Contents

4. Preface

- Manufacturing of „micromechanical components“ very wide field ...
  - Many materials used to build microsystems
    - Silicon, plastics, glass, ceramics, metals, etc.
  - Many aspects
    - Shape, electrical properties, surface properties, optical properties, etc.
  - Many manufacturing technologies applied and combined
    - Lithographic technologies combined with etching and deposition of materials (wet etching, dry etching, CVD, PECVD, sputtering etc.)
    - Mechanical machining
    - Laser ablation
    - etc.

4. Preface

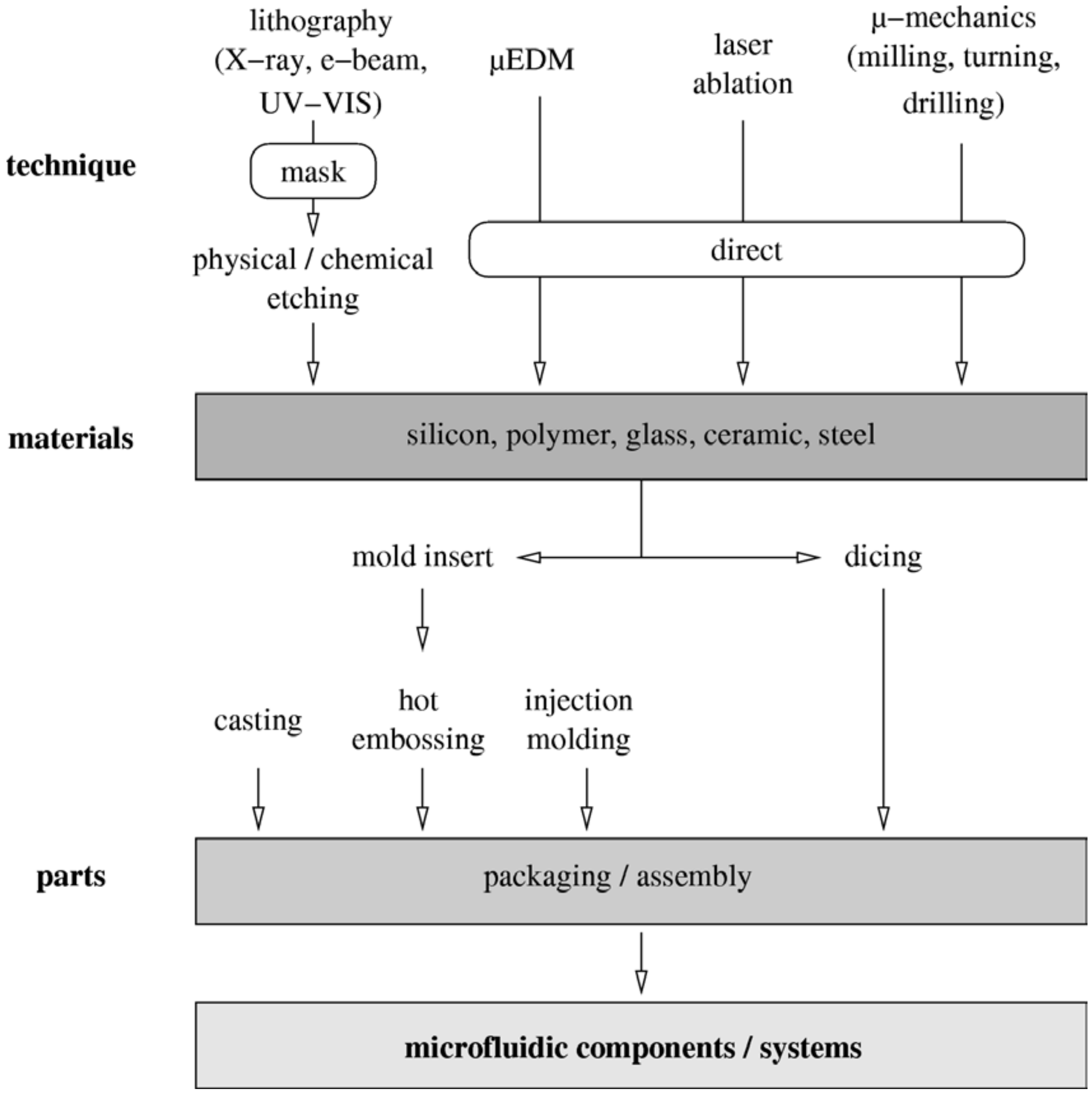
- This lecture covers selected topics relevant for microfluidics!

- Detailed information on microfabrication available

  - FSRM course „Manufacturing Processes for Micromechanical Components“

  - PhD-thesis of Dr. Gordana Popovic „Systematik der Verfahrenswahl zur Fertigung mikromechanischer Bauteile“ TU Vienna (1996)

4. Microfabrication Technologies



technique

lithography (X–ray, e–beam, UV–VIS)

mask

physical / chemical etching

µEDM

laser ablation

µ–mechanics (milling, turning, drilling)

direct

materials

silicon, polymer, glass, ceramic, steel

mold insert

dicing

casting

hot embossing

injection molding

parts

packaging / assembly

microfluidic components / systems

costs!

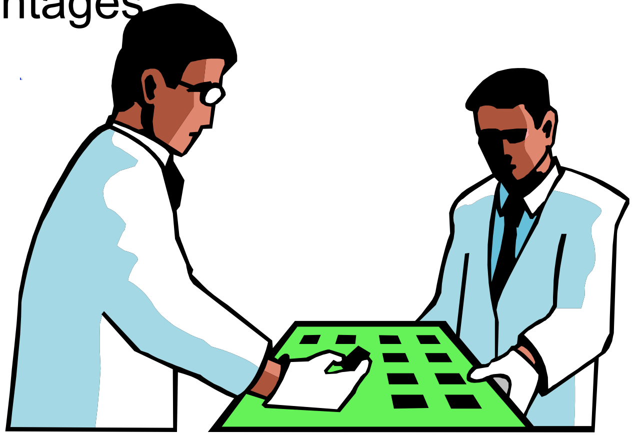
4. Selected Materials & Fabrication Technologies

Contents

1. Silicon
2. Plastics
3. Quartz
4. Glass
5. Other materials
6. Alternative technologies
7. Interconnection technology
8. Summary

1.–2.: standard materials, amenable for high volume production

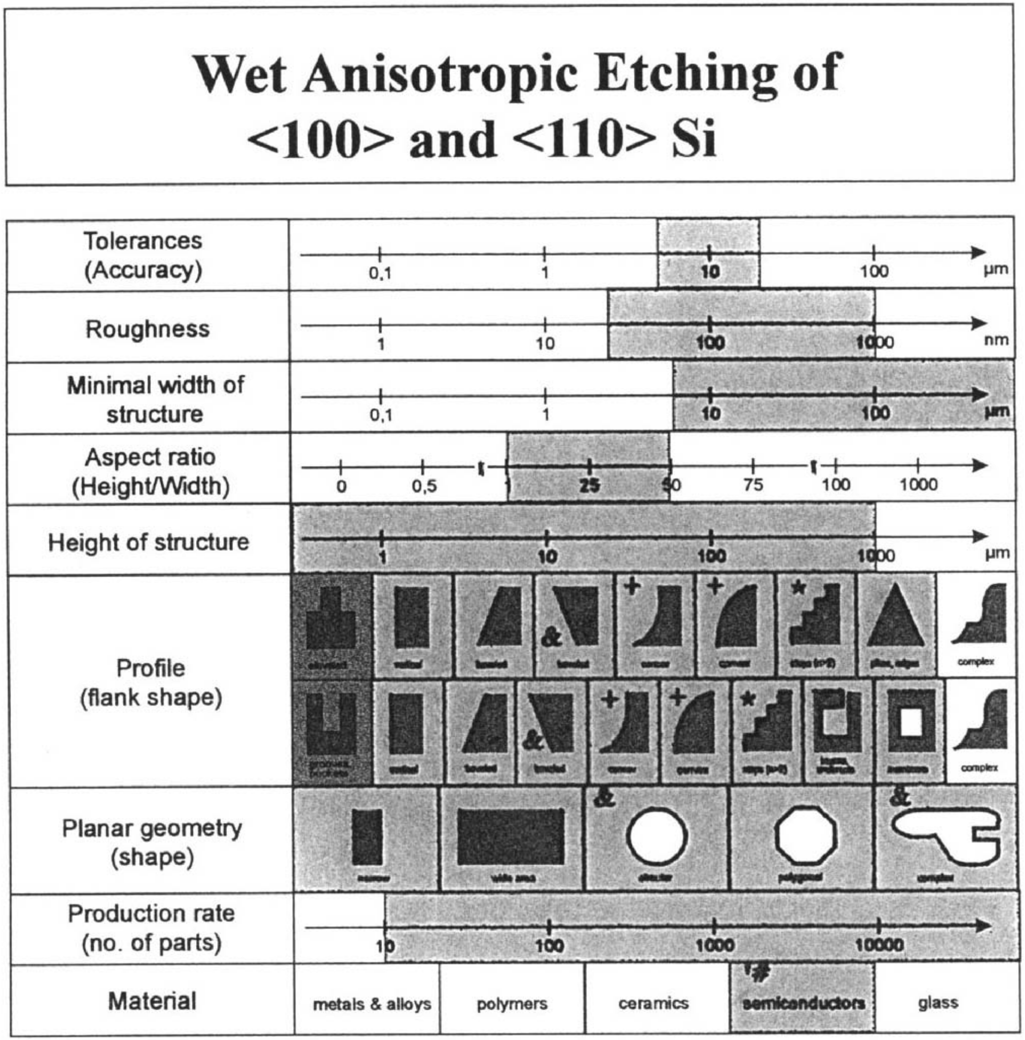
3.–4.: less frequently used materials with specific advantages



4. Microfabrication Technologies

1. Silicon
2. Plastics
3. Quartz
4. Glass
5. Metals
6. Ceramics
7. Alternative Concepts
8. Surface Modifications
9. Interconnection Technology
10. Layout of Microfluidic Systems
11. Ingredients for Commercial Success

4.1. Selection of Fabrication Process

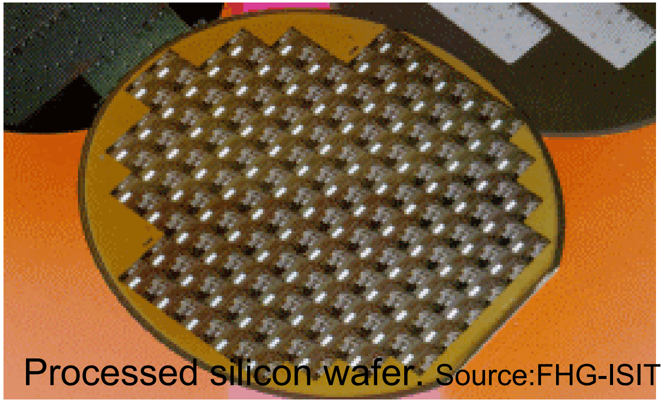


Wet Anisotropic Etching of <100> and <110> Si

Tolerances (Accuracy)	0,1 · 1 · **10** · 100 µm
Roughness	1 · 10 · **100** · **1000** nm
Minimal width of structure	0,1 · 1 · **10** · **100** **µm**
Aspect ratio (Height/Width)	0 · 0,5 · **25** · **50** · 75 · 100 · 1000
Height of structure	**1** · **10** · **100** · **1000** µm
Profile (flank shape)	+ · + · * · & · complex + · + · * · & · complex
Planar geometry (shape)	& · &
Production rate (no. of parts)	**10** · **100** · **1000** · **10000**
Material	metals & alloys · polymers · ceramics · **semiconductors** · glass

4.1. Silicon

- Base material of MEMS
  - ➢ Single crystal wafers
    - Diameter of 4‘‘ to 6‘‘
    - Thickness 200 µm to 1 mm
    - Orientation mostly <110> and <100>



Processed silicon wafer. Source:FHG-ISIT

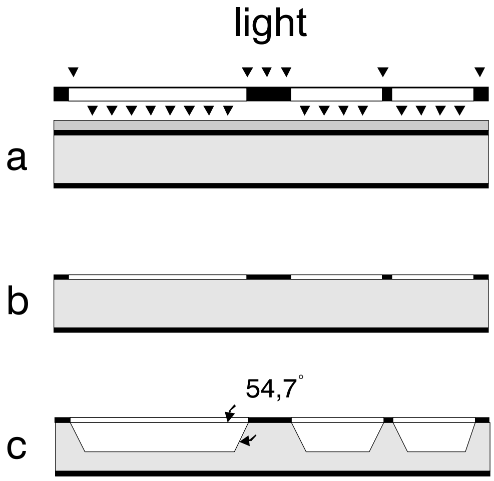
- Workhorse of microelectronics and MEMS
  - ➢ Long tradition in semiconductor and MEMS fabrication
  - ➢ Comprehensive knowledge base on
    - Material properties (worlds best characterized material)
    - Processing

- Different micromachining technologies
  - ➢ Surface micromachining (additive technology for example CMOS)
  - ➢ Bulk micromachining (subtractive technology for example wet etching)

4.1. Structuring of Silicon: Wet Etching

- Principle:
  - Etch rate dependent on crystal orientation and therefore anisotropic
- Basic Process:
  a. Spin coating & exposure
  b. Development
  c. Etching in KOH

  } Lithography (a., b.)



- Properties
  - Batch process
  - Etch rate ≈ 1 µm per minute in KOH
- Drawbacks
  - Limited degrees freedom in capillary pathways (no arbitrary shapes)
  - Cross section of channels defined by etch process (54.7°)
  - Limited channel aspect ratio
  - Oblique channel profile

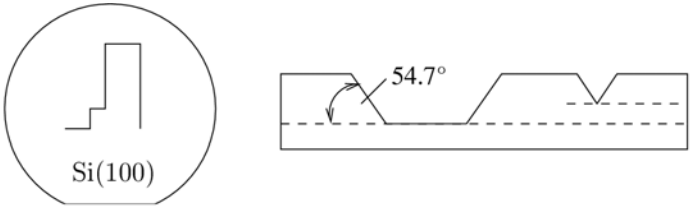


Fig. 4.2. Horizontal and vertical geometries of wet-etched channels in a Si(100) wafer

4.1. Structuring of Silicon: Dry etching (DRIE)

- Principle
  - ➢ Removal of material by bombardment with ions

- Basic Process
  - ➢ Lithography
  - ➢ Reactive ion etching (plasma)

- Properties
  - ➢ Single wafer process
  - ➢ Etch rates between 2 - 20 µm per minute

- Advantages
  - ➢ Arbitrary channel pathways
  - ➢ Rectangular channel cross sections
  - ➢ Etch rate *per wafer* comparable to wet etching
  - ➢ High aspect ratios

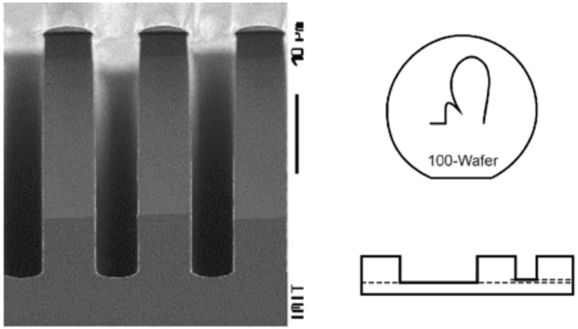
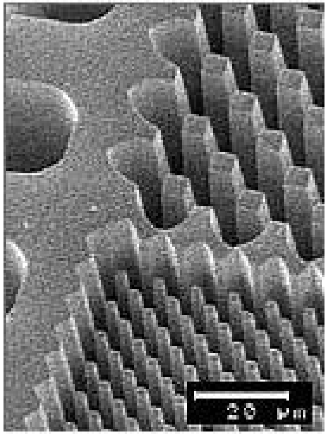


Fig. 4.4. Arbitrary channel pathways with rectangular cross-section can realized with DRIE



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4.1. Bonding of Silicon

- Anodic bonding
    - ➢ Bond between Si and Pyrex based on ion diffusion
    - ➢ Voltage between 200 V and 1 kV
    - ➢ Temperature below 500°C
    - ➢ Advantages
        - Transparent cover lid
        - Process tolerant to surface quality

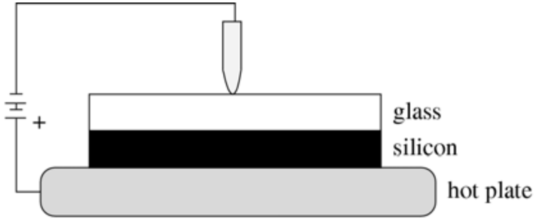


Fig. 4.6. Schematic of anodic bonding. The Si-glass sandwich is put onto a hot plate. By applying a voltage, ions move from the glass towards to Si substrate to build a solid bond by electrostatic forces

- Silicon fusion bonding
    - ➢ Bond between Si and Si based on chemical reaction of silanol (SiOH)
    - ➢ Temperature 1000°C and higher
    - ➢ Problem
        - High surface quality required

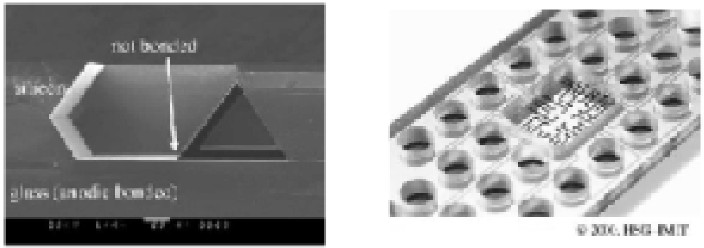


Fig. . Anodic bonds between Si and Pyrex wafers (JD: verify picture source)

4.1. Production Costs in Si-Technology

Process Costs

- Distinction between batch process and single wafer process
  - ➢ Batch: all wafers processed simultaneously
    - E.g. KOH-etching
    - Process time scales with number of batches
  - ➢ Single wafer: each wafer treated separately
    - E.g. silicon dry etching
    - Process time scales with number of wafers

- Costs scale with process times, **not** with geometrical complexity
  - ➢ Operator time; machine time
  - ➢ Many complex and different structures producible in parallel
- Costs of chip proportional to chip area
  - ➢ Example

4.1. Example: Flap Valve

- Fairy-tale of Si micromachining
  - *High production numbers always make prices competitive*
- Reality
  - Cost per 4-inch wafer: >25 $
  - Cost per structuring step: 100 $
- Example: flap microvalve in silicon technology
  - 2 wafers with bond quality: 100 $
  - 2 structuring steps for flap: 300 $
  - 2 structuring steps for valve seat: 300 $
  - Total cost of structured wafers: 700 $
  - Chip area 7 x 7 mm^2 giving 120 chips
  - Yield 70% leaving 85 chips
  - **Approximate cost per chip:** 8 $

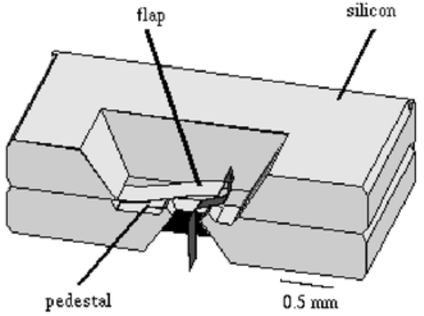
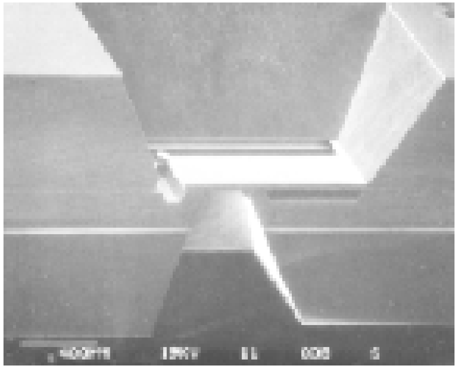


Fig. 5.7. Photo and schematic of flap valve



- *Surface area per chip* dominates production cost!

