experiments could be defined by playing them in a prescribed sequence.

For an actuation frequency of 40 kHz and amplitudes higher than 100 V$_{pp}$, the microcomponents tended to quickly disaggregate and disperse across the chamber, mostly sweeping the outer regions and occasionally crossing the center (see equation (5.7), equation (5.8) and explanation thereby). When approaching the interfaces between water and air bubbles (e.g., at a distance smaller than their length), the microcylinders experienced an increasing shear force. Such strong drag further unpaired the blocks while propelling them significantly (refer to equation (5.9) and the explanation thereby). This was referred to as the Disassembly mode (see also figure 5.10c).
Figure 5.10  Top view of the chamber after (a) loading of the MEMS, (b) Assembly mode and (c) Disassembly mode. During the loading, the microcylinders are accumulated by the liquid in front of the lateral filter. The Assembly mode tends to concentrate the building blocks in the center of the chamber, while the Disassembly mode disaggregates and spread them toward the outer edges. The images have been taken at EPFL DISAL laboratories.
Experiments at 60 kHz showed the microcomponents collectively moving toward and aggregate at the center of the chamber, the tendency being the more pronounced the higher the driving amplitude. Particularly, for voltages larger than 100 V\textsubscript{pp} the microcylinders orbited thereby while erratically and vigorously rearranging their relative positions within the aggregate(s). In this Assembly mode, a high rate of cylinder assembly could be observed within few seconds (figure 5.10b). After about 60 s in Assembly mode, only very few residual cylinders could be found at the borders of the chamber. Only occasionally could the microcylinders leave the center of the chamber.

The opposing effects of the Assembly and Disassembly modes can be qualitatively appreciated by comparing figure 5.10b with figure 5.10c, the latter being captured after the former and showing most of the cylinders no longer paired. By subsequently toggling between Assembly and Disassembly modes, the stochastic formation and dissolution of aggregates of cylinders could be repeatably induced.

Additionally, two Slow-spreading modes for lower values of acoustic energy, i.e. for actuation amplitudes around 40 V\textsubscript{pp} have been identified. For this amplitude value, at an actuation frequency of 40 kHz the microcomponents tended to preserve their relative arrangements into the aggregates. At the same time, the aggregates slowly drifted across the chamber toward one of the sidewalls. When at 60 kHz and for the same amplitude value, the slow collective drift of the aggregates instead coexisted with a Brownian-like motion of the individual microcomponents within the aggregates. Such motion tended to constantly change and reconfigure the coordination of the microcomponents, so that they could switch among configurations, mostly from type $C_2$ to $C_1$ and vice versa. This actuation mode could be roughly represented by the annealing effect of an adequate thermal bath on an ensemble of microcomponents confined within a central potential field.

Table 5.2 summarizes the settings for the four main modes evidenced. The values for the control parameters are nominal since, as implicit from the above description, a continuum of modes with intermediate characteristics exists between the four main ones. Importantly, all the four main modes are highly reproducible and robust. In fact, they were not significantly perturbed by neither a) the eventual and random intervention of spurious air bubbles along the sidewalls of the chamber, nor by b) their random redistribution in the chamber upon mode switching.

Video footage illustrating the action of both the Disassembly and the Assembly modes is available.

Statistics gathered from assembly experiments performed with preset Assembly and Dis-

\footnote{Video (2) can be requested from the author (gokyjo@gmail.com)}
<table>
<thead>
<tr>
<th>Agitation mode</th>
<th>Frequency [kHz]</th>
<th>Amplitude [Vpp]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembly</td>
<td>60</td>
<td>150</td>
</tr>
<tr>
<td>Disassembly</td>
<td>40</td>
<td>150</td>
</tr>
<tr>
<td>Slow Spreading 1</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Slow Spreading 2</td>
<td>60</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 5.2 Nominal values of the control parameters for the four main modes of actuation.

assembly modes are shown in figure 5.11. After approximately 10 sec of agitation in each of the modes, the agitation was disabled and the assembled cylinders were counted. The results were quantified by the relative frequency of occurrence of single cylinders and of the predefined assembly configurations $C_i$ for $i = 1, 2, 3$. For cylinders involved in multiple assembly configurations, only the assembly configuration with lowest energy was counted and the others neglected (refer to section 3.1 and figure 3.2c for details). It can be seen that after 10 s in Assembly mode about 50% of the microcylinders inside the chamber had a connection of type $C_1$, 25% $C_2$, 6% $C_3$, while 19% were still unpaired. After successive 10 s in Disassembly mode, 1% had connection type $C_1$, 3% $C_2$, 6% $C_3$ and 83% were unpaired.

By evaluation of high-speed recordings of their trajectories, maximum detected speeds of microcylinders in water were measured to be $v_{\text{max,d}}=250 \text{ mm s}^{-1}$ during Disassembly and $v_{\text{max,a}}=26.6 \text{ mm s}^{-1}$ during Assembly mode. By taking the maximum height (0.4 mm) of the chamber as characteristic length, the largest $Re$ can be calculated to be $Re_d = 112$ for Disassembly mode and $Re_a = 12$ for Assembly mode respectively, confirming the laminar type of flow in both cases. Strong mixing effects could nonetheless be achieved thanks to acoustic microstreaming, as mentioned. All microcylinder motion instantaneously stopped when the actuation was ceased, confirming the absence of any significant inertial effect.

5.2.4 Discussion

Air bubbles oscillating close to solid obstacles are known to produce strong streaming flows in a hosting liquid. Additionally secondary radiation forces are exerted on particles in proximity of these oscillating bubbles. As experimentally demonstrated in the previous section, these phenomena can be tailored to obtain efficient mixing and aggregation of microcomponents even at low Reynolds numbers. This has been achieved through a two-axes and centro-symmetric arrangement of air bubbles localized within the side-walls of a microfluidic chamber immersed in an ultrasonic field. Such arrangement of

† Video (3) can be requested from the author (gokyjo@gmail.com)
5.2. Reaction chamber

localized, ultrasonically-actuated air/water interfaces enabled the controlled creation of focusing and defocusing flows essential for the driving modes of the chamber. Ultrasonic propulsion in air was already proposed for contactless manipulation and assembly of small components \[6\]. It can efficiently and controllably drive the diffusion of microdevices across planar surfaces in air \[115\]. As in the gas phase, ultrasonic actuation enhances the mobility of microcomponents also in bulk liquids. Besides, in bulk liquids the acoustic radiation pressure subjects the components to additional primary and secondary effects which significantly influence their hydrodynamic interactions. In this scenario, a striking evidence of such effects is represented by long-ranged and self-aligning interactions between the microcylinders. Through high-speed recordings, pairs of cylinders were seen at times aligning and locking together in direct contact by bridging gaps of up to 20 µm. This range of attraction is two orders of magnitudes longer than for the hydrophobic interaction \[50\]. We attribute this type of occasional pairings between microcylinders to locally induced cavitation bubble streaming \[116\] effects, bringing the particles into close contact.

An additional attractive force is caused by secondary radiation forces, not only acting between bubble and particle, but also between the rigid particles themselves. These forces are attractive in case the direction of wave propagation is perpendicular to the direction joining the centers of the particles and repulsive if the two directions are parallel \[117\]. Here we assume the primary axis of wave propagation perpendicular to the particle sep-
Chapter 5. Major µFluiSA Components

aration distance $D$, and therefore attractive forces. Such attractive forces are of short range ($\propto 1/D^4$) and significantly smaller than hydrophobic and van der Waals forces for distances in the range of few $\mu$m (for the largest particle velocities we observed). Moreover, secondary radiation forces do not depend on the size of contact area of the particles, in contrast to hydrophobic and van der Waals interactions. Therefore they do not contribute to the preferred self-assembly of microcylinders into configuration $C_1$. Once particle distances are decreased below 1 $\mu$m, inter-particle secondary radiation forces may be suspected to enhance particle attraction. However, since the preferred $C_1$ configuration is most frequently observed and the inter-particle secondary radiation forces are of shorter range than hydrophobic and van der Waals interactions, we account the main driving forces to the latter.

Generally, the dynamics of the microcomponents within the chamber is largely stochastic and nonlinear. It is affected by local, fluidic and acoustic interactions with neighboring microcomponents and by the mean flow field in the chamber. The latter in turn depends on the modes of actuation and the geometry of the chamber, as well as on its actual boundary conditions—which include the distribution of the microcomponents along with that of the air bubbles. In addition, the cylinders are often observed to rotate out of the horizontal plane and to displace vertically, crossing the focal plane of the camera objective in doing so. Both instances tend to decrease significantly the geometrical yield of the SA process.

To get a deeper understanding of the behavior of the chamber under the main driving modes, the corresponding flow fields in presence of hydrophilic latex beads (Invitrogen, 9 $\mu$m in diameter) have been high speed tracked. This type of analysis evidenced substantial differences between the modes. Particularly, only the 60 kHz modes show stagnation points in their flow fields, roughly in correspondence with the center of the piezoelectric actuator, whereas at 40 kHz the beads appear always uniformly distributed. Taking the size of the used latex beads into account and referring to equation (5.8), the secondary radiation force exerted from the bubble onto the beads is three orders of magnitude smaller than for the applied microcylinders. From this one can infer that a switch of sign in $\sin(\Delta \Phi)$ (thesis 2) accounts for the change in behavior, rather than the overruling of secondary radiation forces over drag forces (thesis 1). Also, the bubble oscillations are more pronounced at 60 kHz rather than at 40 kHz, which would not be the case if thesis 1 would hold true. The global vorticity of the flow fields change significantly inside the chamber when switching between Assembly and Disassembly modes. At the same time it is to be expected, as showed to be the case, that the main agitation modes of the chamber

\[\text{Video (4) can be requested from the author (gokyjo@gmail.com)}\]
be excited at frequencies related to physical properties of the chamber and of the piezo-electric transducer. In fact, the numerically-simulated first resonance frequency of the chamber (i.e., 42 kHz) is very close, given a reasonable tolerance on geometrical dimensions due to the fabrication process, to the actuation frequency for the Disassembly and Slow-spreading 1 modes (40 kHz). By the same token, the measured resonance frequency of the piezoelectric transducer matches exactly the actuation frequency for both the Assembly and the Slow-spreading 2 modes (60 kHz). These observations provide a structural reason for the robustness of the main actuation modes against random perturbations of the distributions of air bubbles in the chamber.

The 60 KHz modes show component aggregation and mixing at the center of the chamber with increasing mobility for higher agitation amplitudes. Though at this frequency it seems possible to increase the amplitude of agitation to a level at which correctly assembled components are separated, it is not constructive to use this mode for disassembly purposes as the components constantly reassemble within the centering flows. In fact, this behavior can be observed already for amplitudes used in the assembly mode (see table 5.2). This emphasizes the value of the disassembly mode, in which dispersion of the building blocks is given and the separation of correctly and incorrectly assembled components happens at the outer borders of the chamber. Finally, one could in principle imagine to make the two resonances match—either by modifying the geometry of the chamber, or using a different piezoelectric actuator. This would maximize the transfer of energy from the actuator to the chamber, yet at the same time reduce the number of qualitatively different actuation modes. The availability of a variety of actuation modes is critical to achieve efficient SA [118].

The overall appearance of the aggregated components in the assembly mode (as shown in figure 5.10b) is controlled stochastically. Yet unlike simple diffusion-limited aggregation the configurations of the microparticles are reversible within the aggregates, so that driving the system leads to their evolution toward the lowest energy states (refer to the analysis in section 5.2.2). In this respect, our acousto-fluidic multipole setup is advantageous over other multipole setups, for instance dielectrophoretic [119]. Outbalancing drag and stiction forces of the microparticles requires relatively high driving forces, which are not easily generated e.g. by dielectrophoretic effects. With the introduced system the need of surfactants reducing particle aggregation, as described in other self-assembly approaches [120], can be avoided. Additionally, the time to create aggregation of micro-components is significantly reduced within our acousto-fluidic setup. This behavior suits the massively parallel SA of large quantities of components (in our case, the pairwise $C_1$ connection between cylinders).
The assembled state of the microcylinders is very fragile, due to the low magnitude of the combined hydrophobic and van der Waals interactions (as described in section 3.1). This notwithstanding, it is showed that a significant improvement in the distribution of the assembly configurations could be achieved by the driving modes of the chamber.