4. Microfabrication Technologies

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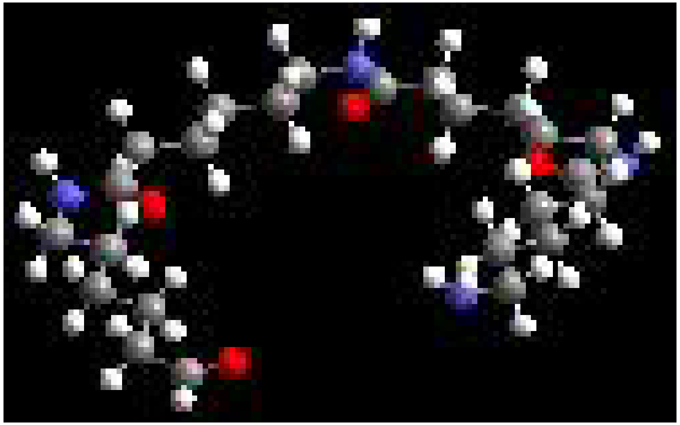
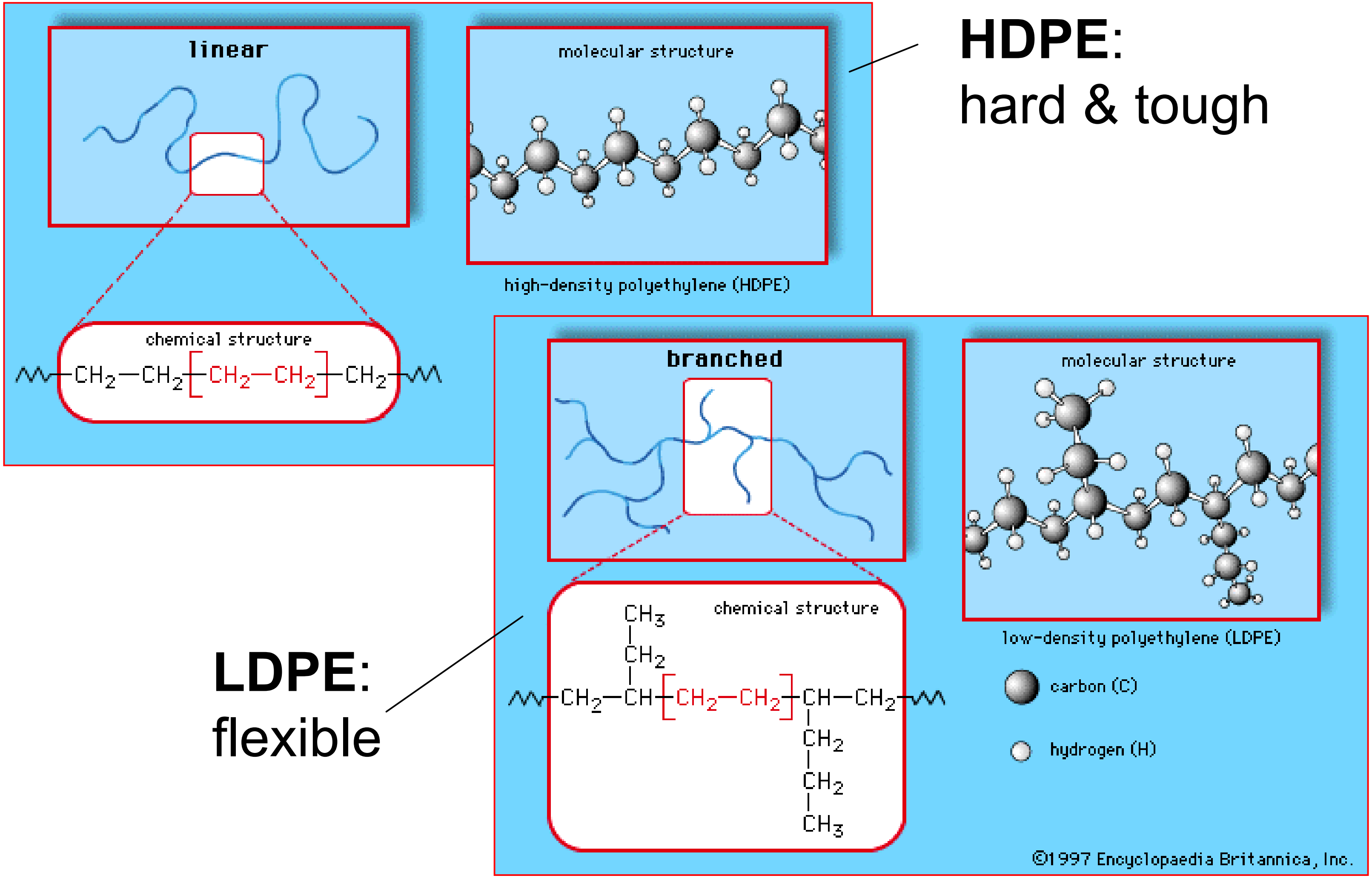
4.2. Plastics



- Long, chainlike molecules (polymers)
- Molecular weights
  - Tens of thousands and several million Daltons
- Distinct properties
  - Rooted in large molecular weight and structural properties
- Two fundamental forces govern properties
  - Strong **covalent intramolecular bonds** constitute backbone
  - Individual chains electrostatically attracted by neighboring macromolecules
  - Rather weak **electrostatic coupling** between single molecular constituents accumulates along whole extension of chain molecules
  - Strong overall electrostatic forces
    - Plastics keep their shape after molding

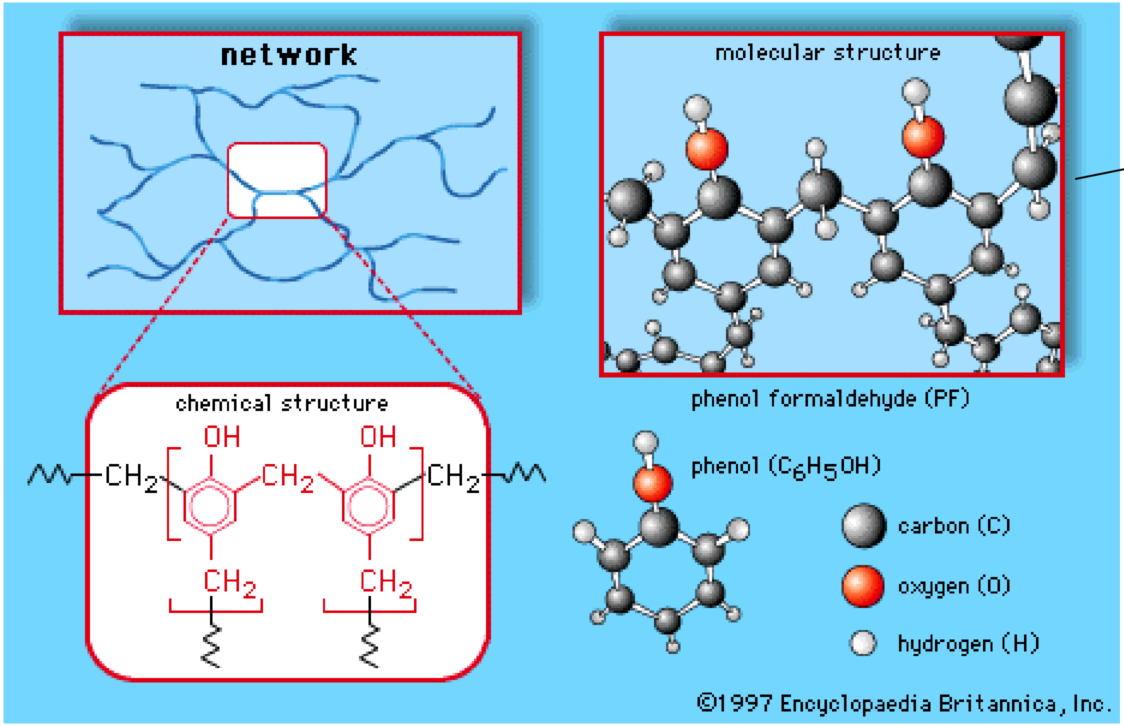
4.2. Polymer Configurations



HDPE:
hard & tough

LDPE:
flexible

4.2. Polymer Configurations



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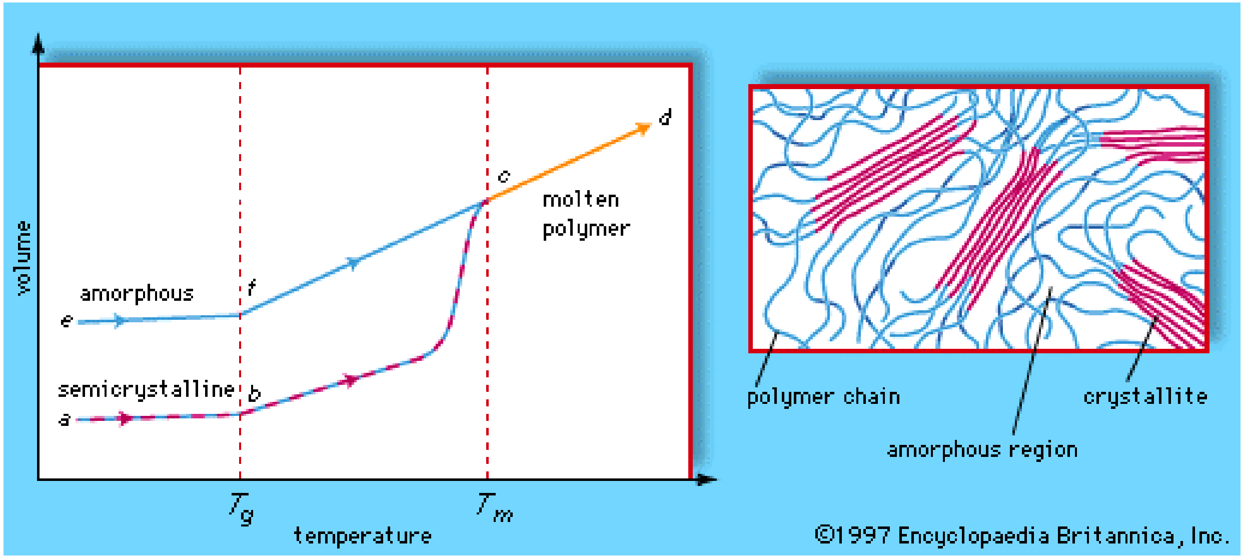
Network:
high density,
rigid and brittle

4.2. Amorphous and Semicrystalline Plastics



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- Glass transition temperature T_g
  - Rubbery state
- Melting point T_m
  - Crystalline regions resolve

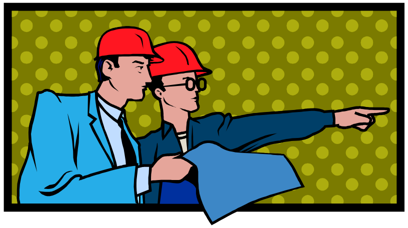
4.2. Industrial Classification

- Commodity resins
  - High volume
  - Low cost
  - Mostly for disposable items and durable products
  - Examples
    - Polyethylene (PE)
    - Polypropylene (PP)
    - Polyvinyl chloride (PVC)
    - Polystyrene (PS)

4.2. Industrial Classification

- Specialty resins
  - Application-specific material properties
  - Low volume
  - „High“ cost
  - Engineering plastics (or resins)
    - Polyacetal, polyamide, polytetra fluoroethylene (“Teflon”), polycarbonate, polyphenylene sulfide, epoxy and polyetherether-ketone
    - Widely spread in replacing metal parts and components in plumbing, hardware and automotive industry

4.2. Engineering Properties



- Thermoplastic resins (thermoplastics)
  - Amenable to successive reheating / reshaping cycles
  - Constituent molecules
    - Linear or branched
    - Either low or very high atomic weight
  - Separated and thus mobile molecules flowing past one another

- Thermosetting resins (thermosets)
  - Delivery of heat to thermosetting resin induces formation of intermolecular bonds to large molecule

4.2. Structuring of Plastics: Basics

Small lot production

- Bulk technologies
  - Etching
  - Mechanical micromachining
  - Laser ablation (e.g. excimer)
  - LIGA
  - etc.

- Additive technologies
  - Stereolithography, photoforming
  - Additive laser micromachining
  - etc.

Mass production

1. Master tool fabrication
   - Mechanical micromachining
   - Silicon micromachining
   - Galvanic forming (see LIGA)
   - Electrodischarge machining
   - etc.

2. Replication technology
   - Injection Molding
   - Hot embossing
   - Casting techniques
   - Lamination techniques
   - etc.

4.2. Hot Embossing

Basic steps of hot embossing process

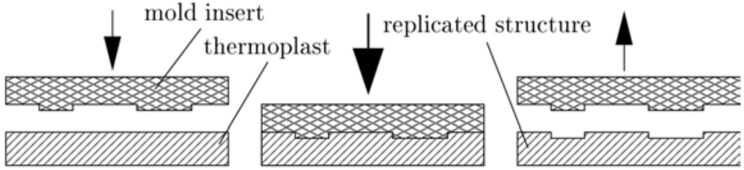


Fig. 4.13. Schematic of hot embossing (HE). The heated mold insert is pressed against a thermoplastic substrate assuming its inverse shape. Upon cooling, the replicated structured is released

1. Introduction of plastic substrate (foil, bulk piece etc.) into mold insert
2. Heating of mold insert to glass transition temperature of material
3. Application of high pressure/force to mold insert
4. Cooling down below glass transition temperature
5. Removal of workpiece from mold insert

Hot Embossing machine HEX 01

(Source: Jenoptik Mikrotechnik)

4.2. Hot Embossing

Characteristics of technology

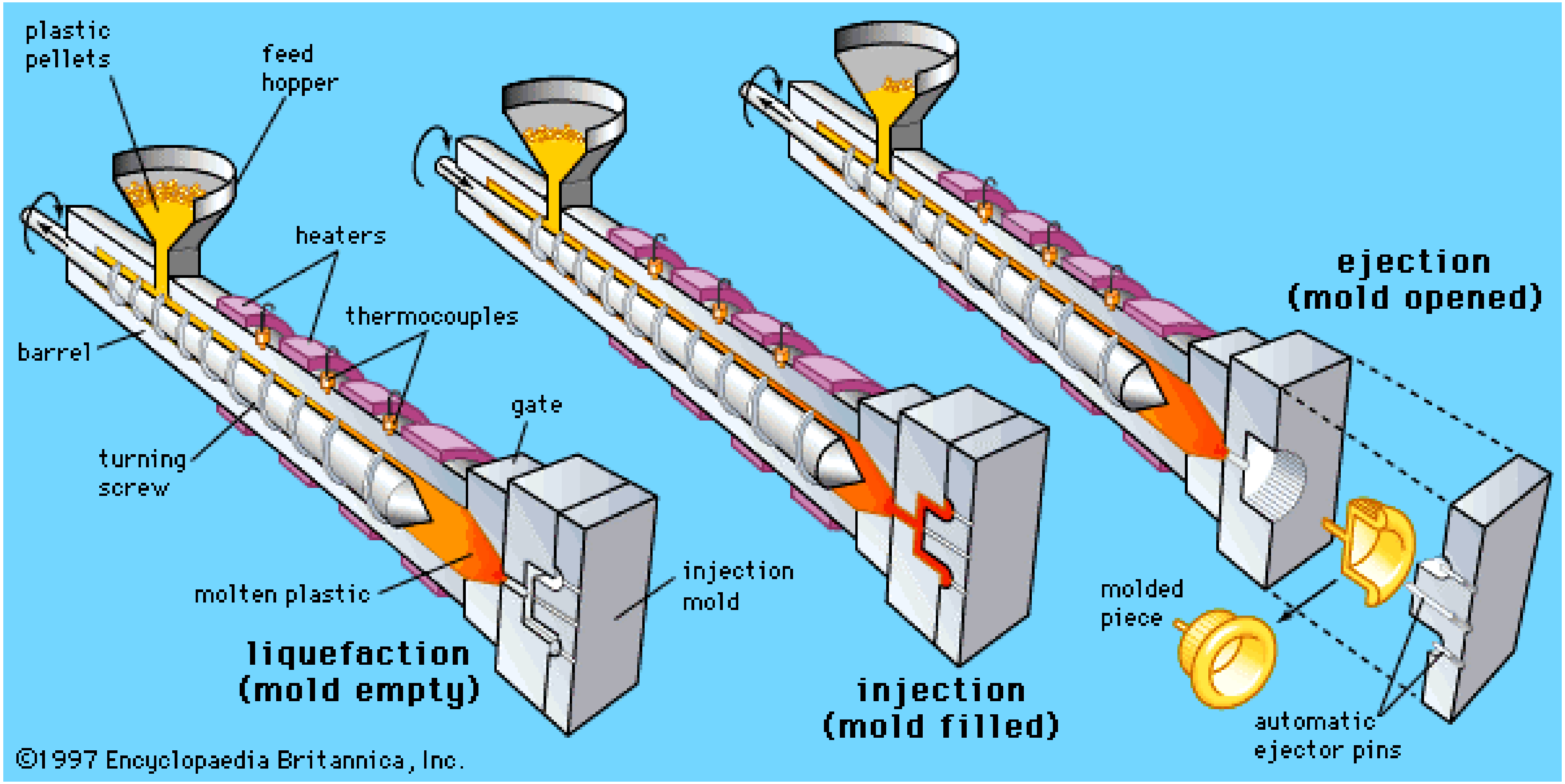
- Mold inserts: Manufactured by mechanical micromachining, laser machining, µ-discharge machining, silicon micromachining or LIGA
- Aspect ratios: Up to 500 (according to FZK)
- Feature size: From 10 µm to 1 mm
- Substrate size: Range of several cm² (Jenoptik 130 cm²)
- Others:
  - Flexibility in materials due to amenability to most thermoplastics
  - Foil thickness down to 100 – 30 µm possible
  - Also suited for small lot production

Initial costs

- Costs for mold insert: 3,000 $ – 50,000 $ per mold insert (depending on production process and complexity)
- Machine costs: Investment of 100,000 – 300,000 $

4.2. Injection Molding

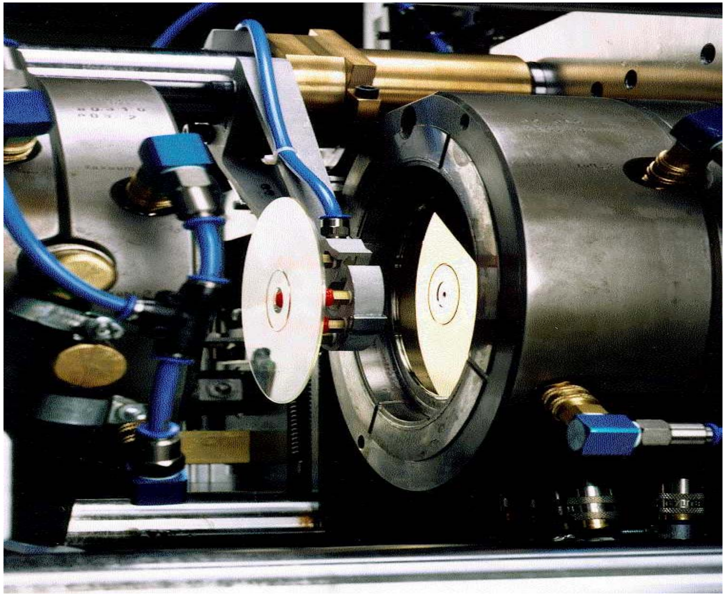
Macro-injection molding (IM) process



4.2. Injection Molding

Industrial machines and tools:

Automatic injection molding machine
(Source: Ferromatik Milacron)



Base mold with mold insert and automatic ejector

4.2. Injection Molding

Characteristics of IM-technology

- Mold inserts: Manufactured by mechanical micromachining, laser machining, µ-discharge machining, silicon micromachining or LIGA
- Aspect ratios: Up to 100 (variotherm processes, long duration)
- Feature size: Width: several µm to mm

  Height: sub µm up to several mm
- Substrate size: „Arbitrary“
- Procss deveoplment: Costly, depending on structure
- Others:
  - Flexibility in materials like hot embossing
  - In most cases faster than hot embossing
  - Variotherm processes needed for long and high aspect ratio structures, increasing time and costs

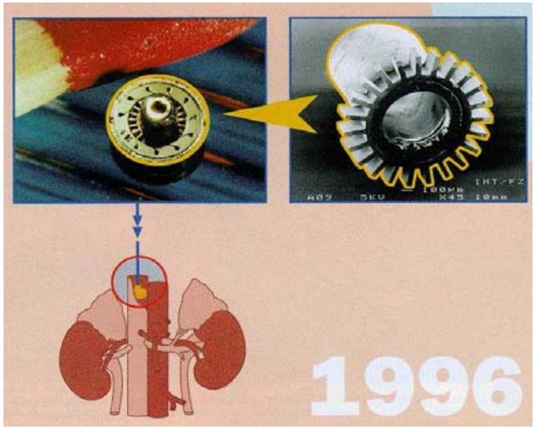
Initial costs

- Costs for mold insert: 3,000 – 50,000 $ per mold insert
- Costs for base mold: 5,000 –10,000 $
- Machine costs: Invest of 10,000 – 300,000 $

4.2. Injection Molding

Final remarks & examples:

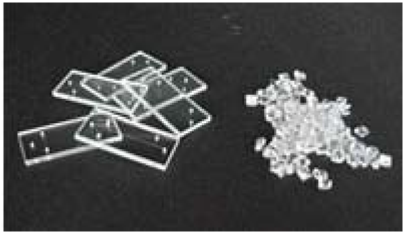
- Simple microstructures like compact disks fabricated within few seconds
- High-aspect ratio structures usually require variotherm process
  - ➢ Resin solidifies prior to filling master
  - ➢ In particular for channels displaying high flow resistance
- Typical cycle times of variotherm-based IM protocols range on order of several minutes
- IM process prone to internal stresses and shrinkage as whole structural body initially in (hot) liquid phase
- Disadvantage: no very high aspect ratios



micro milling tool for medical applications (Source: Forschungszentrum Karlsruhe)

Microplate out of PMMA
(Source: Steag Microparts)

Microfluidic ChipShop



4.2. Other Plastic Fabrication Techniques

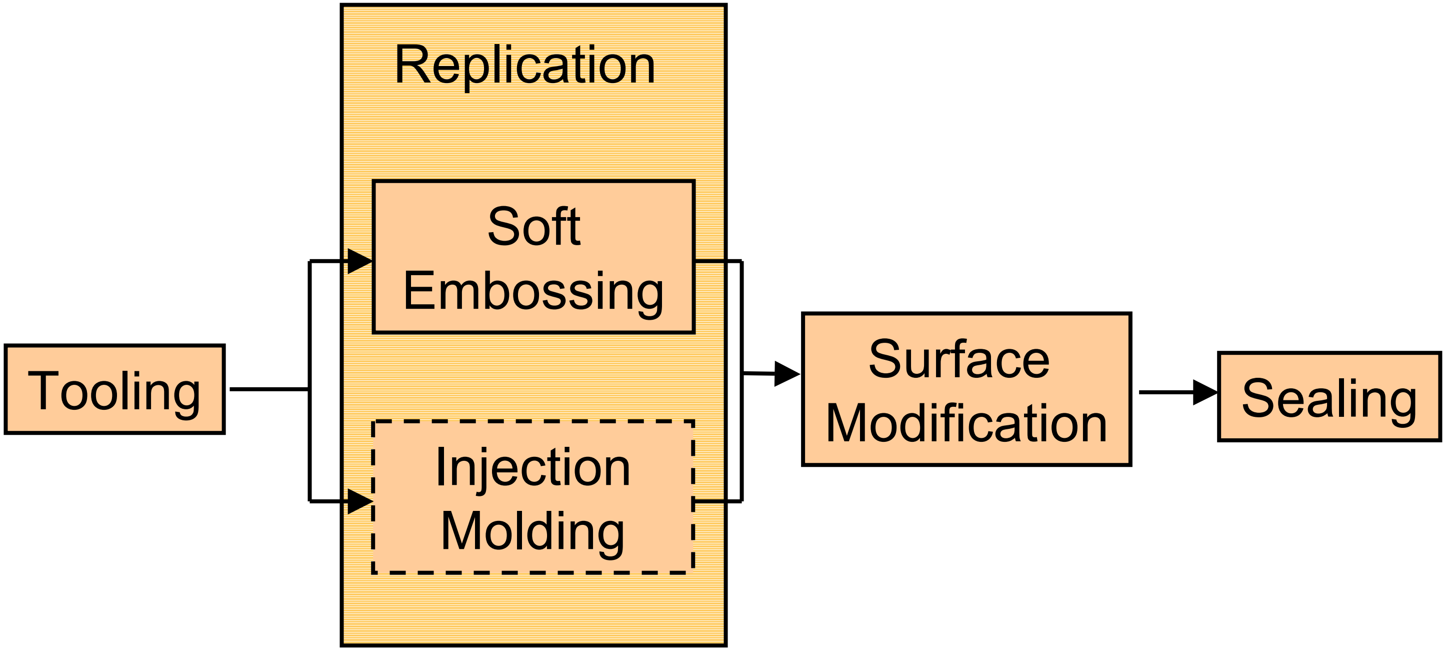
- Lamination
  - Structuring of thin films
  - Stacking of several layers
  - Bonding by polymerization between interfaces

- Bonding & sealing
  - Lamination: covering by self-adhesive plastic film
  - Ultrasonic welding
  - Laser welding
  - Thermal bonding under pressure
  - Gluing
    - UV-curable
    - Solvent-based
  - Molding of PDMS (polydimethylsiloxan) against microfabricated master, PDMS adhesion to plain surfaces used as cheap bonding method

- Drilling

- Many more...

Example: Soft Embossing



Replication

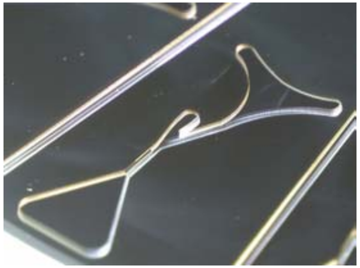
Tooling

Soft Embossing

Injection Molding

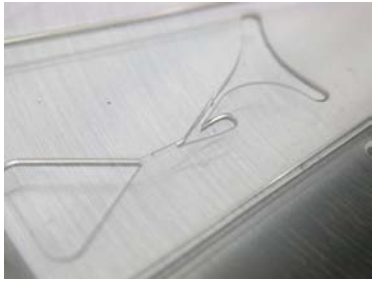
Surface Modification

Sealing



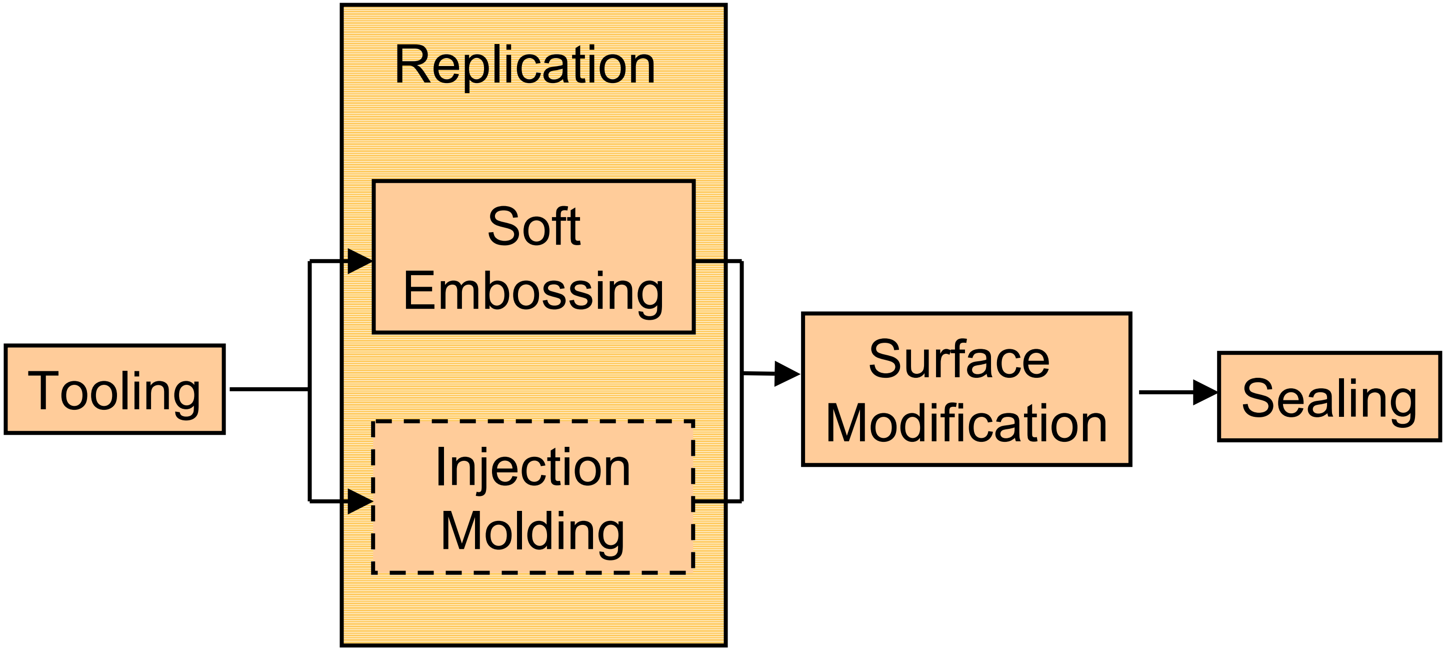
SU-8

PDMS



COC

Process Technology Chain



Tooling

Replication

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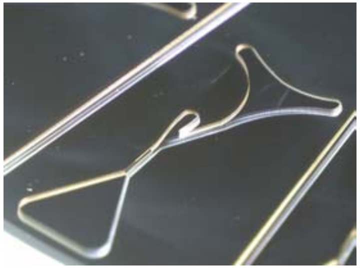
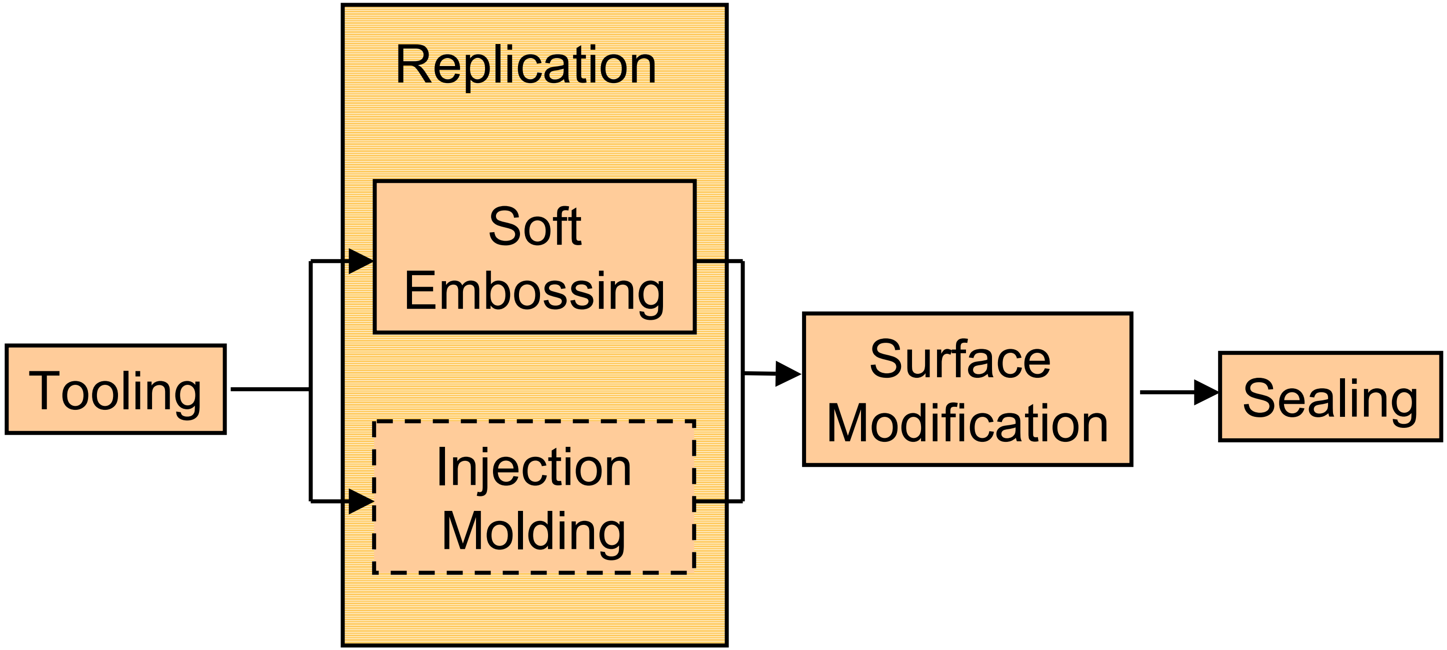
Sealing