5.2.5 Conclusions and Outlook

A novel acousto-fluidic chamber that efficiently assists the self-assembly of microcomponents in bulk liquid was developed. The chamber can drive a few differing modes of actuation by modulating in frequency and amplitude the ultrasonically-driven acoustic microstreaming of air bubbles through a simple setup. Particularly, the availability of Assembly and Disassembly modes—inducing aggregation and dispersion, respectively—was functional to the repeatable achievement of fair geometrical yield of assembled ($C_1$ configured) building blocks within few seconds. This result was obtained in spite of a minimalist design and absence of additional surface functionalizations for the microcomponents — the latter could enhance the effect of hydrophobic interactions by increasing the native water contact angle of SU-8 further. The SA yield can be enhanced by introducing stronger, more selective and anisotropic interactions among the blocks, as shown in literature\,[120, 121]. Magnetic interactions and specific (e.g., DNA-based) surface derivatizations, when combined with a more elaborated block design to exploit mutual shape-matching and allow the assembly of more complicated structures, can be envisioned for this purpose. Recent findings with this assembly chamber setup, available at EPFL DISAL (extended with an advanced vision and tracking concept), show the controlled formation of desired microtile configurations. This is achieved by closed loop alternating assembly and disassembly agitation of the microtiles inside the chamber (for details refer to Mastrangeli et al.\,[122]). Further automation of the process can lead not only to higher yields — by a more efficient use of the various modes — but also allow the investigation of the time evolution of the building blocks during assembly. Additionally, tuning the air bubbles resonances over a range of frequencies may further widen the spectrum of actuation modes available, and afford more precise spatial control of the SA inside the chamber.

The demonstrated functionality of the system proves acoustic streaming valid to effectively drive MEMS microfluidic SA, which is relevant for the efficient bottom-up assembly of hybrid microdevices.

Aggregation and dispersion of sub-millimeter sized building blocks have been demonstrated. Evidence from literature supports the possibility of applying the technique for smaller (i.e. micron sized) particles, as well\,[93, 95]. Given the force exerted by and the
spatial range of influence of acoustic microstreaming, upscaling this technique to stir and drive millimeter sized components may require higher agitation amplitudes and a more sophisticated system design. Even though this may be technically possible, the greatest technical potential of this system is anticipated in the assistance of the SA of sub-millimeter to micron sized N/MEMS.
5.3 Sorting

As expected from section 3.2 and shown in the experimental results of section 5.2 yields of SA are below 100%. Therefore, the integration of a sorting device for separation of assembled, unassembled and overassembled components into the μFluiSA is essential.

Theoretical considerations and sorting unit have been submitted for publication in the following manuscript: Jonas Goldowsky et al. “Dielectrophoretic separation of meso-scale objects with highly non-uniform fields in microfluidic channels”. Submitted to Microelectronic Engineering (2013).

Sorting and separation are reoccurring challenges in microfluidics applications. Cell separation according to their phenotype is fundamental for biology and medical biotechnology[123]. Particle separation is a necessary preparation step in many biological microassays and common in microchemical processing[124]. Hence, a large variety of sorting and separation systems have been developed for various applications. A good overview is given by Kersaudy-Kerhoas, Dhariwal, and Desmulliez[124], where optical, magnetic, dielectrophoretic (electrical), fluidic-only (passive) and ultasonic standing wave (USW) separation techniques are discussed. In table 5.3 reported sorting strategies are summarized and rated with respect to the ability of volume and geometry dependent separation. Furthermore it is indicated if special particle treatments would be needed for handling SU-8 particles, whether the process is parallel and for which component sizes the method is applicable. All listed separation methods are applicable for volume dependent, parallel

<table>
<thead>
<tr>
<th>Separation Method</th>
<th>Volume Dependent</th>
<th>Parallel</th>
<th>Geometry Dependent</th>
<th>No Particle Treatment Needed</th>
<th>Applicable Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEP</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>nm~mm</td>
</tr>
<tr>
<td>Passive</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>nm~mm</td>
</tr>
<tr>
<td>USW</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>μm</td>
</tr>
<tr>
<td>Optical</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>nm~μm</td>
</tr>
<tr>
<td>Magnetic</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>nm~μm</td>
</tr>
</tbody>
</table>

Table 5.3 Comparison of different sorting strategies. Listed are the volume dependency, geometry dependency, whether no additional particle treatment is needed for SU-8 components and the applicable size of components to be sorted for strategies taken from Kersaudy-Kerhoas, Dhariwal, and Desmulliez[124].

sorting of micrometer sized components. Magnetic separation relies on magnetic properties of the entities to handle, which are not available by default for SU-8 components. To keep the generic characteristic of the μFluiSA approach, magnetic separation is neglected.
even though there are SU-8 composites available which have magnetic properties (SU-8 doped with magnetic nanoparticles)\cite{125}. Ultrasonic standing wave techniques are volume dependent. Optical separation techniques are bulky and a lot of equipment is needed for an optical sorting device. Additionally, submillimeter sized components require forces that are barely reachable with available optical traps. In fact, handling of such large components is only reported for passive and dielectrophoretic approaches.

Passive separation techniques can be designed for geometry dependent sorting. However, the design has to be adopted for each and every component configuration that should be sorted. Long design, prototyping and testing cycles have to be performed when new components are to be sorted by the device.

For dielectrophoretic (DEP) approaches, however, it has been shown that the manipulation of submillimeter sized components is possible\cite{126}. Additionally, the underlying physical effects are reported to be volume and geometry dependent\cite{127}. Furthermore, SU-8 can be handled by DEP systems without an alternation of material properties and the experimental setups are reasonably complex for dielectrophoretic systems. Therefore, a dielectrophoretic approach is investigated for the sorting of SU-8 MEMS components in the following.

5.3.1 Theory, design and fabrication

Theoretical background

The dielectrophoretic force is defined by Pohl \cite{128} to the generally accepted equation:

$$\vec{F}_{\text{DEP}} = (\vec{p}_{\text{eff}} \nabla) \vec{E}_0$$  \hspace{1cm} (5.11)

where $\vec{p}_{\text{eff}}$ is the effective dipole moment and $\vec{E}_0$ the external non-uniform electric field. The simplest derivation of the dielectric force is accomplished by summing the forces on two equal electric charges ($\pm q_c$) of opposite sign placed a vector distance $\vec{d}$ apart (dipole) in a non-uniform electric field\cite{129}, resulting in:

$$\vec{F}_{\text{DEP}} = q_c \vec{E}_0 (\vec{r} + \vec{d}) - q_c \vec{E}_0 (\vec{r})$$  \hspace{1cm} (5.12)

This can be reformulated under the assumption of much smaller distances ($\vec{d}$) than scales of field non-uniformity\cite{129} and by neglecting higher order terms of the taylor series approximation\cite{130} to the well known equation

$$F_{\text{DEP}} = 2\pi r^3 \varepsilon_m \Re [f_{\text{CM}}] \nabla E_0^2$$  \hspace{1cm} (5.13)
5.3. Sorting

where \( r \) is the particle radius, \( \varepsilon_m \) is the dielectric constant of the medium and \( \nabla E_0 \) the gradient of the applied electric field. The Clausius-Mossotti factor \( f_{CM} \), which is the polarization factor for spherical particles, is defined as

\[
p_{sph} = f_{CM} = \frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_p^* + 2\varepsilon_m^*}
\]

with \( \varepsilon_p^* \) and \( \varepsilon_m^* \) being the complex dielectric permittivities of particle and medium, respectively.

For particle sizes of concern and electrode designs generating a highly non-uniform electric field (such as planar, one sided electrodes), the assumption of much smaller effective dipole diameters than scales of field non-uniformity, makes the usage of equation (5.13) inaccurate. A solution can be found in multipolar dielectrophoretic force calculation as described by Washizu and Jones [131], which is non-trivial and results in long multidimensional expressions of the net force. That is why, it is proposed here to approximate the forces onto particles exceeding the scales of non-uniformity of applied electric fields by the introduction of two dimensionless factors, but still calculating only a force onto a dipole.

Firstly, the dipole induced onto particles, which diameters \( d \) are much smaller than the scales of non-uniformity of the applied electric field, will cover the whole particle, as charges are symmetrically distributed over the particle and it is \( d = 2r = d_e \), where \( d_e \) is the diameter of the effective dipole. However, if particle size exceeds scales of non-uniformity of the applied field, the symmetry point is shifted towards higher field strengths. Hence, the effective dipole diameter needs to be calculated accordingly.

Secondly, the derivation of equation (5.13) relies on the taylor series approximation \( \vec{E}(\vec{x}_0 + d_e) \) about \( \vec{x}_0 \) to calculate the field acting on the second charge of the dipole [130]. In subsequent derivation steps of equation (5.13) higher order terms of the taylor series approximation are neglected and by that a constant gradient with value \( \delta \vec{E}_0 / \delta \vec{x} \bigg|_{\vec{x}_0} \) (i.e. a linear regression of the \( E_0 \)-field) across the effective dipole is assumed. These inaccuracies when dealing with meso-scale particles in highly non-uniform electric fields need to be addressed when equation (5.13) should be applied for such systems. That is why the dimensionless factors \( k_d \) and \( k_{nl} \), named dipole matching factor and non-linearity factor, respectively, are introduced in the following.

For estimation of the two factors the electric field for a planar, one sided electrode is simulated and the results are exported. Subsequently, simulation results are loaded and evaluated with the statistical computation program R. The main goal is to estimate a function for the electric field in close proximity of an electrode, in the following form:

\[
E_0\left(x'\right) = a \left(x' + b\right)^c + d
\]
where $E_0 (x')$ is the electric field strength, $x'$ the axis of the dipole and $a, b, c$ and $d$ free variables for a non-linear best fit. By choosing the $x'$ axis as dipole axis, the multidimensional expression $\frac{\delta E_0}{\delta x} \bigg|_{x_0}$ reduces to a one dimensional gradient $\frac{dE_0 (x'_0)}{dx'} = E'_0 (x'_0)$. The dipole is aligned with the field gradient and therefore pointing towards the electrode. Simulation results are obtained along the dipole axis. Here the dipole is assumed to be located above the electrode edge. However, the field is very similar if the dipole is located in an angle towards the electrode edge, so that similar results are expected.

When the function of the field strength is known, the length of the dipole can be calculated by determining the intersection of $x'$-axis and the induced field on the particle, given by

$$E_1 (x') = -a (x' + b)^c + d_1, \quad (5.16)$$

where $a, b$ and $c$ are the constants estimated for equation (5.15) and $d_1$ is a constant given from the assumption of overall uncharged particles to be:

$$d_1 = \frac{a}{2r (1 + c)} \left[ (b + 2r + h_0)^{1+c} - (b + h_0)^{1+c} \right], \quad (5.17)$$

where $h_0$ is the distance between particle and electrode and $r$ the radius of the particle. The intersection point can then be calculated by

$$x'_i (r, h_0) = \left( \frac{d (r, h_0)}{a} \right)^{\frac{1}{c}} - b. \quad (5.18)$$

One of the dipole charges is assumed to be located at the surface of the particle (at the side of high field strength), leading to the dimensionless dipole matching factor in form of

$$k_d (r) = \frac{x'_i (r, h_0)}{r} \quad (5.19)$$

and the effective dipole length $d_e = 2r k_d (r)$. If the particle is small compared to non-linearities of the applied electric field the dipole matching factor assumes values close to one ($\lim_{r \to 0} k_d (r) = 1$). In opposite, when the particle is larger than the field non-linearities the factor is smaller than one ($\lim_{r \to \infty} k_d (r) = 0$). For details on the derivation of the dipole matching factor see also section C.

With knowledge of the matched dipole length one can estimate the field gradient over the effective dipole. As the function of the electric field on the $x'$-axis is known from simulations, the field gradient over the effective dipole can be calculated from the values of equation (5.15) at the specific point charge locations of the dipole ($x'_0 = h_0$ and $x'_1 = h_0 + d_e$, where $x'_0$ and $x'_1$ are the locations of first and second dipole charges, respectively). The
5.3. Sorting

difference of these two values is related to the field gradient taken for the conventional approach as $E'_0(h_0)$. Hence, the relation of the non-linearity factor $k_{nl}$ is expressed by:

$$k_{nl}(r) = \frac{E_0(x'_1) - E_0(x'_0)}{dE'_0(x'_0)} = \frac{E_0(2rk_d(r)) - E_0(h_0)}{2rk_dE'_0(h_0)}.$$

Figure 5.12 shows a plot of simulation results for the electric field as function of distance from the electrode edge (simulated with COMSOL Multiphysics). With these results the constants of equation (5.15) can be estimated to be $a = 4.529e^4$, $b = 3.246e^{-3}$ and $c = -5.905e^{-1}$ ($d$ was set to be zero). Even though a better fit can be obtained when $d$ is left as variable for fitting, the resulting curve would have negative values for distances larger 0.35 mm from the edge. Hence, $d$ is set to be zero, as the minimum field strength is zero for an infinite deep channel. The offset is accounted to the finite depth of the channel in the simulation.