SU-8



Process Technology Chain



Tooling

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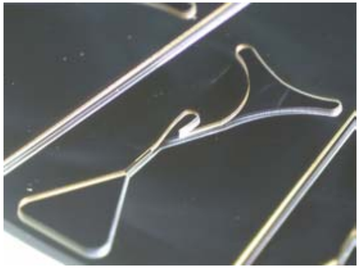
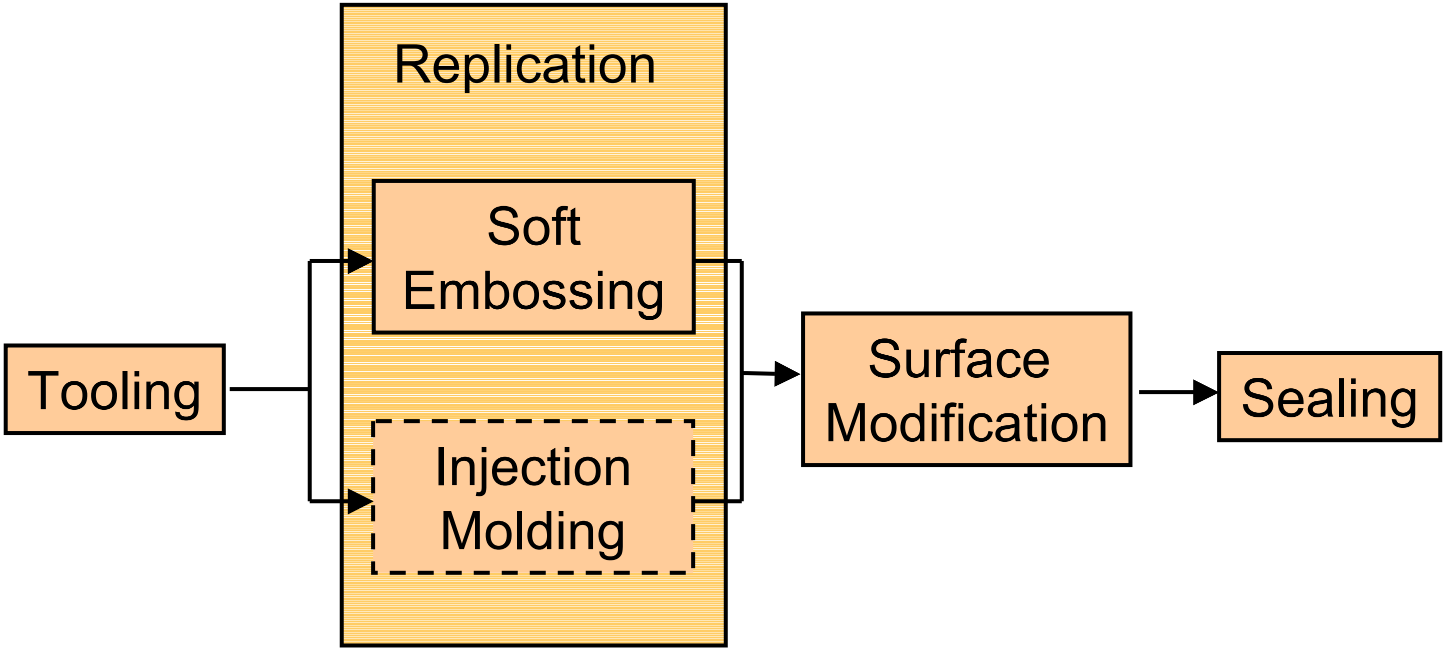
Sealing

SU-8



PDMS

Process Technology Chain



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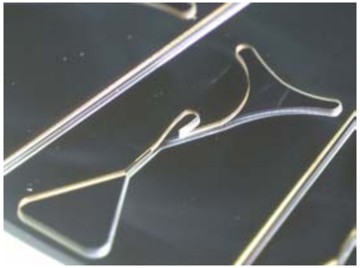
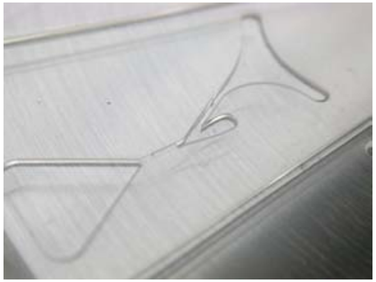
SU-8

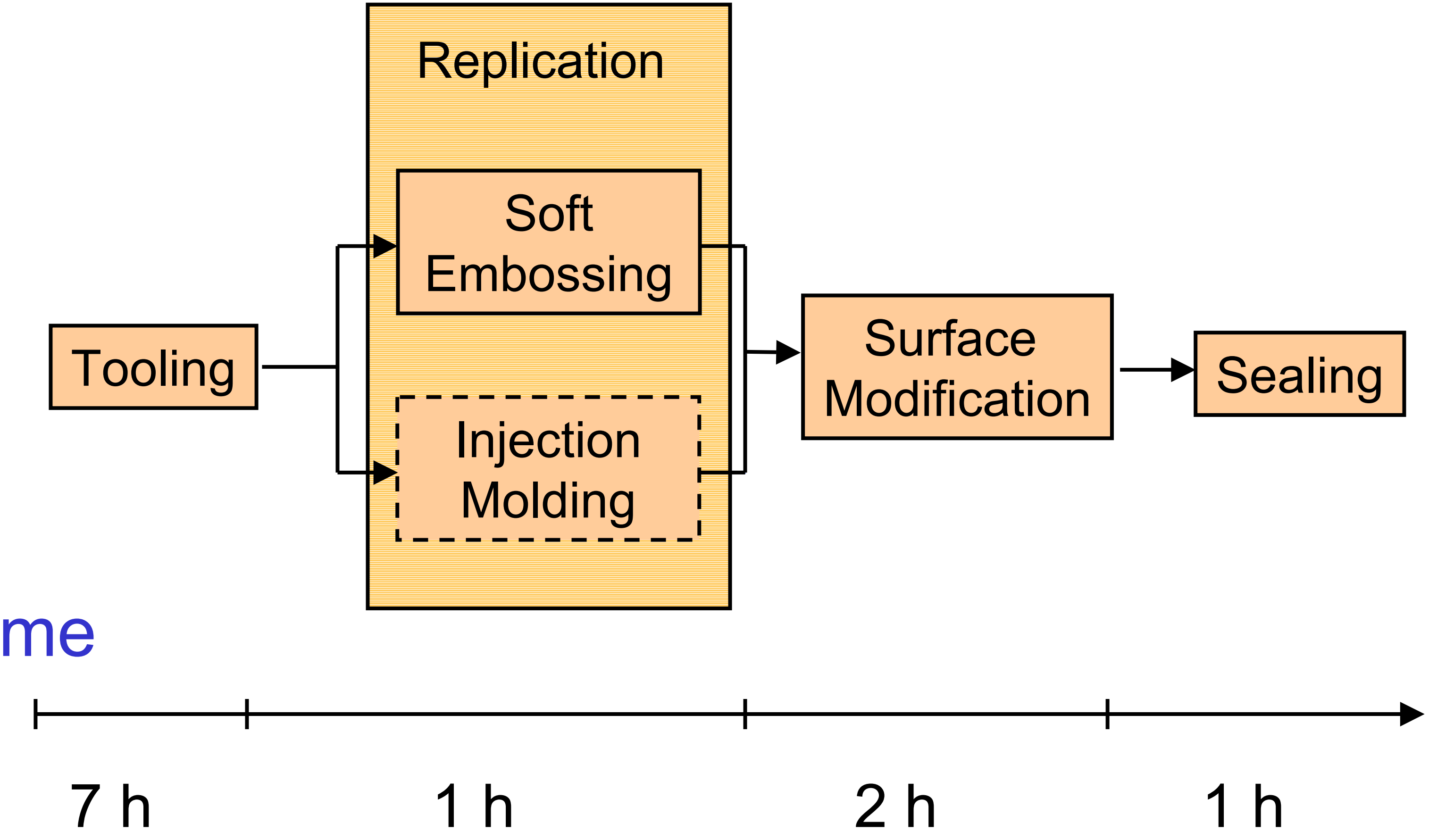


PDMS

COC

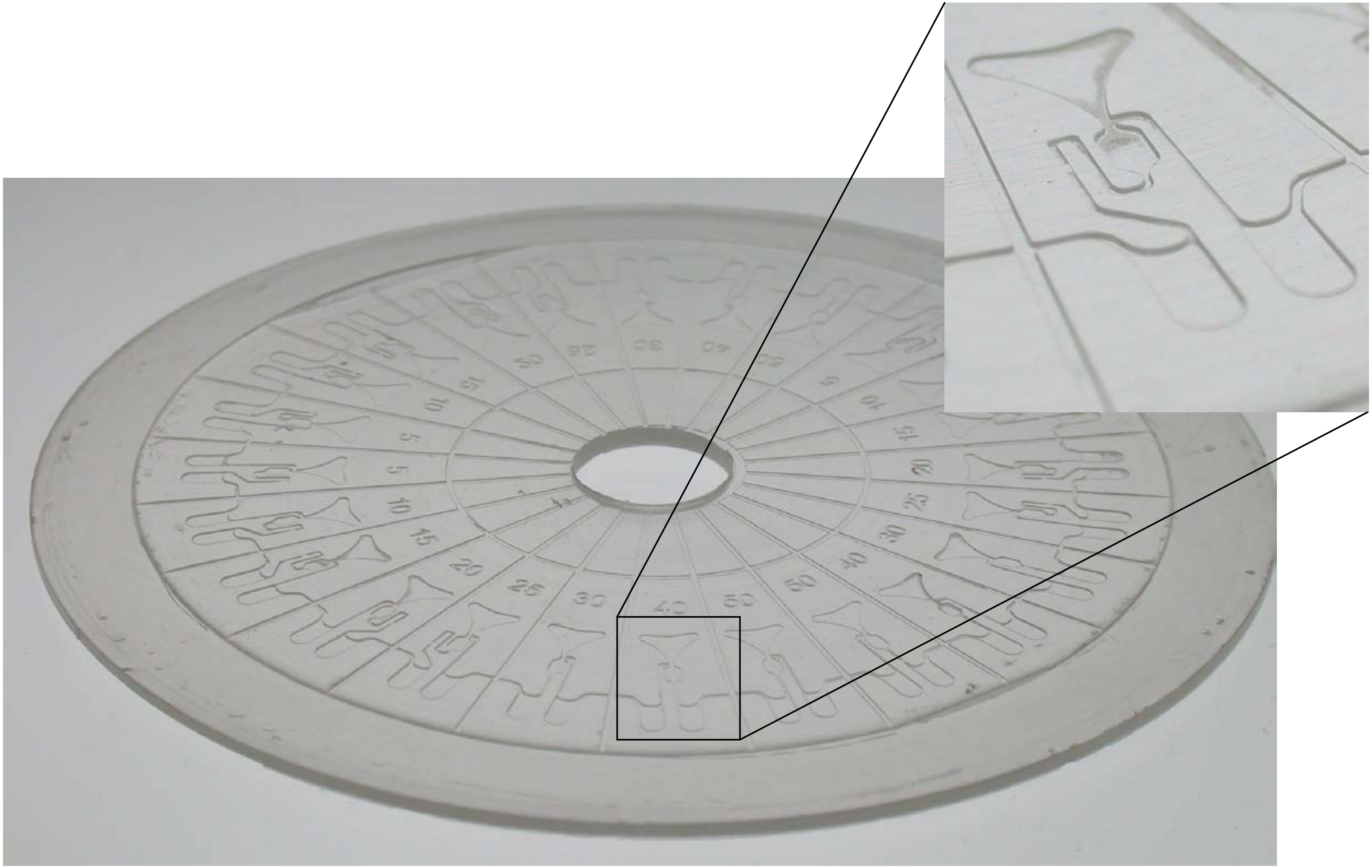


Process Technology Chain



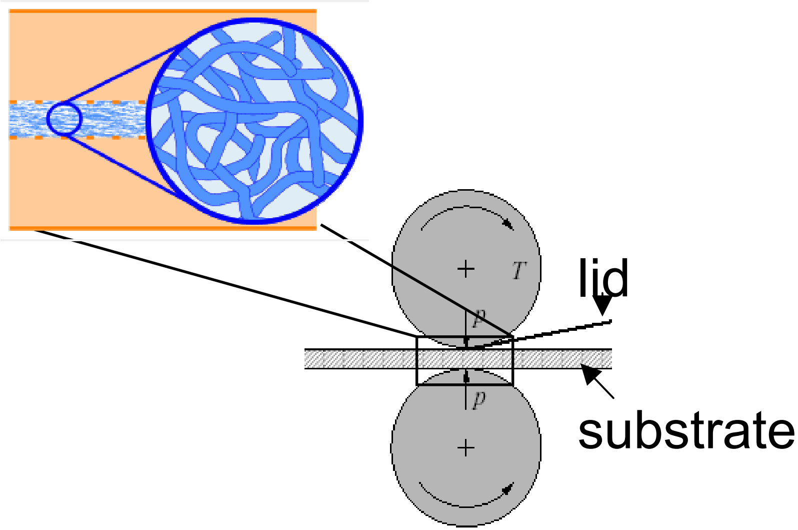
Full prototyping process: 1-3 days

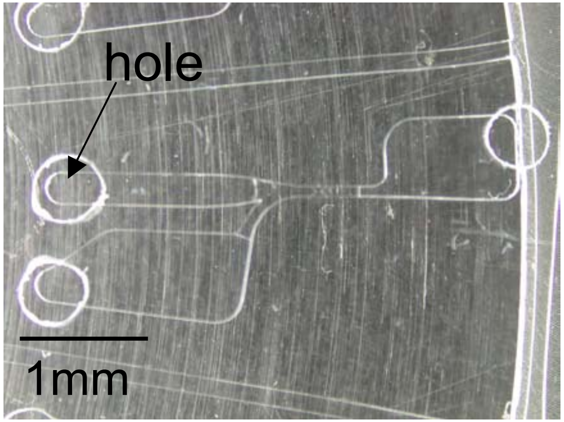
Embossed Disk



Sealing

- Thermal diffusion bonding
  - Intimate contact at interface
  - Heat induced cross-linking of polymer-chains
- Lamination
  - Pressure *p*
  - Temperature *T*

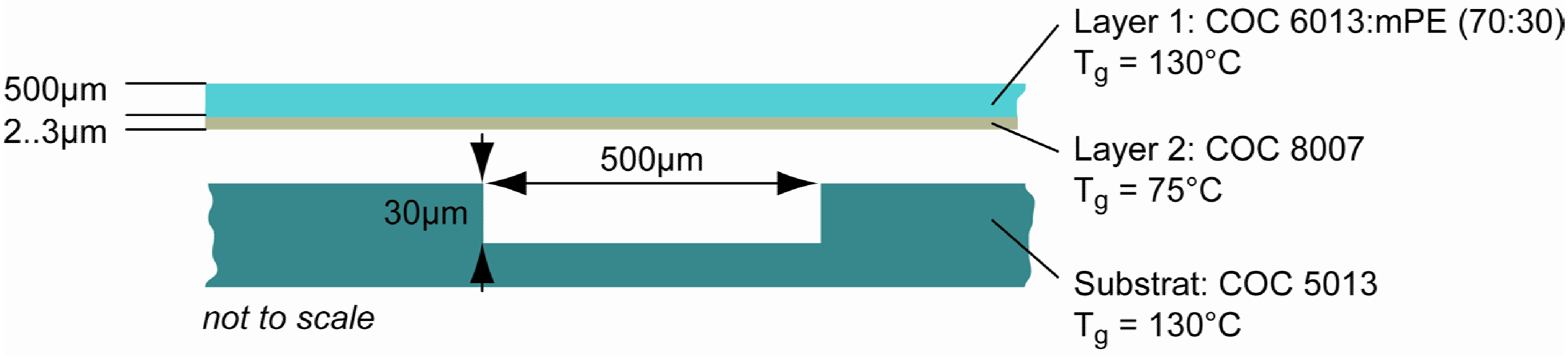




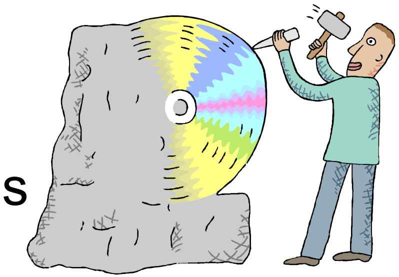
Example: Sealing

sealing

- Lamination of multilayer cover (cf. Axel‘s presentation)
  - 1st layer for mechanical stability
  - 2nd layer with low glass transition temperature T_g, acts as adhesive



4.2. Summary: Plastics in Microfabrication



- Material costs in general no issue due to small size
- Considerable investments and fixed costs
- Facilitated manufacturing by replication technologies
  - In molten state
  - With molds / casting /embossing
- Amenable to mass fabrication at moderate costs
- Material properties tunable over wide range
- Rapid prototyping possible by standard µM, SU8 / LIGA, mechanical precision engineering, laser ablation, …

=> Plastic technology first choice for many MEMS applications not relying on special electronic properties of semiconductors (sensors, actuators, etc.), thus also for most of microfluidics

4. Microfabrication Technologies

1. Silicon
2. Plastics
3. Quartz
4. Glass
5. Metals
6. Ceramics
7. Alternative Concepts
8. Surface Modifications
9. Interconnection Technology
10. Layout of Microfluidic Systems
11. Ingredients for Commercial Success

4.3. Quartz

- Name quartz old German word of uncertain origin
- Second most abundant mineral in Earth's crust after feldspar
- Many varieties consisting primarily of silica, or silicon dioxide SiO_2
- Minor impurities such as lithium, sodium, potassium, and titanium
- Instead of natural quartz, grown quartz often used
  - Commercially available in large single crystals or cut into 3-inch wafers
- Two crystalline forms
  - α and β
- Piezoelectric properties
- Quartz wafers (blanks) used in MEMS technology
- Blanks in same price range as silicon

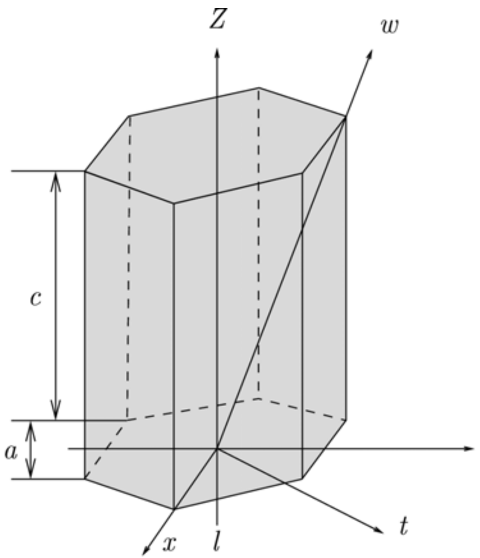
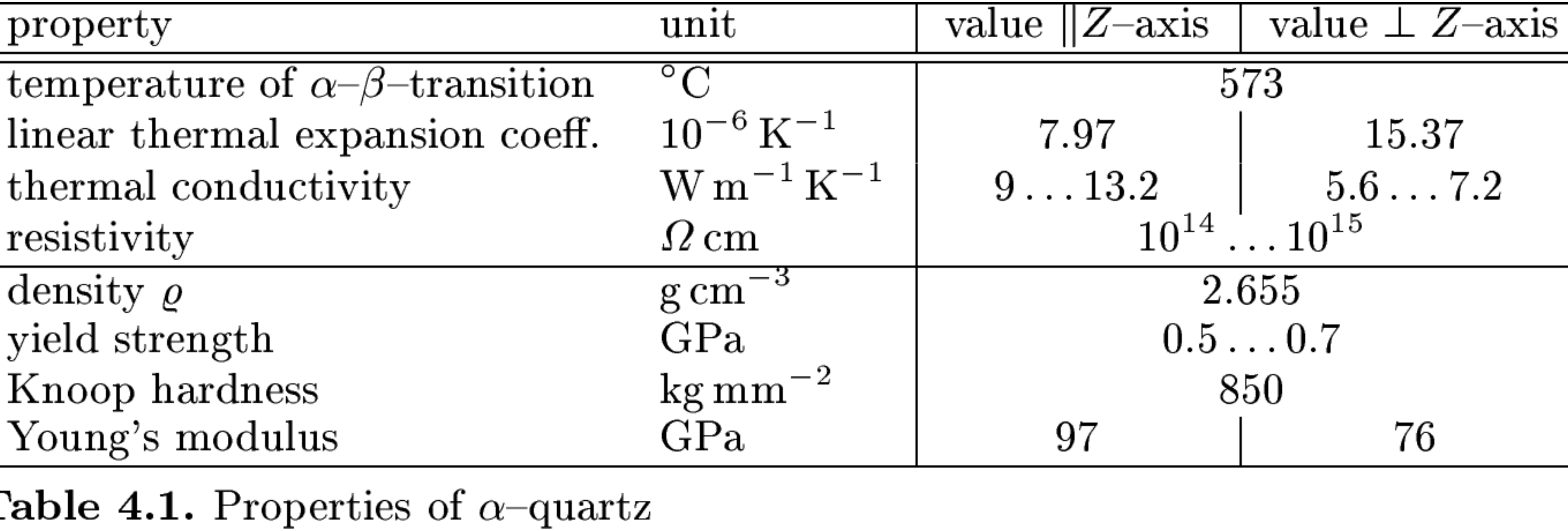


Fig. 4.15. Schematic of the quartz crystalline structure. Crystal axes lik
trigonal Z– (or c–) axis and the polar x– and y–axes are indicated

4.3. Properties of Quartz



property	unit	value $\parallel Z$–axis	value $\perp Z$–axis
temperature of α–β–transition	$^\circ$C	573	
linear thermal expansion coeff.	$10^{-6}\,\mathrm{K}^{-1}$	7.97	15.37
thermal conductivity	$\mathrm{W\,m^{-1}\,K^{-1}}$	$9 \ldots 13.2$	$5.6 \ldots 7.2$
resistivity	$\Omega\,\mathrm{cm}$	$10^{14} \ldots 10^{15}$	
density ϱ	$\mathrm{g\,cm^{-3}}$	2.655	
yield strength	GPa	$0.5 \ldots 0.7$	
Knoop hardness	$\mathrm{kg\,mm^{-2}}$	850	
Young's modulus	GPa	97	76

Table 4.1. Properties of α–quartz

4.3. Structuring of Quartz: Overview

- Mechanical machining
  - Diamond saw cutting
  - Grinding, lapping and polishing to manufacture glass plates as thin as 100 µm only
  - Ultrasonic machining for structuring on millimeter range (serial process, not suitable for mass production)
- Patterning by photolithography
  - Metal layers as masks
- Wet etching to batch-fabricate structures in sub-millimeter range
  - HF/NH_4F solution
  - Strongly anisotropic etch rates peaking in *Z*-direction
  - Therefore, often *Z*-cut quartz wafers used in micromachining
  - Typical etch rates 1 µm / min
  - Etch rate in *Z*-direction typically exceeds etch rates in *x*- and *y*-direction by factors of 50 and 500, respectively

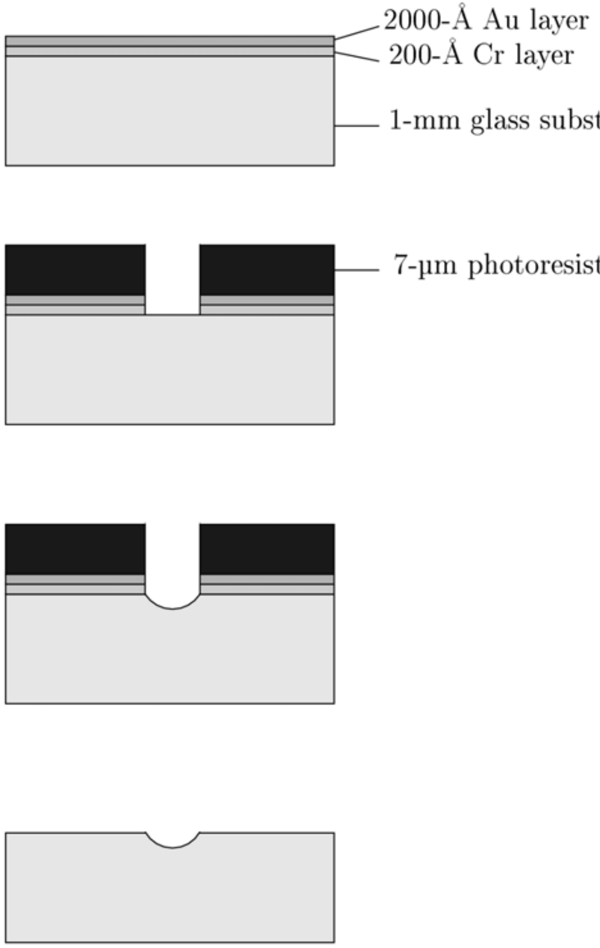


Fig. 4.16. Structuring of a quartz substrate. The same process may also be applie
to Iwaki code 7740 glass

4.3. Bonding of Quartz

- HF bonding process
  - Careful cleaning to prepare surfaces for bonding
  - Stacking base plate and cover plate upon each other
  - Dispensing 1%-diluted HF solution to gap between two plates
  - Solution spreads by capillary action
  - Pressure supported bonding at room temperature
  - Enhanced bonding performance reported at elevated temperature, e.g. 60°C
- Through holes
  - Covering both sides of substrate by photoresist
  - Photoresists structured to mark through holes and to protect surfaces for subsequent bonding steps from mechanical damage
  - Ultrasonic drilling of through holes

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4.4. Glass

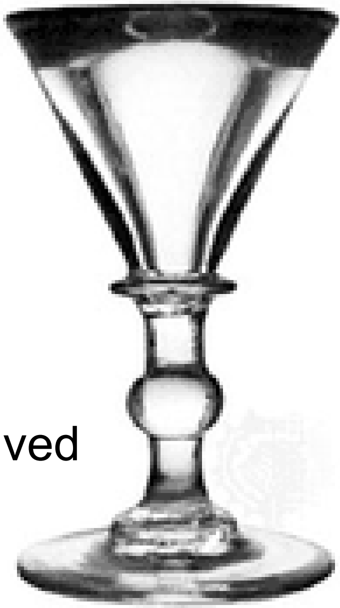
Main properties of „glass“

- Solid material
  - Atomic structure of liquid at room temperature
  - Amorphous material featuring isotropic properties
  - Lustrous, transparent, great durability
  - No plastic deformability
  - No melting point defined

- Glass formed by cooling of molten liquid while avoiding ordering via crystallization

4.4. Glass

Main properties of „glass“



- Most important glass family
  - Silica-based oxide glasses
  - Silica as raw material (or silicon dioxide SiO_2) found in quartz or beach sand
  - Silica glass (or vitreous silica, also called fused quartz if derived from melting of quartz crystals)
  - Exclusively composed of silica
-
- High service temperature, very high thermal shock
  - Resistance, high chemical durability
  - Very low electrical conductivity
  - Good ultraviolet transparency

4.4. Glass

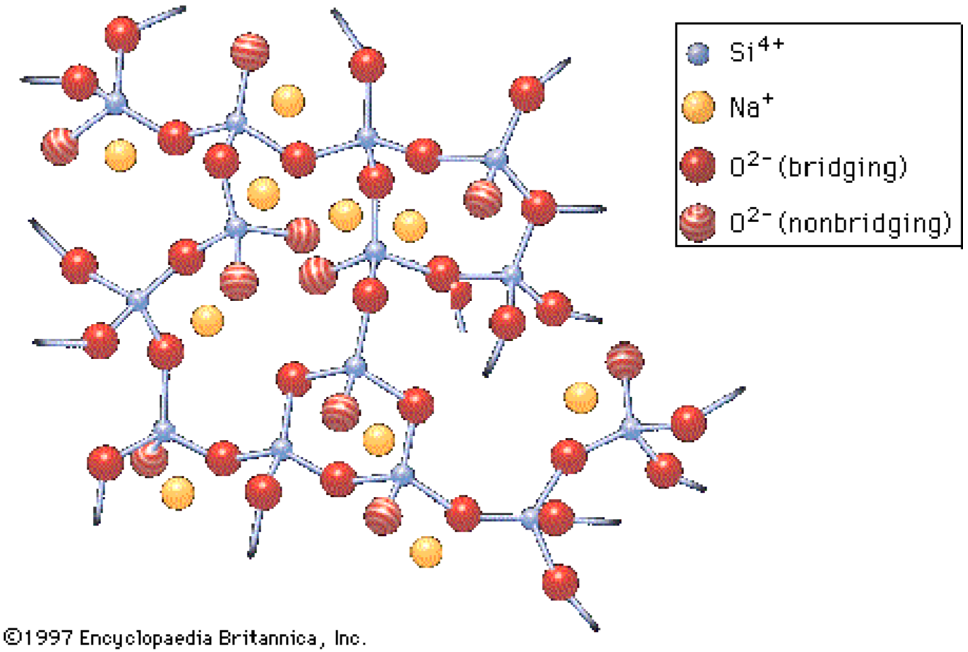


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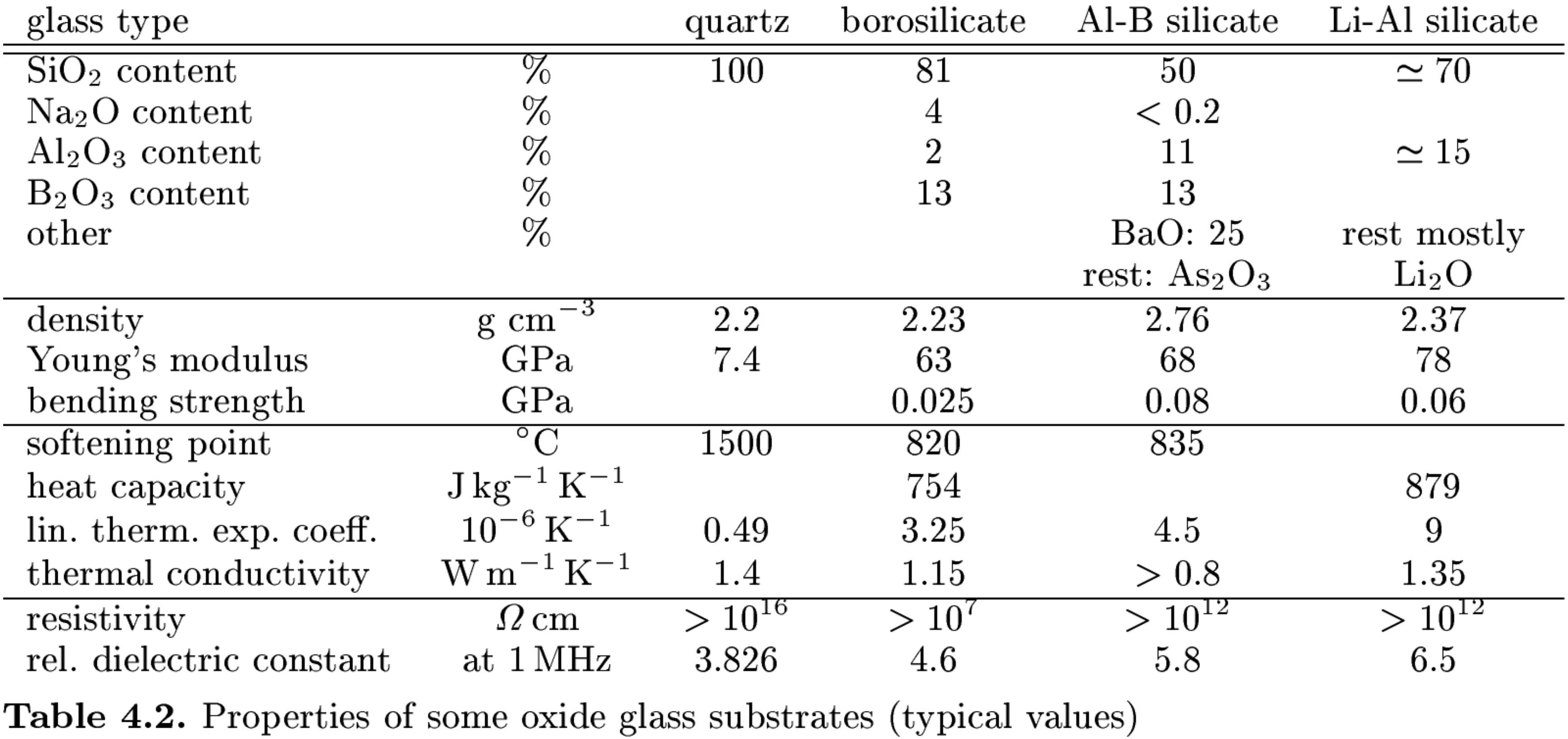
Fig. 4.17. Irregular arrangement of ions in a sodium silicate glass

- Basic constituents of sodium silicate glass
  - Polyhedra around network forming (NWF) cation (Si^{4+})
  - Positive charge surplus compensated by tetrahedrical bonding to SiO_4
    - Bridging oxygen: O^{2-} anion connecting two tetrahedra
    - Nonbridging oxygen: O^{2-} anion bonded to one SiO_4 cation, only

4.4 Glass



glass type		quartz	borosilicate	Al-B silicate	Li-Al silicate
SiO_2 content	%	100	81	50	$\simeq 70$
Na_2O content	%		4	< 0.2	
Al_2O_3 content	%		2	11	$\simeq 15$
B_2O_3 content	%		13	13	
other	%			BaO: 25 rest: As_2O_3	rest mostly Li_2O
density	$g\,cm^{-3}$	2.2	2.23	2.76	2.37
Young's modulus	GPa	7.4	63	68	78
bending strength	GPa		0.025	0.08	0.06
softening point	°C	1500	820	835	
heat capacity	$J\,kg^{-1}\,K^{-1}$		754		879
lin. therm. exp. coeff.	$10^{-6}\,K^{-1}$	0.49	3.25	4.5	9
thermal conductivity	$W\,m^{-1}\,K^{-1}$	1.4	1.15	> 0.8	1.35
resistivity	$\Omega\,cm$	$> 10^{16}$	$> 10^{7}$	$> 10^{12}$	$> 10^{12}$
rel. dielectric constant	at 1 MHz	3.826	4.6	5.8	6.5

Table 4.2. Properties of some oxide glass substrates (typical values)