![Simulation plot](image)

**Figure 5.12** Simulation results for the electric field of a specific planar electrode located at the channel bottom. Particle ($\approx 80 \mu m$ diameter, $h_0 = 10 \mu m$) including its charges (light gray) and resulting effective dipole (dark gray) are sketched.

It is assumed in the following that the gravitational force is holding the particles at the channel bottom, hence it applies: $h_0 = 0$. To estimate explicit values for the components of interest here, firstly the dipole matching has to be calculated. For 100$\mu$m and 200$\mu$m diameter spherical particles it results in $k_d=0.625$ and $k_d=0.583$, respectively. Subsequently the dimensionless non-linearity factor $k_{nl}$ can be calculated to be $k_{nl}=0.073$ and
Figure 5.13  Dipole matching and non-linearity factor as function of particle radius calculated from simulation data of the electronic field in close proximity of an electrode as defined in equation (5.20). Specific values for particles of $r=50 \, \mu m$ and $r=100 \, \mu m$ are $k_d=0.625$, $k_d=0.583$ and $k_{nl}=0.073$, $k_{nl}=0.042$, respectively.

$k_{nl}=0.042$, respectively. A plot of both factors as function of particle radius is illustrated in figure 5.13.

The well-known equation for the calculation of the dielectrophoretic force onto spherical small particles is extended with the dimensionless factors $k_d$ and $k_{nl}$ to make the estimation of forces on larger particles possible. The adopted equation is given as:

$$F_{DEP} = 2\pi k_d (r)^3 \varepsilon_m \Re \left\{ f_{CM} \right\} k_{nl} (r) \nabla E_0^2$$  \hspace{1cm} (5.21)

where the dimensionless dipole matching factor $k_d$ is correcting the shift of the dipole due to field non-uniformity across the particle and the dimensionless non-linearity factor $k_{nl}$ is accounting for the non-linearity of the field. $\nabla E_0^2$ here is the gradient of the electric field squared in direction of the dipole in close proximity of the electrode, as found for small particles ($\leq 5 \, \mu m$ radius).

By this equation (5.21) can be applied for the calculation of forces exerted onto meso-scale particles, as the subsequent derivation steps of equation (5.13) are also valid for equation (5.21), when calculated with the effective dipole diameter. It should be noted though, that advanced models of the polarization factor, such as the influence of the surface conductivity \footnote{132}, are not applied in a straight forward manner under these circumstances, as dipole diameter and particle diameter are unequal. Additionally, it should
be emphasized, that the given equation is rather an approximation of force values expected and not an exact solution for the force onto meso-scale particles in highly inhomogeneous electric fields. More precise results can be obtained when multipole models are taken into account, but this leads to long, multidimensional equations that have to be solved to determine dielectrophoretic forces under such conditions.

Especially for sorting applications the polarization factor (for spherical particles called Clausius-Mossotti factor) plays an important role. While the gradient of the electric field and the size of the particle are only affecting the magnitude, this factor influences magnitude and direction of the dielectrophoretic force acting on a particle. It is therefore the polarization factor that effects whether a particle experiences positive DEP (pDEP, the particles are attracted towards higher electric field gradients) or negative DEP (nDEP, the particles are pushed away from higher electric field gradients). Especially the point \( \Re [p] = 0 \) is of high interest, as here the transition between pDEP and nDEP is defined and no force is acting on the particle. This is advantageous for example in sorting applications when the system can be set to influence all but one specimen of multiple targets. The complex dielectric permittivity is defined as

\[
\epsilon^* = \epsilon - j \frac{\sigma}{\omega}, \tag{5.22}
\]

where \( \epsilon \) is the dielectric constant, \( j^2 = -1 \), \( \sigma \) the conductivity and \( \omega \) the angular frequency of the applied electric field. So that with equation (5.14), equation (5.22) and \( \Re [p] = 0 \) the so called crossover frequency (transition between pDEP and nDEP) can be calculated for spheres to:

\[
f_{\text{crossover}} = \frac{1}{2\pi} \sqrt{\frac{(\sigma_p - \sigma_m)(\sigma_p + 2\sigma_m)}{(\epsilon_m - \epsilon_p)(\epsilon_m + 2\epsilon_p)}} \tag{5.23}
\]

with the size dependent particle conductivity

\[
\sigma_p = \sigma_{\text{int}} + \frac{2K}{r} \tag{5.24}
\]

\( \sigma_{\text{int}} \) being the internal (bulk) conductivity, \( K \) the surface conductivity and \( r \) the particle radius. Hence, the crossover frequency depends on material properties of particle and medium and particle size, which is especially interesting in sorting applications. As pointed out earlier, inaccuracies are expected when equation (5.24) is applied for particles that are considerable larger than scales of field non-uniformity. Still it is tried here to estimate the general behavior of the particles by the size dependent particle conductivity where \( r \) is set to the full particle radius.

Table 5.4 shows an overview of material properties of interest for DEP applications for Polystyrene and SU-8, water and isopropanol (IPA) as particle and medium materials,
Chapter 5. Major µFluiSA Components

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity (\sigma) [S m(^{-1})]</th>
<th>Surface conductivity (K) [S]</th>
<th>Relative permittivity (\varepsilon_r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polystyrene</td>
<td>1.5e-13 (\text{[134]})</td>
<td>5e-9 (\text{[133]})</td>
<td>2.4</td>
</tr>
<tr>
<td>SU-8</td>
<td>3.33e-5 (\text{[135]})</td>
<td>-</td>
<td>4 (\text{[136]})</td>
</tr>
<tr>
<td>Tap water</td>
<td>(\sim 1e-3)</td>
<td>-</td>
<td>80 (\text{[43]})</td>
</tr>
<tr>
<td>DI water</td>
<td>1e-6 (\text{[43]})</td>
<td>-</td>
<td>80 (\text{[43]})</td>
</tr>
<tr>
<td>Isopropanol (IPA)</td>
<td>6e-6 (\text{[137]})</td>
<td>-</td>
<td>18.6 (\text{[137]})</td>
</tr>
</tbody>
</table>

Table 5.4 Material properties of interest for DEP applications.

respectively. Permittivities of water and isopropanol lead to the fact that for polymers – such as Polystyrene and SU-8 – the denominator of the crossover frequency equation (5.23) gets positive and the equation is only solvable for \(\sigma_p > \sigma_m\). For all other cases \((\sigma_p < \sigma_m)\) no crossover frequency can be found, meaning that either pDEP or nDEP is resulting for all frequencies of the applied electric field. Micrometer sized polystyrene particles can be separated utilizing crossover frequencies \(\text{[138]}\) in many mediums only, because the surface conductivity has essential influence on the overall conductivity of the particles. For a particle diameter of 10 µm the conductivity is increased to \(\sigma_p \approx 1e-3\) S m\(^{-1}\), giving rise to the fact that for mediums like IPA and deionized water a crossover frequency can be found. Increasing particle dimensions lead to decreasing influence of the surface on the overall conductivity. Hence, the larger the particle, the more likely no crossover frequency is defined.

In figure 5.14 a 3D-plot of the polarization factor for spherical polystyrene particles in deionized water as a function of particle radius and frequency of the applied field is given. One can see that for increasing frequency and particle size the polarization factor is moving towards is lower boundary value \(f_{CM} = -0.5\), thus nDEP acts on such particles. Its higher boundary \((f_{CM} = 1)\) is reached for small particles and low electric field frequencies, leading to pDEP effects acting on the particle. Further it can be concluded that for large particles (100 µm) the crossover frequency is in kHz range. While deionized water has a conductivity for which a valid crossover frequency can be found, higher conductivities of other fluids, such as drinking water and commonly used buffers, lead to the fact that no crossover frequency can be found for such large components. For illustration of this context, figure 5.15 shows curves for polarization factors of 100 µm sized spherical Polystyrene particles suspended in deionized and drinking water as a function of frequency of the applied electric field. Particles of this size are experiencing nDEP forces for all applied frequencies of the electric field when suspended in tap water.

Besides these well known models for spherical particles, investigations of the behavior of rod-like particles (cells) in dielectrophoretical applications have been made by various
5.3. Sorting

Figure 5.14 3D plot of polarization (Clausius-Mossotti) factor as a function of frequency and particle radius for polystyrene spheres suspended in deionized water (material properties from table 5.4).

Figure 5.15 Polarization factor as function of frequency for polystyrene spheres (for material properties see table 5.4) with a radius of $r=50\mu m$ in DI and tap water.

authors. Cylindrical (rod-like) models were first reported by Pohl, Pollock, and Crane
and calculated by Morgan and Green \[139\] to:

$$F_{\text{DEP,cyl}} = \frac{1}{3} \pi r^2 L \epsilon_m \Re \left[ \frac{\epsilon_p^* - \epsilon_m^*}{\epsilon_m^*} \right] \nabla E_0^2$$  \hspace{1cm} (5.25)

hence the polarization factor is defined by:

$$p_{\text{cyl}} = \frac{\epsilon_p^* - \epsilon_m^*}{\epsilon_m^*} \hspace{1cm} (5.26)$$

A main difference to spherical particles can be found in the boundary values of the corresponding polarization factors. While the Clausius-Mossotti factor stays between 1 and -0.5 for all complex dielectric permittivities, there is no upper boundary for equation (5.26). For small particles and low frequencies of the applied electric field a very high polarization factor can be achieved theoretically (for more detailed information refer to Morgan and Green \[139\]).

For meso-scaled SU-8 cylinders in mediums of interest here, the crossover frequency can be calculated to be below 1 kHz and differences between two cylinders of equal radius but different length are marginal. Meaning that for sorting applications of such entities the crossover frequency is barely allocatable as separation criterion. To avoid electrolysis at the electrodes for high voltages required to penetrate particles in the 300 $\mu$m thick channel at reasonable flow rates, frequencies above 10 kHz are needed. As the main focus lies on the separation of cylinders, the frequency of the applied electric field is shifted to a region (100 kHz) where also preliminary tests performed with Polystyrene beads are in nDEP region. Giving rise to that a) only negative DEP is expected for meso-scaled SU-8 cylinders and PS beads and b) the difference between cylindrical and spherical component models vanishes as the lower boundary value of both polarization factors is -0.5 and -1. That is why, for ease of calculation and clarity, from here on only spherical particle models are taken into account for further discussion. Even though there are differences in the exact solutions, further considerations for the design are based on calculations made for spherical components.

**Device design considerations**

While increasing particle dimensions lead to barely allocatable differences in crossover frequencies, gravitational effects get relevant for particles in the targeted size. A dielectrophoretic sorting system utilizing gravitational effects has been built by Wang et al. \[140\], based on Field Flow Fractionation (FFF) technologies. Giddings \[141\] introduced Field Flow Fractionation as “[..] a family of separation techniques that use fields or gradients that can interact with solute macromolecules to force them differentially into the
slow streamlines of a flowing fluid\footnote{142}. The principle is based on fields that are oriented perpendicular to the corresponding liquid flows, which can be of any origin (gravitational, electric, magnetic, etc.). Examples for FFF systems can be found in applications of particle washing\cite{54}, cell\cite{143} and particle\cite{140} separation, deploying ultrasonic standing wave (USW)\cite{54}, dielectrophoretic\cite{143} or combined gravitational/dielectrophoretic\cite{140} force fields.

Wang et al.\cite{140} separated polystyrene beads of similar diameter \((10.57 \pm 1.03 \, \mu m \) to \(9.44 \pm 0.95 \, \mu m\)\) due to variations of the force equilibrium heights of different particles within the microfluidic channel. Depending on the dielectrophoretic properties of polystyrene beads the balance between gravitational and dielectrophoretic forces acting on the particles can be found at different distances to the electrodes. As the flow velocity is decreasing towards the channel walls, this distance to the electrode leads to a difference in particle velocity, by which the particles can be separated. For this method, particles have to enter the channel simultaneously, which is incompatible with the requirement for continuous, parallel sorting of MEMS defined here. It is, however, showed that differences in gravitational effects and the relocation of the handled entities within the fluid flows of the channel enable the sorting of geometrically very similar entities.