4.4. Special Glass Types

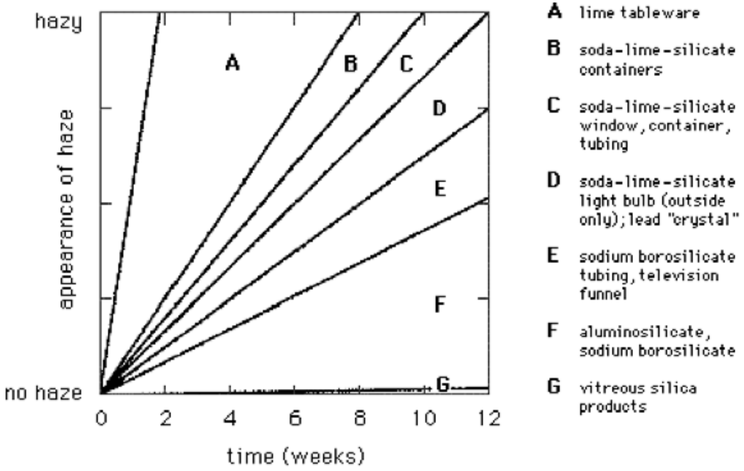


Fig. 4.18. Weatherability of some silicate glasses . The strongest weatherability is related to the glasses exhibiting the smallest slope. Lime tableware (A) displays the least weatherability and vitreous silica (G) the greatest weatherability

- Amount of „non-silica“ constituents affects and changes physical properties of glass
- Soda-lime glasses
  - ➢ Adding defined amounts of soda (or sodium oxide, Na_2O) and / or lime (or calcium oxide, CaO) to silica base material

4.4. Glass in MEMS Technology

- Quartz glass made from pure SiO_2
  - High thermal resistivity and transparency for UV radiation
  - Used as mask blanks in photolithography or substrates for subsequent thin film technology
  - Difference to quartz
    - Isotropic properties, no anisotropic etching possible!
- Borosilicate glass
  - Pyrex TM , Tempax TM and Corning 7740 TM
  - Thermal expansion coefficient adapted to silicon
  - Borosilicate wafers thus frequently used for bonding with silicon wafers (main application of glass in MEMS)
- Li-Al silicate glass wafers (FOTURAN TM)
  - Amenable for photostructuring due to special composition
  - Fine structures down to 25 µm with high aspect ratios possible

4.4. Structuring of Glass (FOTURAN)

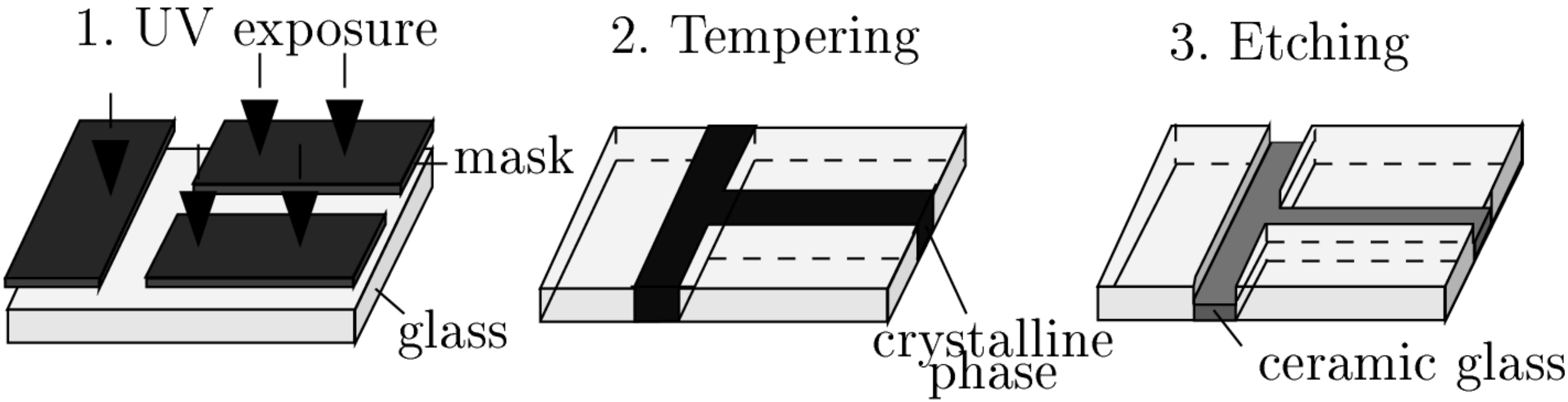
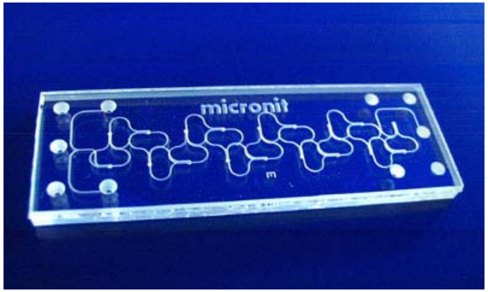


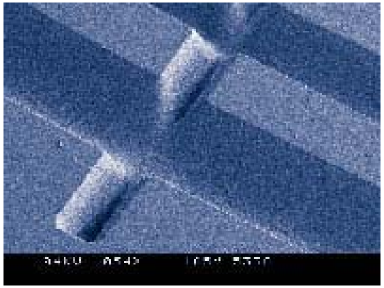
Fig. 4.19. Structuring of photosensitive glass (FOTURAN™) by UV–lithography, tempering and etching

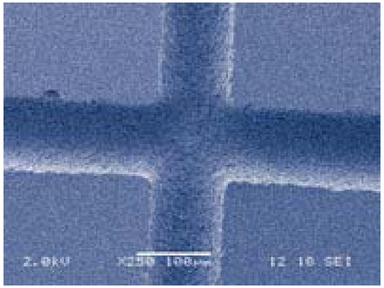
1. UV-exposure via metal (chromium) mask (no photo resist needed!)
2. „Transformation“ of exposed regions upon heating
3. Etching with 10% HF, etch rate up to 10µm per minute

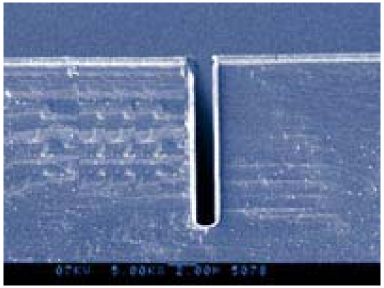
Micronit

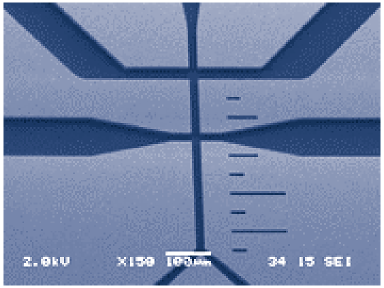
mixer

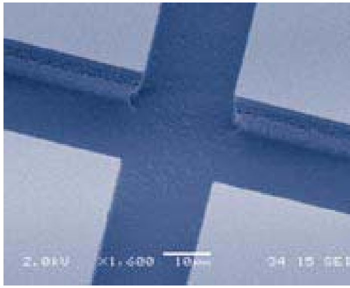




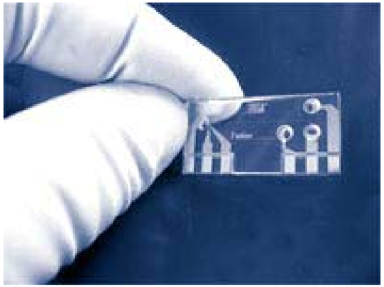








detection



4.4 Bonding of Glass

- Gluing
  - Fast-setting glues
- Thermal diffusion bonding
  - Pressure-assisted thermal bonding at several 100°C for several hours
  - Joining of two polished glass wafers
  - By diffusion, new chemical bonds form at these temperatures
  - Strong bond after cooling without application of adhesive reagents etc.
- Glass soldering
  - Interesting alternative to thermal bonding
  - Diffusion bonding may not be possible for instance due to high thermal stress on substrates
  - For these structures, vacuum-tight bonds may be accomplished by low-melting point solder deposited via screen printing
  - Glass soldering applicable to glass-glass interfaces as well as to bonding of glass with other materials
- Leakage problems common with glass after assembly!

4. Microfabrication Technologies

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4.5. Metals

- Mostly used as mold masters for subsequent replication
- E.g. via injection molding or hot embossing
- Microreactors
  - Permanent use
  - High aspect ratios
  - LIGA
  - High costs acceptable
- Inkjet printheads
  - Photoetched stainless steel

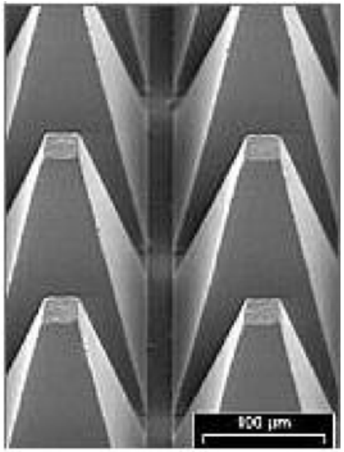

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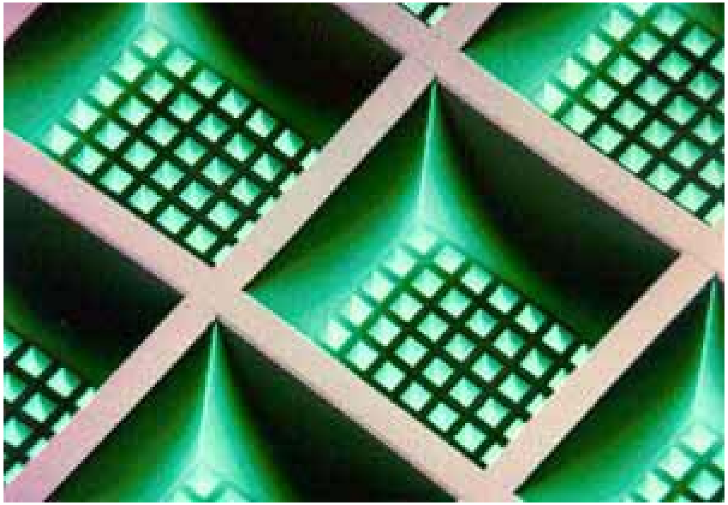
Fig. 4.21. Mold master fabricated by mechanical machining



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2. Plastics
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4.6. Ceramics

- Ceramic tape-based systems technology
- Ceramic powders for injection molding
- Slip casting of ceramic microcomponents
- Laminated ceramic microfluidic components for microreactor applications

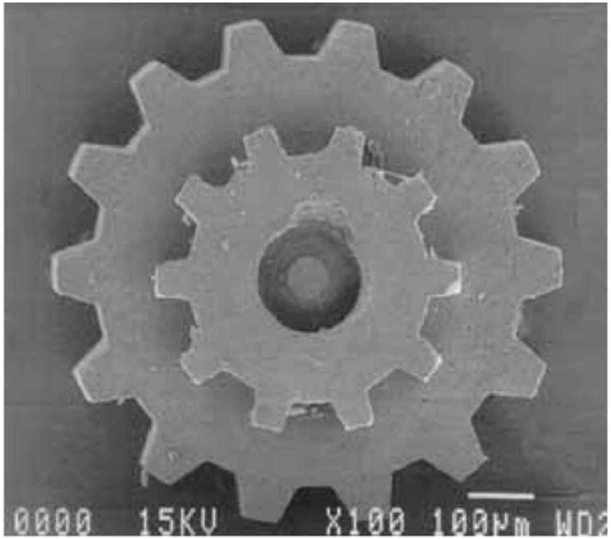

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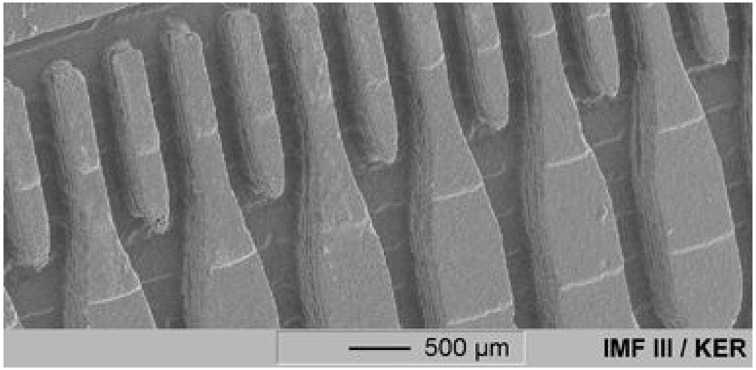
Fig. 4.20. Miniature gear wheel fabricated by ceramics injection molding



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2. Plastics
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6. Ceramics
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4.7. Alternative Concepts

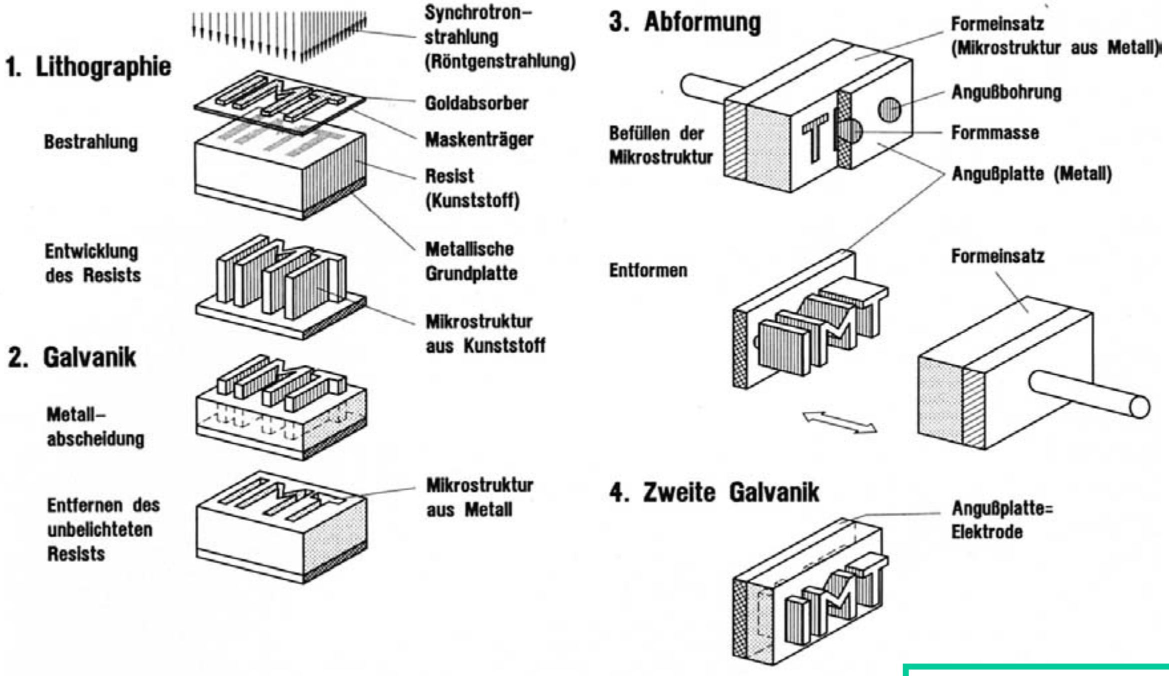
- Mass production
  - ➢ Hardly any alternatives to **lithographic processes** for
    - Silicon
    - Quartz
    - Glass
    - etc.
  - ➢ And (master-based) **replication processes** for
    - Hot embossing
    - Injection molding
    - Casting
    - Similar (plastics, ceramics, metals etc.)
- Alternative technologies for masks, mold inserts or prototypes
  - ➢ LIGA
  - ➢ SU8
  - ➢ Powder blasting
  - ➢ Laser ablation
  - ➢ Mechanical machining
  - ➢ Electrical discharge machining (EDM)
  - ➢ Photoforming

4.7. LIGA Technology

The LIGA process according to Prof. W. Menz

(**LIGA** = **Li**thographie, **G**alvanisierung, **A**bformung)

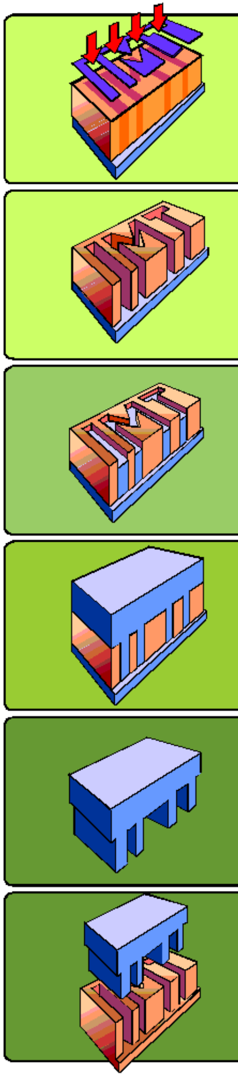
Lithography, Galvanization, Imprinting



LIGA one of first micro replication techniques

Also other ways to produce master
and for replication.