Here a system combining gravitational effects and classical dielectrophoretic approaches is introduced, avoiding the need for synchronous entry of particles into the sorting device. By this sorting gets available in continuous manner. The system is based on so-called deflector structures\cite{138}, electrodes that deflect the particles crossing the channel selectively. A sketch of the working principle is given in figure 5.16. The deflector electrodes are crossing the channel in a defined angle \(\beta\). Dielectrophoretic effects create a force perpendicular to the electrode, which combined with a resulting drag force create an overall force directed along the electrode.

To explain the principle of particle differentiation envisioned here in more detail, the force equilibrium of a particle in proximity of an electrode should be discussed. Referring to figure 5.17 the force equilibrium is the point in which the particle is stopped in front of the electrode – nDEP is assumed for the applicable frequencies – and just not lifted by the vertical portion of the DEP force. In figure 5.17 a negative DEP force is illustrated, so that opposite signs are taken for calculations. Hence, it is:

\[
\begin{align*}
F_x &= F_{Dx} + F_{DEP} \cos \alpha = 0 \\
F_z &= F_G + F_{DEP} \sin \alpha = 0
\end{align*}
\]  

(5.27a)  

(5.27b)

Leading to four cases:
Chapter 5. Major µFluiSA Components

Figure 5.16 Explanation of the DEP deflection structure. A particle approaching the deflection barrier defined by the electrode with a certain angle $\beta$ experiences a dielectrophoretic force (here nDEP) directed perpendicular to the electrode. Combined with a resulting drag force the particle is pushed along the electrode. In the background an image of a manufactured (laser ablated) electrode is given.

1. $(F_{DEP_x} \geq F_{Dx}) \land (F_{DEP_z} < F_G)$: The particle is deflected in front of the electrode, staying on the bottom of the channel (gliding along the electrode).

2. $(F_{DEP_x} < F_{Dx}) \land (F_{DEP_z} > F_G)$: The particle is pushed across the electrode and is levitated.

3. $(F_{DEP_x} \geq F_{Dx}) \land (F_{DEP_z} > F_G)$: The particle is levitated into the channel, where dielectrophoretic forces are decreased and drag force is increased. Hence, the particle is pushed across the electrode with increased velocity.

4. $(F_{DEP_x} < F_{Dx}) \land (F_{DEP_z} < F_G)$: The particle is pushed across the electrode, staying at the bottom of the channel.

Full deflection can be found for case 1., which is desired for one of the entities to be separated, here the bigger entities. While one species has to be deflected with this first case, for the other species one of the cases 2. to 4. must apply. While for 2. and 4. only the magnitude of the dielectrophoretic force can be utilized to reach this selective deflection, 3. implies selectivity based on gravitation. It should be noted, that in fact sorting is possible in all three cases as forces on the $200\,\mu m$ spheres are expected to be approximately 4 times stronger than on $100\,\mu m$ spheres (calculated with equation (5.21), with equation (5.13) this factor would be 8). However, when exploiting additional gravitational differences of the particles by increasing the flow velocity to a point where the smaller particles can be levitated across the electrode (above their levitation velocity), separation can be enhanced. The transition point between 2. and 3. is found by solving both equations for $F_{DEP}$ and
5.3. Sorting

Combining them to the relation

\begin{align}
F_D &= F_G \frac{1}{\tan(\alpha)} \\
F_D &= 6\pi \rho \mu v \\
F_G &= V \Delta \rho g, \text{ with } \Delta \rho = \rho_p - \rho_m
\end{align}

where \( V \) is the volume of the particle, \( \rho_p \) and \( \rho_m \) densities of particle and medium, respectively. From equation (5.28) the levitation velocity can be calculated for spherical particles to

\[ v_{\text{lev}} = \frac{2 \pi^2 \Delta \rho g}{9 \mu} \frac{1}{\tan(\alpha)}. \]

The levitation velocity \( v_{\text{lev}} \) only depends on the angle \( \alpha \) and not on the absolute value of \( F_{\text{DEP}} \). Assuming a sufficient magnitude of the dielectrophoretic force to hold back the particle up to the levitation velocity it follows for \( v < v_{\text{lev}} \) that:

**Figure 5.17** DEP force balance in gravitational plane. Particles with diameter \( d=100 \, \mu m \) and \( d=200 \, \mu m \) are displayed. The background color are representing field gradients (\( \Delta E^2 \)) between 0 (blue) and \( 1e^{16} \) (red), resulting from a simulation of a planar electrode with 164 V applied and water as medium. nDEP pushes the particle away from strong field gradients, resulting in a levitation force caused by DEP. Gravitational (\( F_G \)), buoyancy (\( F_B \)) and a fraction of the dielectric force (\( F_{\text{DEPz}} \)) are acting in z-direction, while drag (\( F_{\text{Dx}} \)) and another fraction of the dielectrophoretic force (\( F_{\text{DEPx}} \)) are acting in x-direction.
• forces in x direction are balanced by variations of the distance to the high gradients of the electric field at the electrode edge,

• ramping up the flow velocity leads to an approximation of the equilibrium point towards the electrode edge (in x direction, towards high field gradients) and therefore increase of the dielectrophoretic force,

• differences of forces in z direction may be compensated by an additional force exerted by the channel wall onto the particle (when the particle touches the bottom wall) but no levitation takes place \( F_G \geq F_{DEP} \sin(\alpha) \),

• once the flow velocity goes beyond the levitation velocity the force equilibrium cannot be maintained, leading to an acceleration in positive z-direction (levitation).

It should be emphasized that the levitation velocity \( v_{lev} \) depends on the square of the particle radius, which gives a reasonable separation criterion. This separation criterion is independent from the absolute value of the dielectrophoretic force, as long as the force is sufficient to hold the particles for velocities larger than the levitation velocity.

**Design of sorting device and peripherals**

Table 5.5 shows a summary of system designs from literature. Those systems are used for the handling of micron-sized objects (max. 15.5 µm) and need to be upscaled for the handling of sub-millimeter sized components. It has to be ensured that components of 200 µm diameter do not clog the channel of the device, hence the channel height is chosen to be 300 µm. The electric field and the factor \( \nabla E_0^2 \) of equation (5.21) extend further above the electrodes with increasing inter-electrode distances\[143\]. Therefore, in reference to the design given by Auerswald and Knapp \[144\], an inter-electrode distance of 300 µm is adopted. As electric field strength is a function of electrode distance and applied voltage the increased inter-electrode distance has to be compensated by higher voltages in order to create sufficient field gradients, which can be calculated by equation (5.21) including the dimensionless factors, to \( \nabla E_0^2 \approx 2.62e^{15} \ V^2 \ m^{-3} \) for 200 µm PS beads in IPA for anticipated flow rates (\( \sim v_{lev} \) of 100 µm beads). Cascaded sorting electrodes are designed to increase chances of successful separation. For separation devices based on deflector structures, it is essential to focus all particles in a defined position within the channel before the selective separation of the targeted entities can be executed. As visible in figure 5.16, a second electrode is placed in front the sorting electrode focusing all particles. Alternatively the channel is designed such that a sheath flow can be utilized to focus the particles within the channel. Figure 5.18 shows a top view of the partially assembled system. Inlets for
5.3. Sorting

<table>
<thead>
<tr>
<th>Source</th>
<th>Inter-electrode distance [µm]</th>
<th>Channel height [µm]</th>
<th>Max. applied voltage [V]</th>
<th>Max. species size [µm]</th>
<th>Medium conductivity [mS m⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green and Morgan [145]</td>
<td>4</td>
<td>-</td>
<td>20</td>
<td>0.216</td>
<td>15</td>
</tr>
<tr>
<td>Auerswald and Knapp [144]</td>
<td>10</td>
<td>30</td>
<td>20</td>
<td>6</td>
<td>0.06-100</td>
</tr>
<tr>
<td>Markx, Rousselet, and Pethig [143]</td>
<td>10-40</td>
<td>200</td>
<td>5</td>
<td>8</td>
<td>0.5-2000</td>
</tr>
<tr>
<td>Wang et al. [140]</td>
<td>50</td>
<td>400</td>
<td>1</td>
<td>15.5</td>
<td>2.2-10</td>
</tr>
</tbody>
</table>

Table 5.5  DEP electrode design (inter-electrode distance) and applied voltages from literature for design reference.

Particle carrying liquid and sheath flow are located on the right side and the separation outlets, namely deflected and non-deflected outlet, are located on the left.

![Diagram of sorting device](image)

Figure 5.18  Partially assembled sorting device composed of copper clad board (bottom), NBR gasket and PC cover. Sheath and particle inlet are located on the right, deflected and non-deflected outlets on the left. Focusing electrode is in direction of the flow located in front of the separation electrode, which is cascaded to enhance separation.

The flow is provided by two peristaltic pumps (Ismatec Reglo Digital MS-4/12) which are used to regulate the flow precisely. While voltages for common microelectrode designs can be supplied directly from frequency generators, the upscaling of the system gives rise to the need for amplification of the signal for the electrodes. As cross-over frequencies for mesoscale particles are low and foreseen frequencies of the electric field are in range of 10 kHz to 100 kHz, standard audio components can be used for the amplification of the needed signals. Here a custom designed amplifier is used. For more information refer to section [D].
Fabrication

For fabrication of the electrode, a copper clad board (KELAN - 149054) is milled to its outer contours. Subsequently, the board is aligned on the pico-second laser where the electrode contours are structured (refer also to section 4.1.1). To avoid leakage of the system, cavities created during electrode structuring are then filled with cyanacrylat (UHU Sekundenkleber) and cured over night for 12 h at 65° at high relative humidity. Afterwards, polishing of the substrate removes residual adhesive from the electrodes and generates a smooth surface for sealing. By that it can be guaranteed that no additional offset between electrode and particle is created by residual adhesive.

A gasket defining the contours of the channel is fabricated from 1 mm thick NBR by laser structuring (refer to section 4.1.1). The PC cover of the channel is fabricated by micromilling. It includes a 0.6 mm deep cavity fitting the outline of the NBR gasket to support form stability of the channel. Supporting structures such as base plate and clamp of the device are micromilled from PMMA. Finally, all fabricated parts are assembled to the final device.

5.3.2 Results and Discussion

As described above, focusing of all particles within the sorting channel is essential for successful sorting with deflector based dielectrophoretic systems. Hence, as a first step in the experimental verification of the fabricated design, a robust focusing methodology has to be set up, capable of focusing all particles for the required flow velocities. Once the focusing is found to be robust, the applied voltage of the separation electrode can be tuned to create a field – and by that a field gradient – sufficient to hold back larger particles which are not levitated. This procedure is carried out for Polystyrene beads of 100 µm and 200 µm radius as well as SU-8 cylinders of 100 µm radius and 100 µm and 200 µm length in IPA. The reason for using IPA instead of water is that SU-8 building blocks stored in water self-assemble into big clusters over time. Once bound in such big clusters (tens or hundreds of particles) they cannot be loaded into the microchannels of our system. Storing the particles in IPA suppresses the spontaneous self-assembly of the building blocks.

The proposed principle of sorting is based on levitation of smaller components, reducing the field gradients levitated particles are experiencing. Thus a certain flow velocity \(v_{\text{lev}}\) has to be reached in order to overcome gravitational effects (see equation \(5.29\) and explanation thereby) for the smaller particle. It is found that for these velocities the dielectrophoretic forces are insufficient for deflection of all particles within the stream. While levitation is
beneficial for the separation of the different entities it is counterproductive for focusing procedures. Field gradients high enough to deflect all particles would have to be created across the full height of the sorting channel in order to utilize dielectrophoretic forces for the focusing within the proposed device. This has not been possible with applied voltages of up to 300 \text{ V}_{\text{pp}}. As a second approach for focusing, a sheath flow can be created within the channel. The location of the particles within the channel is then dependent on the fraction of the flow carrying the particles and the superposed sheath flow. Here, a sheath flow double the particle carrying flow is applied to focus the particles in the lower third of the channel. By this approach a robust focusing of both, PS beads and SU-8 cylinders can be established.

To find parameters for separation of entities in question, the sorting device is supplied with a constant stream of particles with flow rates slightly above the values estimated for the levitation velocity of the smaller components with equation (5.29). With a guess from figure 5.17 for $\alpha \approx 30^\circ$ one can calculate a levitation flow rate for 100 \text{ m}_{\text{m}} sized Polystyrene beads suspended in IPA to be approximately 144 \text{ ml min}^{-1}. Here a flowrate of 180 \text{ ml min}^{-1} is set. Subsequently the voltage applied at the separation electrode is ramped up, until the 100 \text{ m}_{\text{m}} sized particles are levitated and the 200 \text{ m}_{\text{m}} are deflected at the edge of the electrode. For polystyrene beads of 100 \text{ m}_{\text{m}} and 200 \text{ m}_{\text{m}} this point is found at a applied AC voltage (100 kHz) of 184 \text{ V}_{\text{pp}}. Figure 5.19 shows the resulting locations for the differently sized beads. From video footage it gets clear, that the levitated beads get accelerated above the electrode – due to the higher flow velocity in the center of the chamber – and decelerate once they leave the area of influence of the electrode (as found for FFF approaches). The larger beads, even though experiencing a higher drag force when being slowed down by the dielectrophoretic force, do not accelerate when approaching the electrode. From this one can conclude that the theory of gravity amplified separation of mesoscale objects is valid for 100 \text{ m}_{\text{m}} and 200 \text{ m}_{\text{m}} polystyrene beads in IPA.

Further, one can conclude, that the dielectrophoretic force exerted on the particles by an inhomogeneous field created by the electrodes here, is much smaller then calculations with equation (5.13) impose. In fact, when doing the math for the deflection electrode at 184 \text{ V}_{\text{pp}}, the conventional approach yields in a required field gradient for levitation of the smaller particles which is given up to $\sim 100 \text{ m}_{\text{m}}$ distance from the electrode (according to simulation results). In opposite, the matched equation equation (5.21) is yielding in required field gradients that are created by the electrode in distances of approximately 25 \text{ m}_{\text{m}}. For estimation of the levitation height of 100 \text{ m}_{\text{m}}-sized particles the velocity of a particle is estimated from video footage recorded at 10 frames per second and found to be

\[ \text{Video (5) can be requested from the author (gokyjo@gmail.com)} \]
Figure 5.19  Separation of Polystyrene beads in IPA at a mass flow of $q=180 \, \mu l \, min^{-1}$, whereof 60 $\mu l \, min^{-1}$ particle carrying liquid and 120 $\mu l \, min^{-1}$ sheath flow have been applied. At the electrode an AC signal of 100 kHz and 184 $V_{pp}$ is applied. Flow is from right to left. Video footage is available.

maximal $\sim 3.75 \, mm \, min^{-1}$, above the electrodes. By calculating the mean velocity across the particle for a Plane Poiseuille flow\[146\] by

$$u_{mean} = \frac{1}{2r} \int_{h_0}^{2r+h_0} u(z) \, dz,$$

where $h$ is the channel height and axis $z$ is perpendicular to the flow direction (see also figure \[5.17\]). From this the levitation height can be estimated to be $h_{lev} \approx 27 \, \mu m$, confirming the required field gradients estimated by the extended equation equation \(5.21\).

Additionally, field gradients required for the deflection of 200 $\mu m$ beads are assessed to be sufficient throughout the full channel height by equation \(5.13\). However, video footage shows that occasionally also such particles are levitated into the channel, with increased speeds and without being deflected. Thus, deflection forces must be smaller than estimated by the conventional approach. It can be concluded that the inaccuracies arising from particle sizes exceeding the scales of non-uniformity of the applied electric field can be compensated by the introduced dimensionless factors and that valid predictions for the forces can be made by the extended equation.

Analogous to the experimental procedure with Polystyrene beads, experiments with SU-8 cylinders are conducted. The estimation of the levitation velocity for cylindrical objects is advanced as the derivation of the Stokes drag for cylinders itself is non-trivial and the exact orientation of the cylinders in the fluid has to be taken into account. Hence
the levitation velocity has been estimated experimentally for cylindrical SU-8 objects. The ratio of particle carrying to sheath flow is held at the ratio 1:2, for all experiments conducted. Starting from the values estimated for Polystyrene beads, values for the overall flow have been increased until levitation of the smaller SU-8 cylinders could be observed. Subsequently the applied voltage at the electrodes has been tuned to the state of best separation of the two entities. This state is found for an overall flow velocity of $255 \mu l \ min^{-1}$ and an applied voltage of $164 \ V_{pp}$.

For this operational state of the separation device, the $100 \ \mu m$ long cylinders are tumbling across the electrodes while the $200 \ \mu m$ long cylinders are oriented perpendicular to the electrode and follow the electrode edge towards the outer region of the channel. Whereas aside the electrodes cylinders are oriented perpendicular to the flow, rolling around their longitudinal axis through the channel. This rolling behavior is more stable for the longer cylinders. As expected the smaller cylinders are accelerated while crossing the electrode, confirming the levitation theory. Evidence of the system behavior can be found in video footage. A snapshot is shown in figure 5.20.

![Figure 5.20](separator.png)  

**Figure 5.20** Separation of SU-8 cylinders in IPA at a mass flow of $q=255 \mu l \ min^{-1}$, whereof $85 \mu l \ min^{-1}$ particle carrying liquid and $170 \mu l \ min^{-1}$ sheath flow have been applied. At the electrode an AC signal of 100 kHz and $164 \ V_{pp}$ is applied. Flow is from right to left. Video footage is available.

Occasionally random clusters of two or more cylinders are crossing the electrodes. Even though of higher absolute volume these clusters are not deflected by the electrodes. Due to

† Video (6) can be requested from the author (gokyjo@gmail.com)
their outlines such clusters tumble through the channel and the high electric field gradients at the electrode edge are ineffective for such tumbling motion. When two small cylinders are aligned along their rotational axis \( (C_1) \) they can be observed rolling along the electrodes and are deflected. Two aligned 200\( \mu \)m cylinders could not be observed in the experiments conducted.

An analysis of the yield evaluated from videos taken of long run experiments in the distinct modes described above is given in figure 5.21. For both types of entities occasionally smaller particles are deflected by the separation electrode (\( \approx 7\% \)). While for PS beads it seems that the erroneous deflection is due to contact to neighboring particles (e.g. a large particle is deflected and carries a small particle attached), small SU-8 cylinders are deflected even when no contact can be observed to other components. Additionally, no large bead is observed that has not been deflected, but \( \approx 10\% \) of large SU-8 cylinders are crossing the separation electrode while being insufficiently deflected. An explanation for decreased yields of SU-8 cylinder separation experiments compared to PS bead experiments can be found a) in smaller differences of mass of the cylinders (factor 2 instead of factor 8 for beads) and b) in the drag force exerted onto cylindrical objects, which is highly dependent on the cylinder orientation within the flow. Cylinders that are traveling perpendicular to, and along electrode, are occasionally rotated perpendicular to the channel flow. This is accounted to irregularities in the field gradients and pulsations in the channel flow, created by the peristaltic pump.

5.3.3 Conclusions and outlook

A sorting device based on dielectrophoretic, hydrodynamic and gravitational effects for the separation of meso scale uncharged particles in bulk liquids has been developed. For the correct prediction of field gradients needed in order to deflect particles of interest, the conventional equation for the calculation of the dielectrophoretic force has been extended by the dimensionless dipole matching factor \( k_d \) and the non-linearity factor \( k_{nl} \), compensating errors due to highly non-uniform electric fields created by planar, one sided electrodes and large particle sizes. A key parameter for proper separation is defined by the levitation velocity \( v_{lev} \) which has been proven to give valid predictions for spherical and guidelines for cylindrical particles.

The experimentally obtained results are in good agreement with predictions made by the extended equation. Even though based on simulations of the specific electrode used here, it can be supposed that the dimensionless factors are valid for similar electrode designs and large particles.
Yields of separation of meso-scale particles (here PS beads and SU-8 cylinders) can be described as good but not error-free ($\approx 90\%$). It is supposed that these results can be improved by a systematic redesign of the separation unit to values close to 100%. For instance a higher number of cascaded separation electrodes and a confined deflected outlet of the device can be advantageous.

While for beads and cylinders levitation based sorting is directly applicable as those entities are rolling at the bottom of the channel aside the electrodes, the separation of arbitrary shaped objects might bear additional challenges. The tumbling motion of such particles makes the prediction of drag force and dielectrophoretic force difficult. However, if horizontal positioning is controlled (e.g. with a 3D-sheath flow$^{[147]}$) levitation based separation can be a valid possibility for sorting of such objects.

The device has proven to enable the parallel sorting of targeted cylindrical objects in configurations $C_1$ from not assembled single objects. Additionally random clusters of cylinders are not deflected by the electrodes and are therefore separated from $C_1$ configurations. Cylinders in $C_2$ and $C_3$ configurations could not be observed in the experiments conducted here. It is assumed that the binding forces of the SU-8 particles in Isopropanol
in such configurations are small and connections are destroyed when the particles are floated through the system setup.
Chapter 6

Concept for a µFluiSA

In the previous section the major components of the µFluiSA system have been introduced. Experimentally it has been shown for all subunits that their functionality can assist the self-assembly processes of the MEMS components of question. In the following the integration of these subunits to the µFluiSA is discussed. For this discussion, the first concept of the system given in figure 3.4 is extended in figure 6.1, accounting for the experimental results described in the corresponding sections of the subunits. Following the path of the cylinders during the assembly process, the schematic design concept can be summarized by the following:

**Supply**  The supply liquid is pumped with flow rate $q_3$ into closed volume MEMS storage reservoir, in which the MEMS building blocks are located at the bottom. By activating the test tube shaker (see section 4.1), building blocks are homogeneously distributed within the reservoir and are dragged with the supply liquid into the tubings of the system, towards the preparation unit.

**Preparation**  As found in the experimental section of this unit, good transfer conditions are achieved when $q_1 = q_2 = q_3 \approx q_4$, yielding in a collector liquid height $h_c = 1/4h$ approximately equivalent to the designed channel heights of the unit. However, it is also found that $q_4$ can be tuned to influence the particle concentration per fluid volume, as long as the flow is sufficient to drag the particles towards the target outlet of the preparation unit. By the usage of different channel wall materials, such as glass, problems due to sticking and thereby flow rates $q_4$ can be decreased further to enable a greater increase in particle concentration. Closed volume reservoirs (dampers) are introduced before the preparation unit to level out the pulsations created by the peristaltic pumps. Fractions of SU-8 from destroyed building-blocks are separated from the building blocks.
Concept for a complete µFluiSA system. The thick tubings represent the MEMS building block path through the system (from storage to assembled MEMS).

in the preparation unit, when they have smaller mass than the building blocks of question. These particles are transferred to a waste reservoir. The supply fluid loop is here not closed, due to the intentional contamination of the supply liquid by functional liquid. Thus, the contaminated supply liquid is channeled into a waste reservoir. The building blocks are from hereon handled in the functional liquid loop of the system.
A difference between stand-alone preparation unit and integrated version can be found in the positioning of the needle valve. While the valve has been placed behind the target outlet for the stand-alone experiments (see figure 5.4), it is now placed on the residual outlet of the device. There are two main reasons for this adaption, (a) the valve cannot be placed in a stream containing particles, as it would be clogged and (b) the overall hydraulic resistance of the system following on the target outlet is leading to a counter pressure which has to be matched at the residual outlet of the preparation unit.

**Assembly** Leaving the preparation unit, the MEMS building blocks are transferred to the assembly stage. Processes of the assembly unit are semi-parallel as building blocks have to be loaded into the chamber, which is subsequently closed for agitation. In agitation phase all integrated PDMS valves are closed and no flow can pass through the chamber. Hence, the parallel characteristics of preparation and sorting unit can be only fully exploited when at least three assembly chambers are present in the system. In figure 6.2 a timetable for the configuration of valves ($V_{1-6}$) and agitation states ($A_{1-3}$) are given. Essential for the parallel handling of the building blocks is that at all times particles can be transferred into one of the assembly chambers. Additionally the cycle for each assembly unit has to be kept, i.e. loading ($V_1, V_3$ or $V_5$ opened), assembly ($A_1, A_2$ or $A_3$ active) and unloading ($V_2, V_4$ or $V_6$ opened) has to be executed in this sequence. This can only be fulfilled when at least three assembly units are present in a µFluiSA.

An advantage following from this sequential clustering of the three assembly units is given by the decoupling of the flow rates leaving the preparation unit ($\approx q_1$) and the flow rate...
Chapter 6. Concept for a µFluiSA

$q_5$, which is dragging the mixture of assembled and not assembled building blocks towards the sorting unit. This decoupling is advantageous as preparation and sorting units can be supplied with flow rates most suitable for their individual functionality.