4.7. LIGA Technology



Characteristics of technology

Materials:	Metals, plastics
Lithography:	Synchrotron radiation, special masks
Aspect ratios:	Up to 100 (synchrotron radiation) Up to 30 („poor man‘s LIGA“; deep UV/SU8)
Feature sizes:	Heights up to ~ 3 mm, widths below 1 µm
Size of substrate:	Several cm² (typical 25 x 60 mm)
Others:	Access to synchrotron required

Initial costs

Costs for masks:	3,000 to 5,000 $ several masks required
Costs for mold insert:	6,000 $
Lithography:	Synchrotron radiation 100$ / hour
Investments:	- Synchrotron extremely expensive (2 Mio. $) - Hot embossing machine 100,000 – 300,000 $

4.7. High-Aspect-Ratio Microstructures (HARMs)

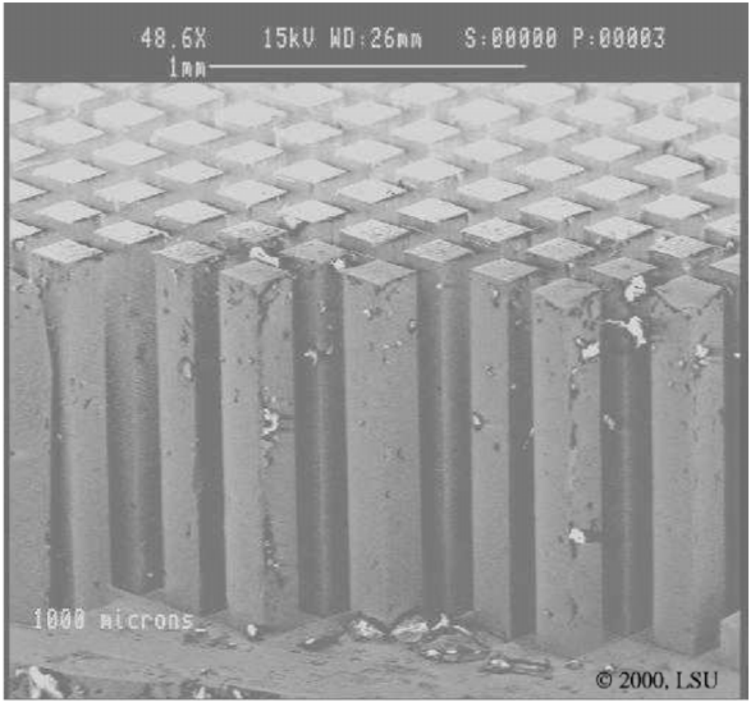


Fig. 4.23. Example of a high aspect ratio microstructure (HARM)

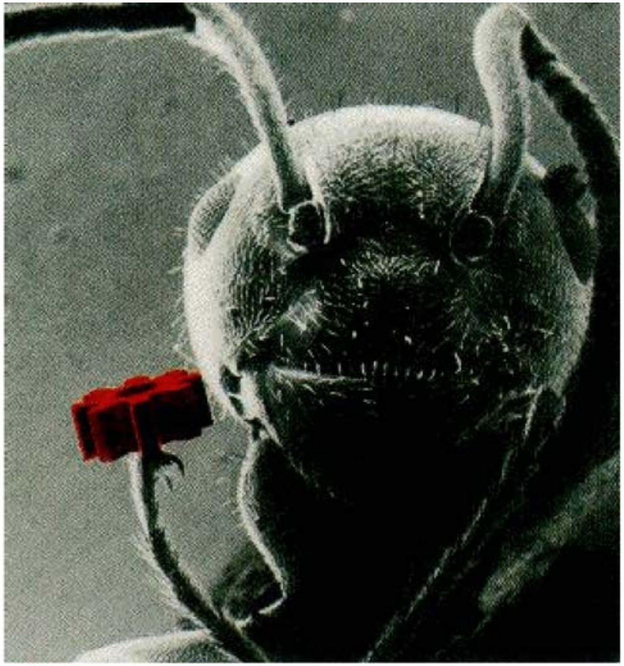
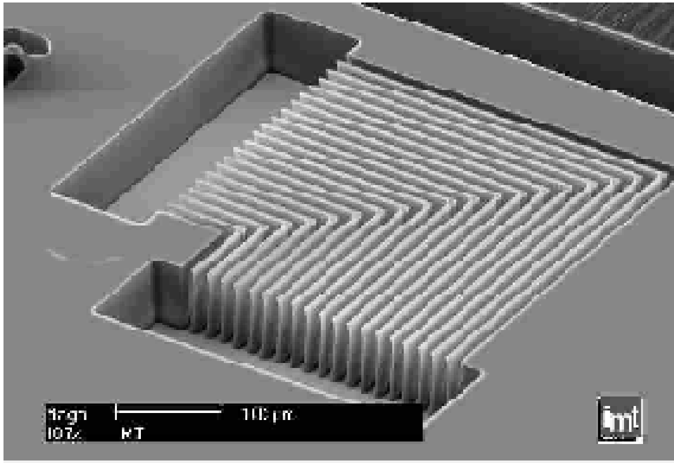


Fig. 4.24. Often cited "shaver" for ants manufactured by LIGA technology at FZ Karlsruhe

4.7. High Aspect Ratio Photo-Resists (SU8)



- Principle
  - Similar to LIGA with different resist and UV exposure
  - Direct manufacturing of prototypes
- Advantages
  - Much cheaper than LIGA
  - Somewhat cheaper than dry etching
  - Multilayered structures can be produced
  - Suitable for biological applications
- Disadvantages
  - No well-defined surface
  - No well-established process for sealing channels
  - Unreacted epoxy groups at surface can be used for further derivatization of interior walls of fluidic channels
- Sealing
  - Sealing fluidic structures one-by-one to glass cover slip with quick-setting glue has been demonstrated

4.7. Powder Blasting (PB)

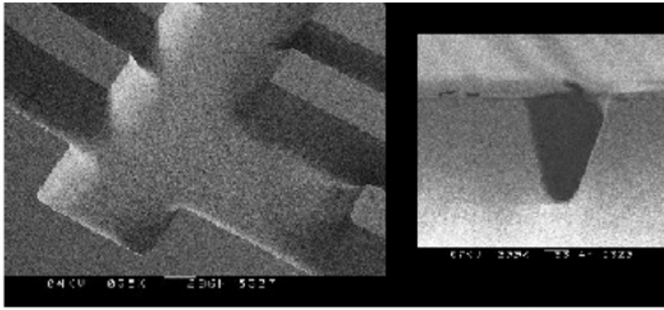


Fig. 4.26. Structures fabricated by powder blasting

- Mere physical process
- Single wafer process
- Structuring by particle bombardment
- Particles accelerated by high pressure air stream
- Particles projected to target at velocity of 700 km / h
- Typical particle size 20 µm to 50 µm
- Employable for structuring brittle materials like glass and ceramics
- Ductile materials difficult to structure
  - Masks
  - Minimum dimension down to 150 µm
- Advantages of PB
  - ➢ No clean room required
  - ➢ Rather inexpensive equipment
  - ➢ Non-isotropic etching possible in isotropic (brittle) media like silicon, glass and ceramics for high aspect ratios
  - ➢ Etch rates 25 times or more greater than RIE

4.7. Laser Ablation

- Precision machining on µ-scale
- Direct or mask assisted process
- Laser radiation with wave length between infrared and ultraviolet
- Laser-substrate interaction depends on material characteristics and can be manipulated by laser
  - Wave length
  - Pulse length
  - Energy density
- Laser types
  - Nd:YAG
  - Excimer laser

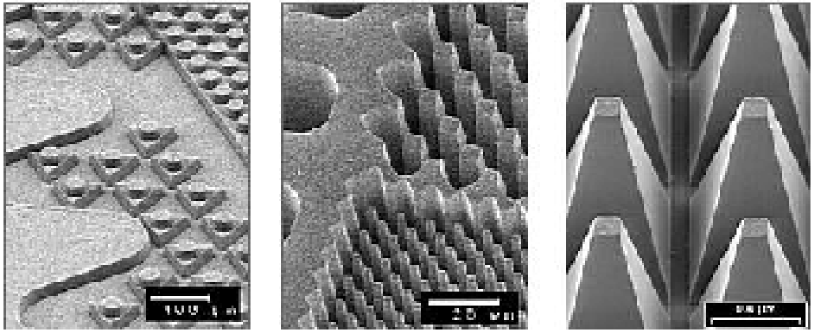


Fig. . Flow structures fabricated by laser machining Microparts00

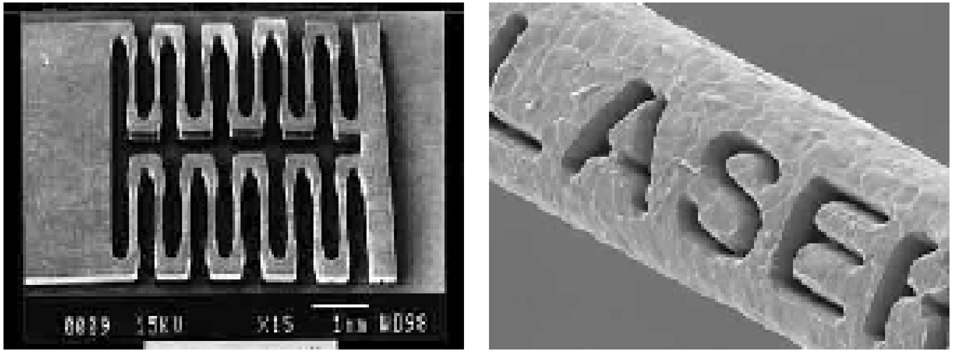


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Fig. . Structures generated by laser ablation. (left) Linear micro-actuator fabricated in NiTi shape memory alloy (right) Human hair (60 µm diameter FZK00

4.7. Electro-Discharge Machining (EDM)

- Principle
  - Workpiece shaped by ignition spark discharge with electrode tool
  - Energy dissipated in local discharge
  - Subsequent melting and evaporation of substrate material
  - Workpiece and tool immersed in insulating liquid such as deionized water or kerosene
- Materials
  - Applies to conducting substrates regardless of their respective conductivity (such as metals or certain semiconductors like silicon)
- Advantages
  - Non-contact method, only small forces exerted on tool and workpiece
  - Allowing for tiny and fragile tools and substrates
  - EDM independent of physical, chemical or mechanical properties of substrate, e.g. allowing hardening prior to EDM treatment
- Drawbacks
  - Wear of tools

4.7. Micro EDM (µEDM)

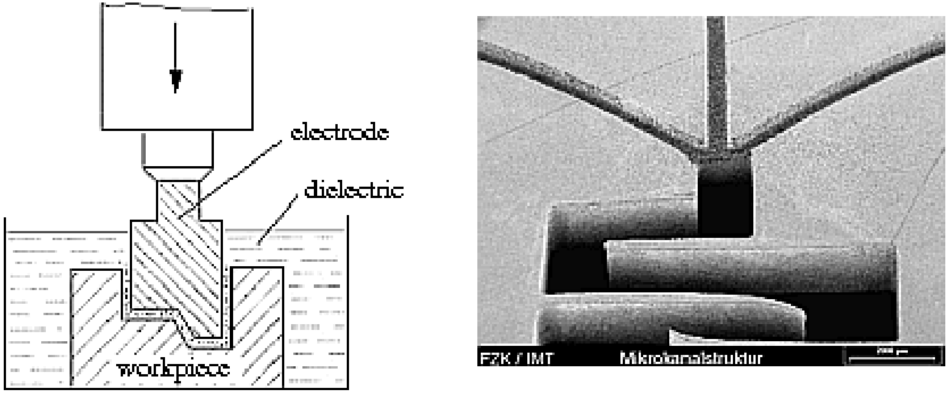

Fig. 4.33. Schematic of µEDM sinking by moving a shaped tool into the workpiece which is situated in a dielectric bath

- Same principle as EDM
- Special features
  - Smallest electrodes
  - Less power
  - Higher frequency
  - Computer controlled wire movement

4.7. Wire-Cutting EDM (µEDM)

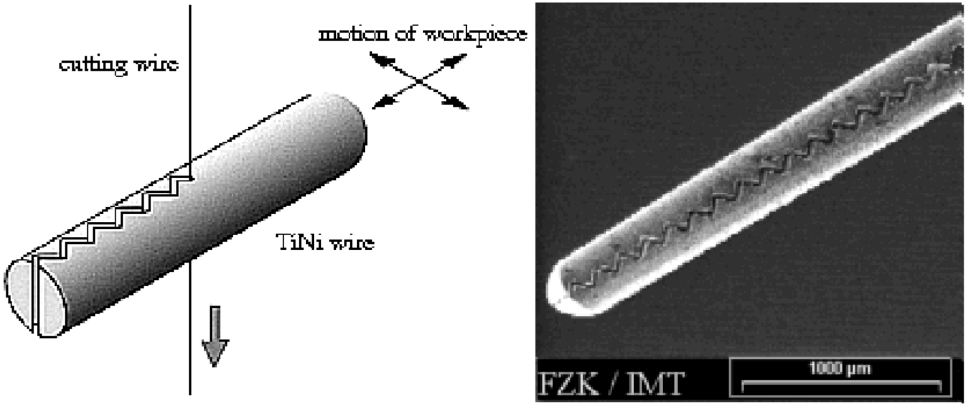

Fig. 4.32. Schematic and example of cutting by µEDM. Using a Ø30-µm cutting wire, a Ø390-µm wire workpiece is cut in a zigzag shape

- Cutting through whole substrate
- Thin wire constitutes electrode
- Wear effects minimized by continuously feeding wire

4.7. Photoforming

- Principle
  - Laser assisted polymerization
  - Structure formed by successively adding new layers
- Materials
  - Light-curable resins
- Application
  - Rapid prototyping

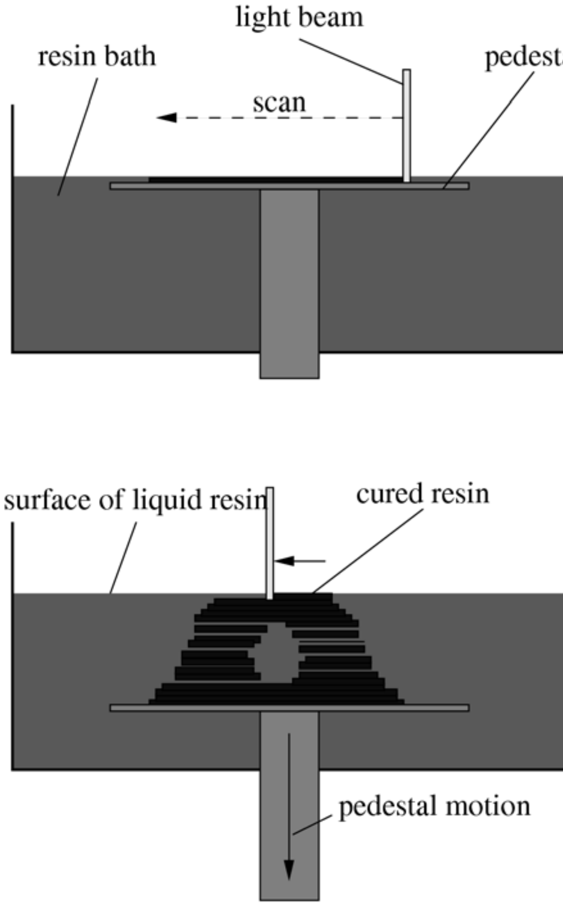

Fig. 4.34. The photoforming process

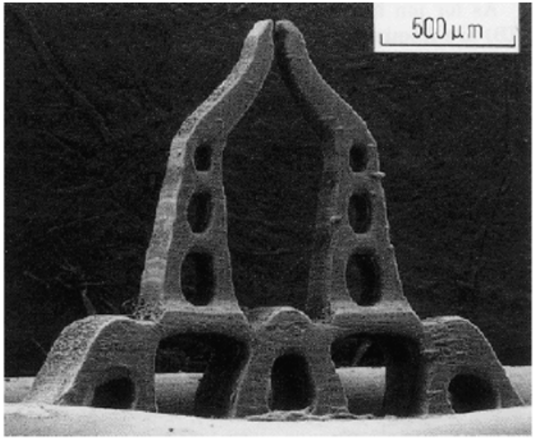

Fig. 4.35. Gripper fabricated by high-resolution photoforming process using photopolymerizing resin and argon laser

4.7. Ground-Plate Supported Insulating Channels / Buried Channels

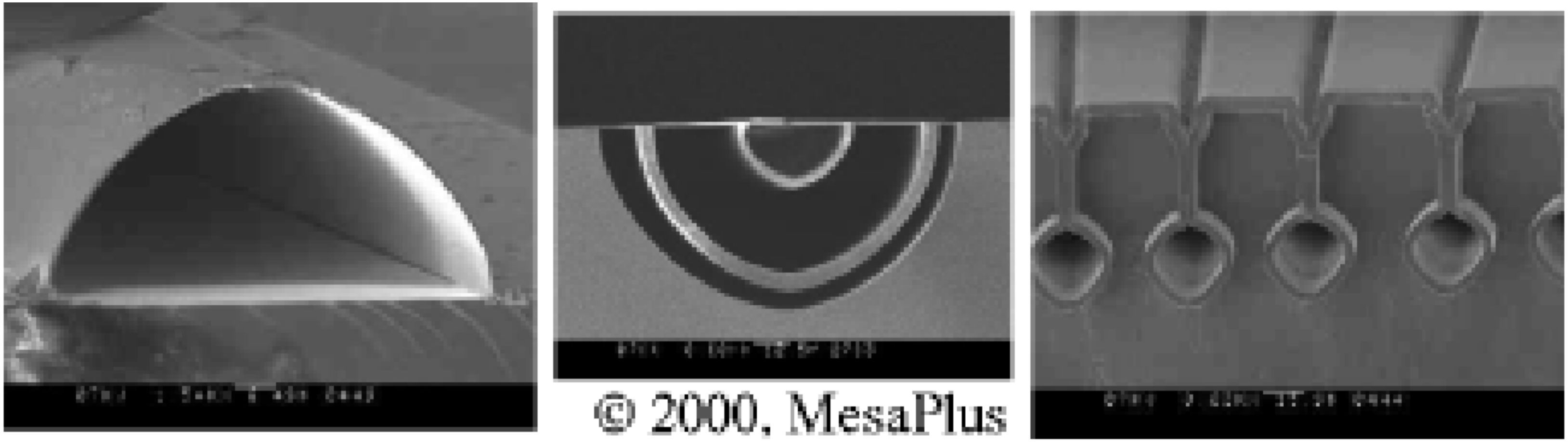

Fig. 4.27. Structures fabricated by GPSIC (left) GPSIC, consisting of a thin layer of silicon nitride bonded to a glass wafer. These channels can be used in electrophoresis applications (middle) a multi walled micro channel. The free-hanging layers consist of porous silicon (right) 4 channels that are buried beneath the surface of the wafer