**Sorting** As the flow velocity in the sorting device is a main process criterion, $q_5$ has to be (and can be, due to the decoupling) adopted to exceed the levitation velocity $v_{lev}$ of individual building blocks but not of assembled $(C_1)$ configurations. The particle inflow of the sorting device can therefore be set exactly to the values found optimal for the separation of SU-8 cylinders ($q_5 = 85 \, \mu l \, min^{-1}$). By that fully assembled MEMS can be separated from single building blocks. Additionally, due to the tumbling motion of random clusters of components, such clusters can be separated from $C_1$ configurations.

Sorting yields of about 80% are found in the experimental section of the sorting unit. If these yields should be increased a well-directed redesign of the sorting unit has to be made, as described in section 5.3.

**Post processing** Correctly assembled MEMS are transferred into a closed volume reservoir for later usage. Single components and clusters are also transferred into a closed volume reservoir and can be resuspended into the MEMS storage container manually. Depending on the amount of not and badly assembled components an automatic solution can be advantageous. Such solution seems possible with an additional preparation unit for resuspension of the MEMS from functional into supply liquid.

The subunits of the system are designed such that a complete system can be built out of the “construction kit” consisting of the three major units, plus supply and post processing units. Images of the designs are given in figure 6.3. By that the needed tools are given to automate a µFluiSA, guiding MEMS building blocks from their release into their assembled state.

The ultimate implementation of this system is left for further work. A major problem faced during the experimental sections of this thesis can be found in the weak binding between the components after assembly, as described in the experimental part of section 5.2. Unfortunately, the selective, strong binding anticipated for the MEMS building blocks designed in the SelfSys project, was not achieved during the time of this thesis. This is leading to the fact, that the formed $C_1$ configurations are being destroyed when flushed out of the reaction chamber, and hence no real assembled components are available for testing of the subsequent units. Even though the proof of principle is given for all subunits of the µFluiSA and a concept has been discussed the final automation of an complete system is only meaningful once sufficient binding forces have been created between the components.
Figure 6.3  Images of the modular designed µFluiSA subunits.
Chapter 6. Concept for a µFluiSA
In this thesis fluidic systems and methods for the assistance of fluidic mediated self-assembly of hybrid MEMS are elaborated. The main focus lies on three major processing units, namely preparation, assembly and sorting, whose availability clears the way for a complete microfluidic system assisting hybrid MEMS self-assembly (µFluiSA). Additionally, capable supply and post-processing strategies are introduced enabling the further automation of MEMS self-assembly processes. The functionality of all subunits is evaluated with a basic MEMS component design of cylinders fabricated from SU-8.

The preparation unit is based on the gravitational sedimentation of particles in question, driving the transfer of particles from supply into receiving liquid. This transfer is shown not only for aqueous to aqueous solutions, but also for Isopropanol to aqueous solution, which is beneficial for the preparation of hydrophobic MEMS building blocks, as spontaneous uncontrolled self-assembly during storage is suppressed in apolar liquids. Using design references from split-thin fractionation devices the unit allows not only the transfer (washing) of particles, but is also capable of separation of various entities. For the preparation of MEMS components this is advantageous as dust particles and fragments of destroyed MEMS building blocks can be removed from the system, enhancing the yield of self-assembly. With proper configuration of the corresponding flows within the preparation unit, transfer yields of 100% could be achieved. To the authors knowledge for the first time, a continuous particle and cell washing is enabled by a gravity driven device which needs no additional control besides the flow rates through the system.

For the assistance of the self-assembly process itself, a unit is designed to introduce random energy in a controlled manner into the system, enabling the propagation of the individual building blocks towards envisioned hybrid MEMS components. Random energy is provided from a piezoelectric transducer and is translated into strong mixing fluid flows by exploiting bubble-induced acoustic microstreaming. By that, a couple of robust driving modes could
be determined, from which the two most important enable a) the controlled clustering
and therefore assembly of MEMS and b) the dispersion and disassembly of MEMS in the
strong vortexes created in close proximity of the oscillating bubbles. Assembly yields of
≈ 50% could be achieved with the basic cylindrical MEMS design used for the evaluation
of the chamber. It is supposed here, that these values can be increased with a more
specific shape of the components and additional surface functionalizations, boosting the
hydrophobicity of targeted assembly surfaces. Utilizing bubble induced microstreaming
to drive self-assembly of the MEMS components enables the continuous redistribution of
microcomponents within the formed multicomponent aggregates, supporting the formation
of desired two-component assembly configurations. This is a major advantage of the
introduced system over other state of the art multipole self-assembly systems e.g. driven
by dielectrophoresis.

Even though, assembly yields reached by the introduced assembly chamber can be im-
proved by adoptions of the components design and surface fictionalizations, self-assembly
remains a stochastic process with yields below 100%. Hence, a sorting unit has been in-
troduced enabling the separation of assembled and unassembled components. Differences
in gravitational, hydrodynamic and dielectrophoretic properties of assembled, unassem-
bled and over-assembled (clustered) components lead to a selective deflection of correctly
assembled entities. Vital differences between dielectrophoretic forces predicted by the
conventional models are found for component sizes and electrodes of interest and are
compensated by two dimensionless factors extending the conventional equation. While
advanced multipole models lead to long multidimensional expressions for the calculation
of dielectrophoretic forces for such conditions, the new approached introduced in this thesis
gives an easy approximation of dielectrophoretic forces.

Furthermore, as an enabling technology for the assembly unit, a detailed investigation
of the behavior of PDMS valves in microfluidic systems has been conducted. Here, the
influence of the permeability of PDMS has been studied and it turned out, that gas bubbles
have been created inside the microfluidic channels of our systems at long closing times of
the valves. To the authors knowledge, this has not been reported in literature but has
significant influence on the usability of thin membrane PDMS valves, which are integrated
in an increasing number of microfluidic setups. A functional solution is found in the filling
of the dead-end pressurized channel of the PDMS valve with oil, by which gas intrusion
into the fluidic channels is suppressed.

A concept for the automation of a complete microfluidic system for the assistance of the
self-assembly of hybrid MEMS building blocks is given as an outlook.

Finally it should be noted that the value of the introduced microfluidic handling units lies
beyond the field of hybrid MEMS handling. The preparation unit can have impact on
the preparation on biological entities such as large cells and small cell-clusters. Sorting
strategies are of interest in a broad range of microfluidic applications and the findings on
the handling of sub-millimeter sized components by highly in-homogeneous electric fields
can also be useful in the fields of biology and medical biotechnology.
Appendix A

Supplementary figures

Figure A.1 Maximum delta pressure $\Delta p = p_l - p_c$ as a function of closing pressure $p_c$ for water at $20^\circ$ C of an uncoated valve. The liquid pressure $p_l$ can exceed the closing pressure by a factor $p_l/p_c \approx 1.5$ before leakage of the valve gets measurable with the used setup. This effect is accounted to van der Waals adhesion forces acting between PDMS and Polycarbonate layers, keeping the valve closed against a certain amount of counter pressure.
Figure A.2  Maximum delta pressure $\Delta p = p_l - p_c$ as a function of closing pressure $p_c$ for isopropanol at 20° C of an uncoated valve. The liquid pressure $p_l$ can exceed the closing pressure by a factor $p_l/p_c \approx 1.5$ before leakage of the valve gets measurable with the used setup.
Figure A.3  (Top) Pressure curve $\Delta p = p_1 - p_c$ for a closed system with a compressible air encapsulation sealed by a thin membrane PDMS valve with closing pressure $p_c=110$ kPa and an input pumping rate of $q_{in}=0.5$ ml/min, until point 5, at which the pump is switched off. Between points 1 and 2 the encapsulated air is compressed while the valve is tightly sealed. Point 3 marks the point where $p_c = p_1$ and leakage can be expected. Beginning from point 4 a stable state is reached where the leakage $q_{out}$ is as big as the input flow rate $q_{in}$, until the pump is stopped at 5 and a relaxation of the gas volume takes place. (Middle) Corresponding leakage volume flow through the thin membrane PDMS valve calculated from the pressure curve above. (Bottom) Corresponding graph of volume flow over $\Delta p$ resulting in a hysteresis following the points of the pressure curve above. The experiment is carried out with isopropanol at $20^\circ$ C and shows great analogy to experiments carried out in water (see paper). This results show that hydrophobic interactions can not be the only reason for adhesion for the surfaces in contact and lead to the assumption of van der Waals interactions being the reson for adhesion.
Appendix B

Derivation of terminal velocity for particle sedimentation

The force equilibrium of a sedimenting particle in direction of gravity is given by

\[ 0 = F_D + F_B + F_L - F_G \]  \hspace{1cm} (B.1)

and the flow perpendicular to the particle can be described in x,y-plane as a Plane Poiseuille flow with the equation [146]:

\[ u(y) = y \left( \frac{h(x)}{2} - \frac{y}{2} \right) = \kappa \left( h(x)^2 - y^2 \right), \]  \hspace{1cm} (B.2)

In difference to small particles, larger particles experience effects caused by the presence of the channel walls in the Plane Poiseuille flow in x,z-plane. Staben, Zinchenko, and Davis [88] report that the motion of particles between two parallel walls \( U \) in low Reynolds number regime is generally slower than the fluid motion \( U_c \) on the centerline of the corresponding channel. If the particle is slightly slower than the channel velocity a relative velocity between particle and fluid is found, which is here defined to:

\[ u_c = 1.5 \tau u(y). \]  \hspace{1cm} (B.3)
where \( \tau \) is the velocity proportion of particle and channel velocity and the factor 1.5 is relating the centerline velocity of the Plan Poiseuille flow in x,z-plane to its average velocity. By fitting the values of table B.1 with a polynomial expression of order four, \( \tau \) is calculated as:

\[
\tau = 1 - \left( -1.225 \left( \frac{2r}{l} \right)^4 + 1.702 \left( \frac{2r}{l} \right)^3 - 1.115 \left( \frac{2r}{l} \right)^2 + 0.113 \left( \frac{2r}{l} \right) + 0.999 \right) \quad (B.4)
\]

The factor thereby results in \( \tau = 0.6874\% \), \( \tau = 4.002\% \) and \( \tau = 15.96\% \) for 25 \( \mu m \), 50 \( \mu m \) and 100 \( \mu m \) radius particles, respectively for the channel design used here.

Particle Reynolds numbers are in laminar regime \( (Re \ll 10^5) \), but due to the perpendicular flow not always in creeping flow regime \( (Re \ll 0.1) \), so that Stokes drag is not applicable in all cases. Hence, the drag force has to be described here by its general expression:

\[
F_D = \frac{1}{2} \rho_m v^2 C_D \pi r^2 \quad (B.5)
\]

with \( C_D \) being the drag coefficient. A major challenge for calculation of the drag force by equation (B.5) is the estimation of the drag coefficient. Haider and Levenspiel \[148\] proposed a relation between Reynolds number and drag coefficient defined by:

\[
C_D = \frac{24}{Re_p} \left[ 1 + A \frac{Re_p}{B} \right] + C \left[ 1 + D \frac{Re_p}{B} \right] \quad (B.6)
\]

where A,B,C and D are constants that are defined for spherical particles to \( A = 0.1806, B = 0.6459, C = 0.4251 \) and \( D = 6880.95 \) and \( Re_p \) is the particle Reynolds number

\[
Re_p = \frac{2r u_{Re} \rho_m}{\mu} \quad (B.7)
\]

While for small Reynolds numbers the drag coefficient behaves alike the Stokes drag \( (C_D = 24/Re_p) \), deviations can be found for increasing Reynolds numbers. The full velocity for estimation of the Reynolds number taking the relative velocity \( u_c \) into account, is given by:

\[
u_{Re} = \sqrt{v_{t,Stokes}^2 + u_c^2} \quad (B.8)
\]

where \( v_{t,Stokes} \) is the standard terminal velocity of sedimenting particles in creeping flow conditions, as used in equation (5.1).

The lift force onto a particle is defined as \[89\ 90\] :

\[
F_L = 6.46 \mu r^2 u_c \sqrt{\frac{\rho_m}{\mu}} |\alpha_r| - \frac{11}{8} \rho_m u_c \alpha_r r^3 + \pi \rho_m u_c \omega_p r^3 \quad (B.9)
\]
where \( \omega_p \) the rotational speed of the particle and fluid and \( \alpha_r \) the fluid shear rate of the mean flow, which can be expressed from equation (B.2) by inclusion of the channel geometry to:

\[
\alpha_r (y) = \frac{du(y)}{dy} = \frac{\kappa}{\mu} \left( \frac{h(x)}{2} - y \right).
\] (B.10)

The factor \( \kappa = \frac{dp}{dx} \) can be calculated from the flow through the device \( q \), its channel depth \( t \) and height \( h(x) \) with the ansatz:

\[
\frac{1}{h(x)} \int_0^{h(x)} \frac{\kappa}{\mu} \left( \frac{h(x)y}{2} - \frac{y^2}{2} \right) dy = \frac{q}{h(x)t}.
\] (B.11)

resulting in

\[
\kappa = \frac{3q\mu}{h(x)^3t}.
\] (B.12)

and by combining equation (B.10) and equation (B.12) it follows:

\[
\alpha_r (y) = \frac{12q}{h(x)t} \left( \frac{h(x)}{2} - y \right) = \frac{12Q}{h(x)} \left( \frac{h(x)}{2} - y \right).
\] (B.13)

where \( Q \) is the two dimensional flow rate. The rotational speed of the particle is here calculated with

\[
\omega_p = \frac{u(y - r) - u(y + r)}{2r} = \frac{\kappa}{2\mu} (2y - h(x)).
\] (B.14)

The lift force is a function of the flow profile within the channel of the device, and by the relations above fully expressed in dependency of this flow profile.

Gravitation and buoyancy force for spherical particles are:

\[
F_B - F_G = \frac{4}{3} \pi r^3 (\rho_m - \rho_p) g.
\] (B.15)

Finally, by combining equation (B.1), equation (B.5), equation (B.9) and equation (B.15) the terminal sedimentation velocity can be calculated to be:

\[
v_t = \sqrt{\frac{1}{C_D} \left[ \frac{8}{3} r g \left( \frac{\rho_p}{\rho_m} - 1 \right) - u_c \left( 4.113 \sqrt{\frac{\mu}{\rho_m}} - \sqrt{|\alpha_r|} - 0.875 t \alpha_r r + 2 \omega_p r \right) \right]}.
\] (B.16)

where the drag coefficient \( C_D \) is calculated by equation (B.6) and equation (B.8), resulting in a dependency of Reynolds number and lift forces on the velocity difference \( u_c \), which is scaling with \( \tau \). Thereby if \( \tau \) is approaches zero, no lift force and Stokes drag are expected. The higher the relative velocity of particle and fluid gets \( (\tau \) increases), the higher the impact of Reynolds number and lift force will be onto the sedimentation path of a particle.
Additionally two forces might be considered to act on particles in curved channels, which are (a) drag forces from secondary flows and (b) centrifugal forces. The magnitude of drag forces caused by secondary flows in curved channels can be estimated with the Dean number $De = Re(D_h/2R_0)^{1/2}$ where $Re = \rho_m U_{\text{max}} D_h / \mu$ is the Reynolds number, $D_h = 2wh/(w+h)$ the hydraulic diameter, $w$ and $h$ width and height of the channel, respectively, $U_{\text{max}}$ the maximum channel velocity and $R_0$ the radius of the curvature. For channels and flow rates of interest it can be shown that Dean numbers are small and therefore drag forces from secondary flows onto the particles can be neglected (see also values from [150]).

By consideration of the force equilibrium of particles in a curved channel, on which centrifugal, buoyancy and Stokes drag forces are acting, to deflection of particles in the curvature can be expressed by the equation:

$$R(t) = R_0 e^{\left(\frac{2\rho_p - \rho_m}{\mu} r^2 \omega^2\right)t}, \quad \text{with} \quad \omega = \frac{\pi v_0}{2R_0}$$

where $R_0$ is the initial curvature path of the particle (neutral line of curvature), $r$ the particle radius, $\omega$ the angular velocity, $v_0$ the initial velocity of the particle at the entrance of the curvature, $\mu$ the dynamic viscosity of the medium, $\rho_p$ and $\rho_m$ densities of particle and medium, respectively. It is neglected here, that in fact $\omega$ is a function of $R(t)$ due to the velocity profile caused by no slip conditions at the channel walls.

![Figure B.1](image.png)

**Figure B.1** Sedimentation lengths $L_s$ as function of flow rate of various particles in tap water. The widening angle $\Omega$ is chosen to be $10^\circ$ and particles are PS beads.
**Figure B.2** Sedimentation lengths $L_s$ as function of flow rate of various particles in IPA. The widening angle $\Omega$ is chosen to be $10^\circ$ and particles are PS beads.

The listing of the Scilab program to produce the plots given above is attached in the following.

```scilab
clear;

function [ r t ] = ys(mu, omega, rho_p, rho_m, R0, Hin, r, t )
    r1 = R0*(exp((rho_p-rho_m)/(18*mu)*(2*r)^2*omega^2*t)-1)+Hin/2;
    if (r1>(Hin-r)) then
        r1 = Hin-r;
    end
    rt = r1;
endfunction

function [ ux ] = fu(Q, Hin, Omega, x, y )
    ux = 6*Q/((Hin+x*tan(Omega))^3)*((Hin+x*tan(Omega))*y-y^2);
endfunction

function [ uy ] = fv(Q, Hin, Omega, x, y )
    uy = 6*Q*tan(Omega)/(Hin+x*tan(Omega))^4*((Hin+x*tan(Omega))*y-y^2);
endfunction
```
*y^2−y^3);
endfunction

function \[ re \]=Re(r,u,rho_m,mu)
re = 2*r*u*rho_m/mu;
endfunction

function \[ c \]=Cd(Rex, A, B, C, D)
c=24/Rex*(1+A*Rex^B)+C/(1+D/Rex);
endfunction

function \[ n \]=tau (t,r)
n = 1−(-1.2247*(2*r/t)^4+1.7018*(2*r/t)^3−1.1145*(2*r/t)^2+0.1125*(2*r/t)+0.9984);
endfunction

function \[ uy \]= vg(Q,Hin,t,Omega,r,g,rho_p,rho_m,mu,cor,u,x,y)
vc = fv(Q,Hin,Omega,x,y);
if ~(cor==0) then
  tauf = 1.5*tau(t,r);
  uc = sqrt((tauf*u)^2+(tauf*vc)^2);
  vsc = (2/9*r^2*g*(rho_p−rho_m)/mu);
  vt0 = sqrt(vsc^2+(uc)^2);
endfunction

//Haider et al. 1988
RE = Re(r,vt0,rho_m,mu);
CD = Cd(RE,0.1806,0.6459,0.4251,6880.95);

hx = x*tan(Omega)+Hin;
//OK
kappa = 12*Q*mu/(hx)^3;
//OK 3.
alphar = abs(kappa/mu*(hx/2−y));
//OK 2.
omega = kappa/(2*mu)*(2*y−hx);
//OK
// Kurose and Komori 1999
l = uc*(4.113*sqrt(mu/rho_m)*abs(alphar)) - 0.8754*alphar*r + 2*omega*r;

// Appendix / Supplementary Information
s = 8/3*g*r*(rho_p/rho_m - 1);

if (s>1) then
    vt = sqrt(1/CD*(s-1));
else
    vt = 0;
end
else
    // Stokes
    vt = (2/9*r^2*g*(rho_p-rho_m)/mu);
end
uy = vc+vt;
endfunction

function [L]=Ls(Q, Hin , t, Omega, r, g, mu, R0, rho_p, rho_m, dx)
x = 0;
v0 = Q/Hin; // calculate velocity through curvature
dt = dx/v0;
y = Hin/2 //
yw = Hin;
cstep = 0;
while (y<yw)
    u = fu(Q, Hin, OmegaR, x, y);
v = vg(Q, Hin, t, OmegaR, r, g, rho_p, rho_m, mu, 0, u, x, y);
x = x + u*dt;
y = y + v*dt;
yw = Hin-r+x*tan(OmegaR);
dt = dx/u;
cstep = cstep+1;
if (v==0) then
Appendix B. Derivation of terminal velocity for particle sedimentation

break;
end
end
L=x;
endfunction

function \[L, yst]=Lsc(Q, Hin, t, Omega, r, g, mu, R0, rho_p, rho_m, dx)\)
    x = 0;
    v0 = Q/Hin;
        // calculate velocity through curvature
    dt = dx/v0;
    omegac = v0/R0;
        // calculate angular velocity omega
    t_curv = \pi R0/(2v0);
        // calculate t for curvature
    dp=rho_p-rho_m;
        // Density difference liquid to particle
    y = ys(mu, omegac, rho_p, rho_m, R0, Hin, r, t_curv)
        // yst = y;
yw = Hin;
cstep = 0;
while (y<yw)
    u = fu(Q, Hin, OmegaR, x, y);
    v = vg(Q, Hin, t, OmegaR, r, g, rho_p, rho_m, mu, l, u, x, y);
    x = x + u*dt;
    y = y + v*dt;
    yw = Hin-r+x*tan(OmegaR);
    dt = dx/u;
cstep = cstep+1;
end
L=x;
endfunction

Qin_min=10;        // Flowrate [ul/min]
Qin_max=1500;      // Flowrate [ul/min]
Qsteps = 25;
t_ch=0.3e-3;       // Channel depth [m]
Omega = 10; // Angle [deg]
Hin = 0.5e-3; // Channel height at inflow [m]
R0 = 0.45e-3; // Channel curvature [m]
x_max = 30e-3;

g = 9.81; // Gravity constant
rho_p = 1050; // Density particle

med = 2;

rho_H2O = 997.77;
muH2O = .89e-3;
rho_IPA = 787; // Density medium
muIPA = 2.4e-3; // Dynamic viscosity medium

rho_m = rho_H2O;
mu = muH2O;
if (med == 2) then
   rho_m = rho_IPA;
mu = muIPA;
end

dx = 5e-5; // Set timestep size

Qmin = Qin_min/(60e9*t_ch); // Calculate 2D flow rate
Qmax = Qin_max/(60e9*t_ch); // Calculate 2D flow rate
OmegaR = %pi*Omega/180; // Calculate Omega in rad

r = 25e-6; // Particle size [m]
Qs = linspace(Qmin, Qmax, Qsteps);
Ls25 = Qs;
dR25 = Qs;
Qcount = 1;
for Qa = Qs
   [Lsc25(Qcount), dR25(Qcount)] = Lsc(Qa, Hin, t_ch, OmegaR, r, g ,mu, R0, rho_p, rho_m, dx);
   Ls25(Qcount) = Ls(Qa, Hin, t_ch, OmegaR, r, g, mu, R0, rho_p, rho_m,
Appendix B. Derivation of terminal velocity for particle sedimentation

, dx);
Qcount = Qcount + 1;
end

r = 50e−6;  // Particle size [m]
Qs = linspace(Qmin, Qmax, Qsteps);
Ls50 = Qs;
dR50 = Qs;
Qcount = 1;
for Qa = Qs
    [Lsc50(Qcount), dR50(Qcount)] = Lsc(Qa, Hin, t_ch, OmegaR, r, g
                                           , mu, R0, rho_p, rho_m, dx);
    Ls50(Qcount) = Ls(Qa, Hin, t_ch, OmegaR, r, g, mu, R0, rho_p, rho_m
                                           , dx);
    Qcount = Qcount + 1;
end

r = 100e−6;  // Particle size [m]
Qs = linspace(Qmin, Qmax, Qsteps);
Ls100 = Qs;
Lsc100 = Qs;
dR100 = Qs;
Qcount = 1;
for Qa = Qs
    [Lsc100(Qcount), dR100(Qcount)] = Lsc(Qa, Hin, t_ch, OmegaR, r,
                                           g, mu, R0, rho_p, rho_m, dx);
    Ls100(Qcount) = Ls(Qa, Hin, t_ch, OmegaR, r, g, mu, R0, rho_p,
                                           rho_m, dx);
    Qcount = Qcount + 1;
end

ResL = 15;
if (mu == muH2O) then
    ResQ25 = 122.4;
    ResQ50 = 227.4;
    ResQ100 = 600;
end
end
if (\mu==\muIPA) then
    ResQ25 = 180;
    ResQ50 = 300;
    ResQ100= 1089;
end

scf(1);
clf(1);
plot2d(Qs*(60e9*t_ch),Ls25*1e3,2);
plot2d(Qs*(60e9*t_ch),Ls50*1e3,2);
plot2d(Qs*(60e9*t_ch),Ls50*1e3,2);
plot2d(Qs*(60e9*t_ch),Ls100*1e3,3);
plot2d(Qs*(60e9*t_ch),Ls100*1e3,4);
plot2d(ResQ25,ResL);
plot2d(ResQ50,ResL);
plot2d(ResQ100,ResL);
xlabel("$$\text{Flow rate}\ \mu l, min^{\sim -1}$$") ;
ylabel("$$\text{Particle sedimentation length mm}\ \text{s}$$") ;
xgrid;
f = gcf();
f.color_map = graycolormap(32);
a2 = get("current_axes");
//a2.frameflag=6;
a2.box = "on";
a2.font_style = 6;
a2.labels_font_size = 5;
a2.x_label.font_size = 5;
a2.y_label.font_size = 5;
a2.data_bounds = [0, Qin_max, 0, x_max*1e3];
a2.children;
a2.children.children(4).thickness = 3;
a2.children.children(4).foreground = 0;
a2.children.children(4).mark_style = 1;
Appendix B. Derivation of terminal velocity for particle sedimentation

h1 = legend (['25\mu m\text{uncorrected}' , '25\mu m\text{corrected}' , '50\mu m\text{uncorrected}' , '50\mu m\text{corrected}' , '100\mu m\text{uncorrected}' , '100\mu m\text{corrected}', "in\_lower\_right"])
Appendix C

Details of DEP force factor derivations

C.1 Dipole Matching

<table>
<thead>
<tr>
<th>Linear</th>
<th>Non-linear</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_0 = mx' + b_0$</td>
<td>$E_0 = -a(x' + b)^c + d_0$</td>
</tr>
</tbody>
</table>

The applied electric field over the particle is defined by the following equations:

Charges on the particle will distribute according the applied electric field and create a field $E_1$ of the particle opposing the external field $E_0$, which can be expressed as:

$E_1 = mx' + b_1$  
$E_1 = -a(x' + b)^c + d_1$

On a electrically uncharged particle the overall charge must be zero and therefore the constants $b_1$ and $d_1$ can be calculated by:

$0 = \int_{r_0}^{2r} E_1(x') \, dx'$

$0 = \int_{h_0}^{2r} (mx' + b_1) \, dx'$

$0 = \int_{h_0}^{2r} (-a(x' + b)^c + d_1) \, dx'$
Appendix C. Details of DEP force factor derivations

\[ b_1 = m(r + h_0) \]

\[ d_1 = \frac{a}{2r(1+c)} \left[ (b + 2r + h_0)^{(1+c)} - (b + h_0)^{(1+c)} \right] \]

With these constants it follows for the intersection with the x-axis that charges on both sides are of equal strength.

\[ E_1(x_i') = 0 \]

\[ x_i' = r \]

\[ x_i' = \left( \frac{d_1}{a} \right)^\frac{1}{c} - (b + h_0) \]

Which represents the midpoint of the effective dipole.

C.2 Program for calculation of the dimensionless factors

The following listing is used to calculate the dipole matching factor \( k_d \) and \( k_{nl} \) from simulation data with the equations given in section 5.3 and section C with the computational program R.

```r
rm(list = ls());

#define fitting function for electric field from simulations
E <- function(a, b, c, x)
{
    return (a*(x+b)^c);
}

#define function for xb
xb <- function(a, b, c, h, x)
{
    d <- a/(2*x*(1+c))*(b+2*x+h)^(1+c)-(b+h)^(1+c));
    return ((d/a)^(1/c)-b);
}

#define function for kd
kd <- function(a, b, c, h, r)
{
    return (xb(a, b, c, h, r)/r);
}

#define derivation of electric field for calculation of m
```

e <- function(a, b, c, x)
{
    return (a*c*(x+b)^(c-1));
}

define derivation of electric field for calculation of m
e2 <- function(a, b, c, x)
{
    return (2*a*c*(x+b)^(2*c-1));
}

#define function for non-linearity factor
knl <- function(a, b, c, h0, r1)
{
    return ((E(a, b, c, h0) - E(a, b, c, 2*r1*kd(a, b, c, h0, r1)))/(2*r1*kd(a, b, c, h0, r1)*e(a, b, c, h0)));
}

#read data from file
data <- read.table("200_CenterOnElectrodeEdge.txt", header=TRUE, sep=" ");

copy data into variables
dE2Field <- data$Height;

#shift xPos 0.1 [um] to make fit possible
xPos <- data$x+1e-4;

#try non-linear fit
reg <- nls(dE2Field ~ E(a, b, c, xPos), start=list(a=1e16, b=-5e-5, c=-5e-1), trace=T, control = nls.control(tol = 1e-6, minFactor = 1e-20, maxiter=1000));

#print summary
print(summary(reg));

#store variables of successful fit
a = as.numeric(coef(reg)[1]);
b = as.numeric(coef(reg)[2]);
c = as.numeric(coef(reg)[3]);

#define values for calculation

#smallest radius to calculate [mm]
r0 <- 1e-3;

#default height of particle [mm]
h0 <- 0;

#define sequence of r for calculation (min, max, stepsize) [mm]
r <- seq(r0, 5e-1, 1e-4);

#create variable to store values of k
k <- r;
kdr <- r;
 kf <- r;
kfn <- r;

#calculate values for k as function of r
for (i in 1:length(r)) {
    k[i] = knl(a, b, c, h0, r[i]);
kdr[i] = kd(a, b, c, h0, r[i]);
kf[i] = kdr[i]*3*k[i]*r[i]*3/r0^3;
kfn[i] = r[i]^3/r0^3;
}

#calculate and output specific values of interest
d0 <- 0.01;
d1 <- 0.1;
d2 <- 0.2;
knl0 = knl(a, b, c, h0, d0/2);
kd0 = kd(a, b, c, h0, d0/2);
print("d0=1e-5_;[m]”);
C.2. Program for calculation of the dimensionless factors

print(kd0);
print(knl0);

knl1 = knl(a,b,c,h0,d1/2);
k1 = kd(a,b,c,h0,d1/2);
print("d1=100e-6[m] ");
print(kd1);
print(knl1);

knl2 = knl(a,b,c,h0,d2/2);
k2 = kd(a,b,c,h0,d2/2);
print("d2=200e-6[m] ");

#plot values from simulation and corresponding fit
plot(xPos, dE2Field, type="l", tck =0.01, ylab=expression(" Electric Field ["V/m"] "), xlab=expression(" Distance to electrode ["m"] "), cex.lab =1.5, cex.axis =1.5, mgp =c (2.5, .5, 0) , lwd =3);
lines(xPos, predict(reg), col="gray", lty =2, lwd =3);
axis(3, tck =0.01, labels =FALSE);
axis(4, tck =0.01, labels =FALSE);
legend(0.12, 1.1e18, c("Simulation Data"," Fitted curve"), col =c(" black"," gray"), lty =c(1, 2), lwd =c(3, 3), cex =1.5);

#plot values for k as function of r into new window
x11();
plot(r1e3,k,type="n",tck =0.01, xlim =c(1,5e2), ylim =c(5e-3, 1),
log="xy", ylab=expression(" Dimensionless factors "), xlab =
expression(" Particle radius ["m"] "), cex.lab =1.5, cex.axis =1.5, mgp =c (2.5, .5, 0) ) ;
abline(h=c(seq(1e-3,1e-2,length=10), seq(1e-2,1e-1,length=10),
seq(1e-1,1,length=10), seq(1,1e1,length=10)), lty =3, col=" gray ");
abline(v=c(seq(1,1e1,length=10), seq(1e1,1e2,length=10), seq(1e2 ,1e3,length=10)), lty =3, col=" gray ");
Appendix C. Details of DEP force factor derivations

```r
lines(r*1e3,k,lwd=3,lty=2);
lines(r*1e3,kdr,lwd=3,lty=1);
axis(3, tck=0.01, labels=FALSE);
axis(4, tck=0.01, labels=FALSE);
box();
legend(1,2e-2,c(expression(" Dipole \_\_\_\_\_\_\_\text{matching}\_\_\_\_\_\_k[d]*"(r))",
expression(" Non-\_\_\_\_\_\_\_\text{linearity}\_\_\_\_\_\_k[nl]*"(r)) ),lty=c(1,2),lwd=c
(3,3), cex=1.5, bg="white");
x11();
plot(r*1e3,kfn,type="n", log="xy",lwd=3,lty=2);
lines(r*1e3,kfn,lwd=3,lty=1);
lines(r*1e3,kf,lwd=3,lty=2);
```
Appendix D

Custom designed power amplifier

The designed amplifier is based on the PA78DK from Apex Microtechnology, a power operational amplifier design for driving piezo electric transducers. With the help of a step-up converter the required voltage is created to a maximum of 300 V. The schematic design is shown in the following figures.
Figure D.1  Custom designed amplifier: schematic overview
Figure D.2  Custom designed amplifier: schematic of boost converter
Figure D.3  Custom designed amplifier: schematic of voltage inverter
Figure D.4  Custom designed amplifier: schematic of amplifier
## List of Tables

2.1 MESA principles from literature ........................................ 8

4.1 Recent PDMS valve designs from literature ordered by principal and year of occurrence .................................................. 27

5.1 Experimentally obtained feeding flow rates for optimal sedimentation and washing ................................................................. 50

5.2 Nominal values of the control parameters for the four main modes of actuation ................................................................. 64

5.3 Comparison of different sorting strategies ................................ 71

5.4 Material properties of interest for DEP applications .................. 78

5.5 DEP electrode design and voltages from literature .................... 85

B.1 Extraction of particle velocity ratios $U/U_c$ ............................ 107
List of Figures

2.1 Time-line of MEMS and micro-fabrication technologies ................. 4
2.2 Micro-assembly concepts ............................................. 6
3.1 A micro-assembled design ............................................. 12
3.2 Schematic drawing and image of the three main configurations ......... 13
3.3 Schematic drawing explaining the hydrophobic effect .................. 14
3.4 System concept ....................................................... 17
4.1 Mold for PDMS casting ............................................... 21
4.2 Particle storage device as image and schematic representation .......... 23
4.3 Process flow for double replica molding .............................. 24
4.4 Comparison Single to Double Replica Molding Process ................. 25
4.5 Symbolic drawing of the thin membrane PDMS valve .................. 29
4.6 Images of the valve setup in top view and cross section ............... 30
4.7 Permeability measurement of the introduced valve .................... 33
4.8 Sectional view of the thin membrane PDMS valve in closed state with coating defect .................................................. 34
4.9 Maximum liquid pressure $p_l$ as a function of valve closing pressure $p_c$ for investigation of parylene coating influence on valve performance ............... 35
4.10 Symbolic drawing of the experimental setup for the estimation of the sealing capabilities of a PDMS valve ........................................ 37
4.11 Pressure curve of PDMS valve characterization ........................ 38
4.12 Maximum flow through thin membrane PDMS valve as a function of applied liquid pressure ............................................... 40
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.1</td>
<td>Maximum delta pressure $\Delta p = p_l - p_c$ as a function of closing pressure $p_c$ for water at 20°C of an uncoated valve.</td>
<td>103</td>
</tr>
<tr>
<td>A.2</td>
<td>Maximum delta pressure $\Delta p = p_l - p_c$ as a function of closing pressure $p_c$ for isopropanol at 20°C of an uncoated valve.</td>
<td>104</td>
</tr>
<tr>
<td>A.3</td>
<td>Pressure and leakage curve of a closed thin membrane PDMS valve.</td>
<td>105</td>
</tr>
<tr>
<td>B.1</td>
<td>Sedimentation lengths $L_s$ as function of flow rate of various particles in tap water</td>
<td>110</td>
</tr>
<tr>
<td>B.2</td>
<td>Sedimentation lengths $L_s$ as function of flow rate of various particles in IPA</td>
<td>111</td>
</tr>
<tr>
<td>D.1</td>
<td>Custom designed amplifier: schematic overview</td>
<td>126</td>
</tr>
<tr>
<td>D.2</td>
<td>Custom designed amplifier: schematic of boost converter</td>
<td>127</td>
</tr>
<tr>
<td>D.3</td>
<td>Custom designed amplifier: schematic of voltage inverter</td>
<td>128</td>
</tr>
<tr>
<td>D.4</td>
<td>Custom designed amplifier: schematic of amplifier</td>
<td>129</td>
</tr>
</tbody>
</table>
Bibliography


List of publications

International Journals


International Conferences


Reports