MESA+, University of Twente

4.7. Ground-Plate Supported Insulating Channels

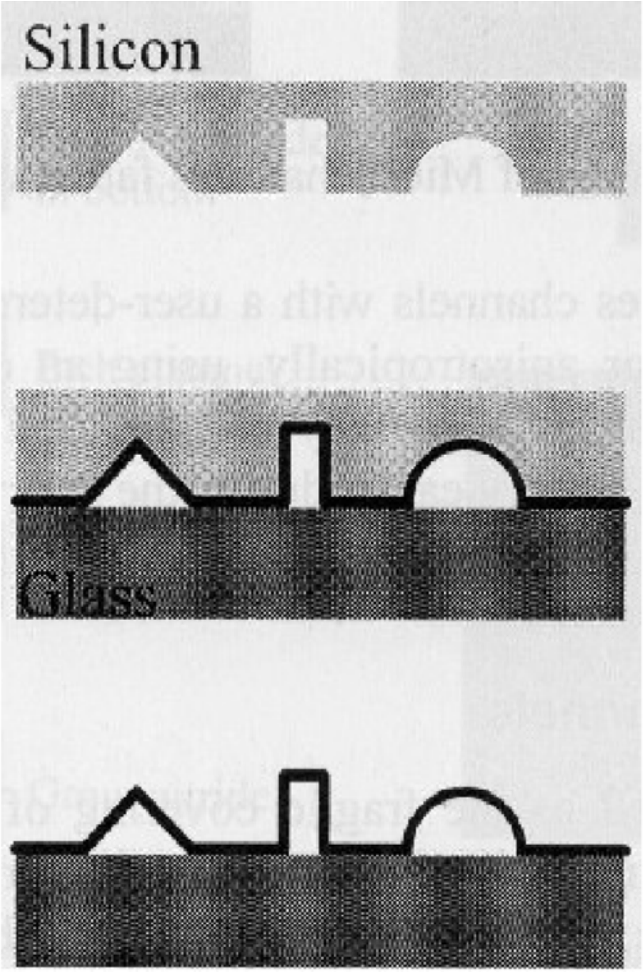

Fig. 4.28. GPSIC process. A silicon wafer is structured and an insulating layer is formed on its surface. After bonding to a glass wafer, the silicon is completely etched until the insulating layer remains as a free standing 3-dimensional structure

4.7. Buried Channels

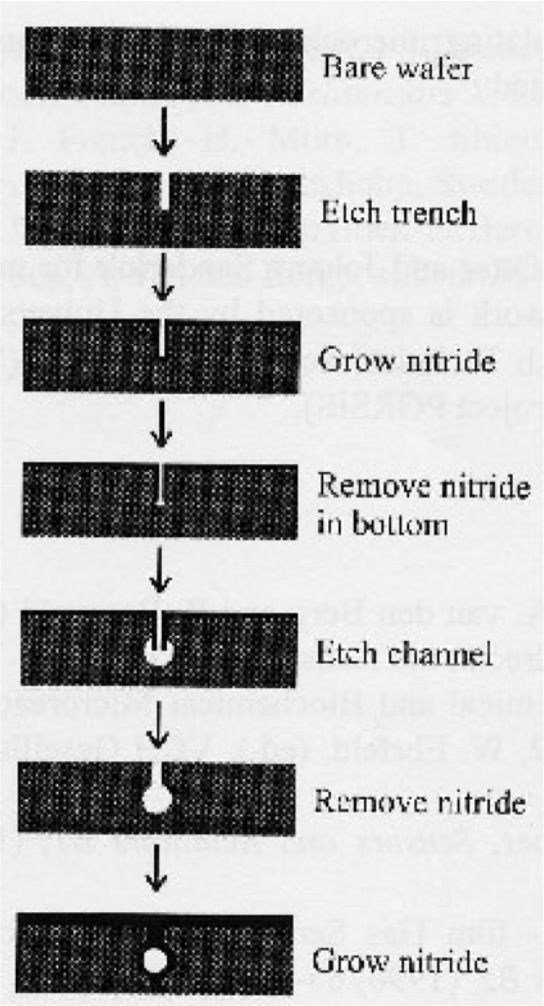

Fig. 4.29. Process steps to generate buried channel structures

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4. Microfabrication Technologies

1. Silicon
2. Plastics
3. Quartz
4. Glass
5. Metals
6. Ceramics
7. Alternative Concepts
8. Surface Modifications
9. Interconnection Technology
10. Layout of Microfluidic Systems
11. Ingredients for Commercial Success

4.8. Surface Modifications

- Surface coatings
  - Self-assembling monolayers (SAMs)
    - Monomolecular layers of long-chain alkenes
    - Well-defined surface, also for covalent binding
  - Plasma treatment
    - Enhancing hydrophilicity of surfaces
    - Problem: long-term stability
  - Hydrophobic layers, e.g. Au (unpolar)
- Dispensing / evaporation
  - Localized application
  - Block of spreading
- Spraying
  - Localized application
  - Also mask based
- Dip coating
  - Treatment of whole substrate
  - UV crosslinking

4. Microfabrication Technologies

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4.9. Interconnection Technology

- Interconnections on same chip usually no problem
  - Part of integrated microfabrication process

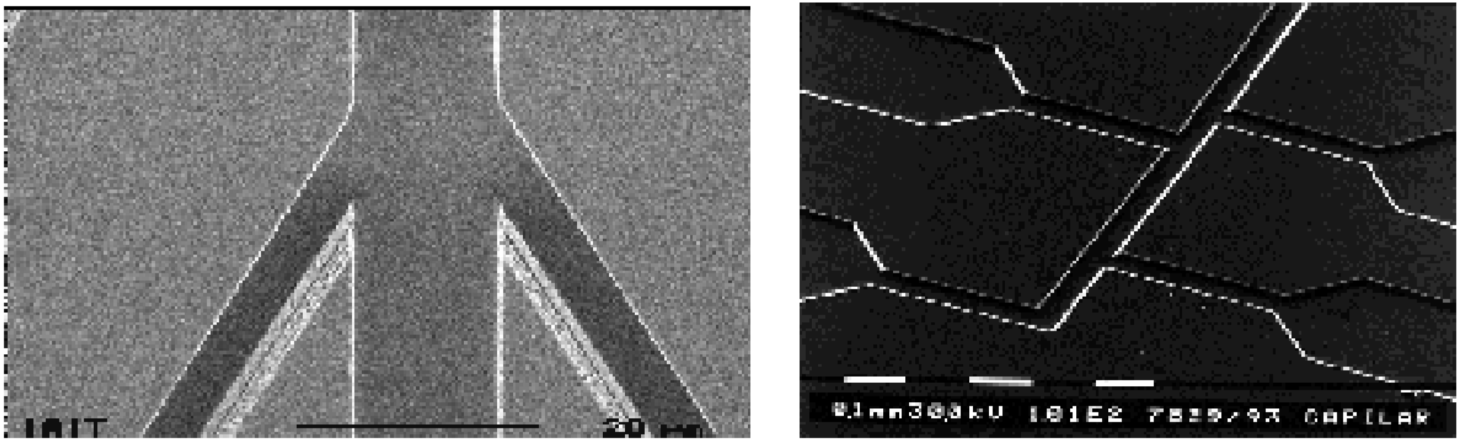


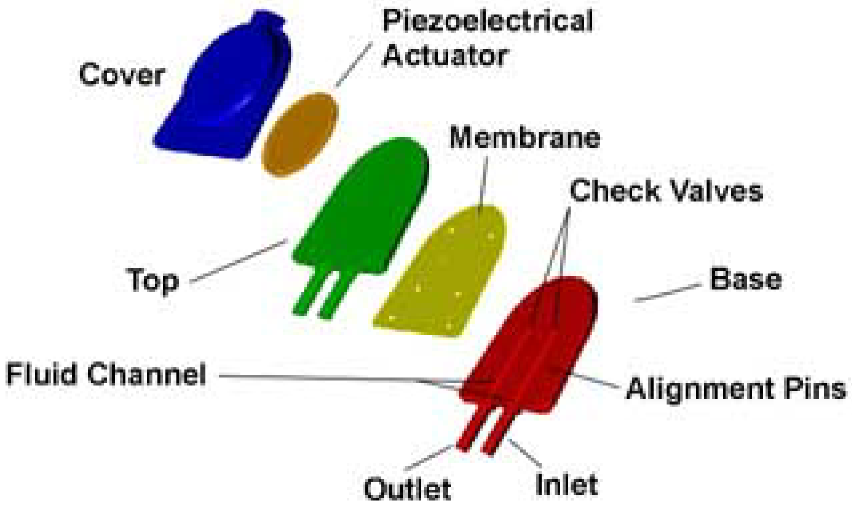
Fig. 4.36. Connections between vessels on the same chip can be established by integrated microfabrication

HSG-IMIT

- Real problems
  - Connectors between microdevice and macroscopic world or within hybrid multi-component microdevices

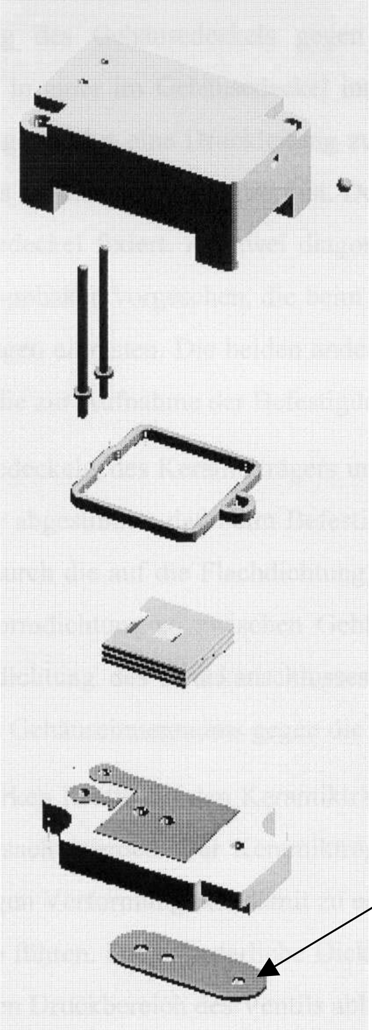
4.9. Tube Connections

- Injection molded plastic parts can be provided with suitable tube connections
  - ➢ Example: plastic micropump
- Advantage
  - ➢ Cheap interconnection solution
- Disadvantage
  - ➢ Large dead volume
  - ➢ Danger of trapping bubbles due to differently sized channel diameters
  - ➢ Danger of leakage at high pressures



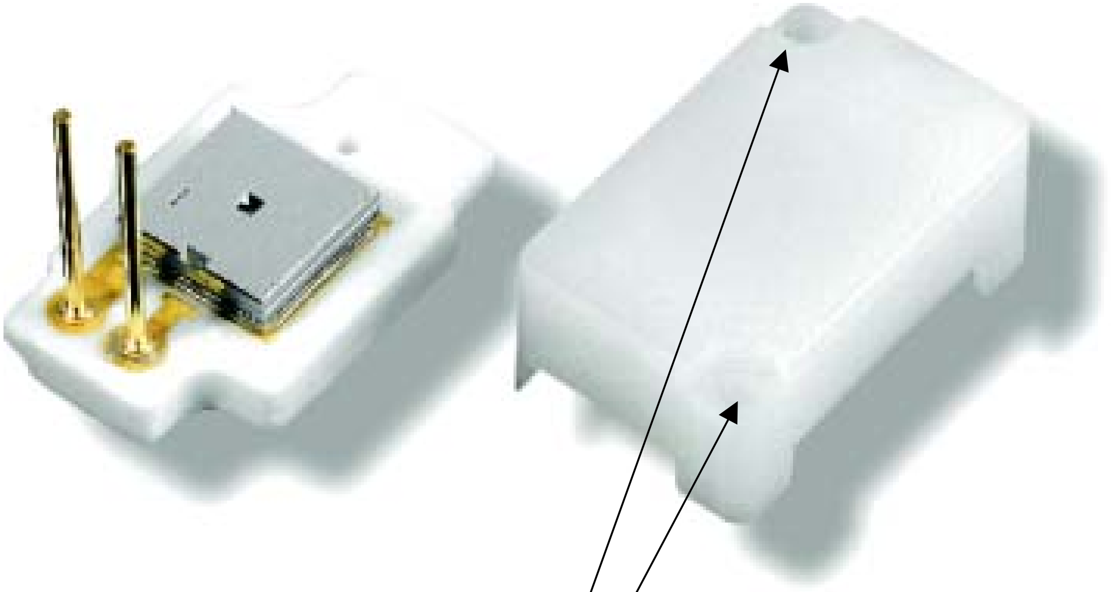
Source: IMM Mainz

4.9. Flange Joints: Example MegaMic



Pneumatic valve: MegaMic

Source: HSG-IMIT

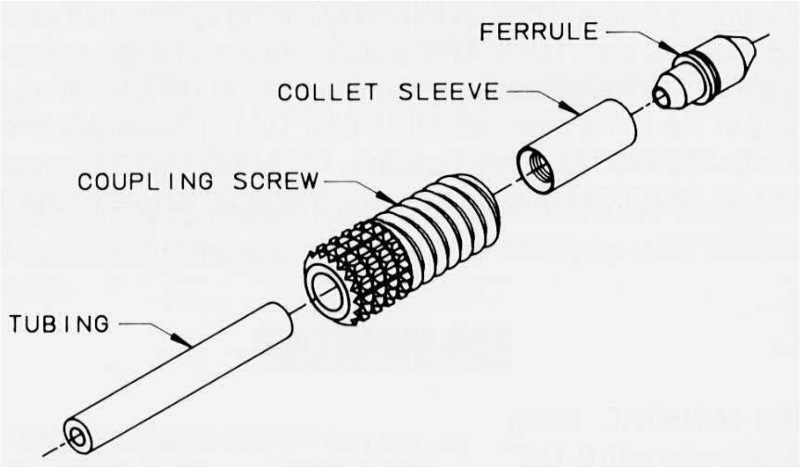


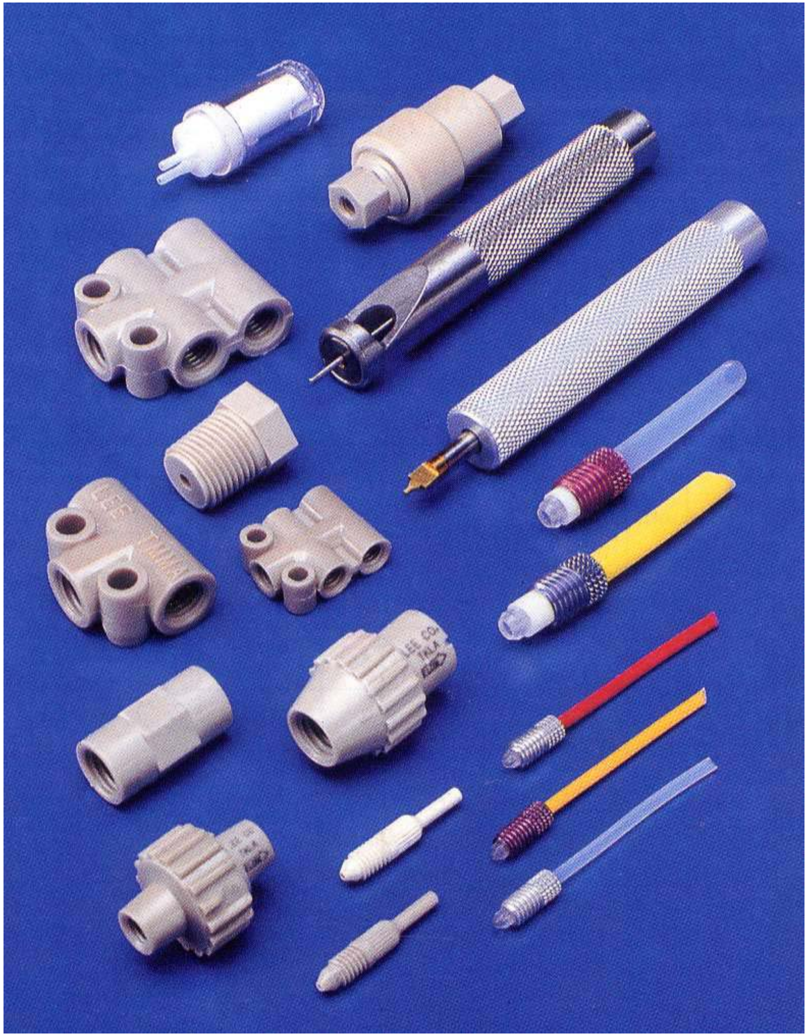
Flange joints by screw connection through housing, pressure resistant up to 20 bar

4.9. Lee-System

- The company Lee provides various connection and tubing systems
  - Easily applicable to microfluidic systems if joints fitting to 0.8 mm MINSTAC 062 System are provided

MINSTAC 062 System





4.9. Special Individual Solutions

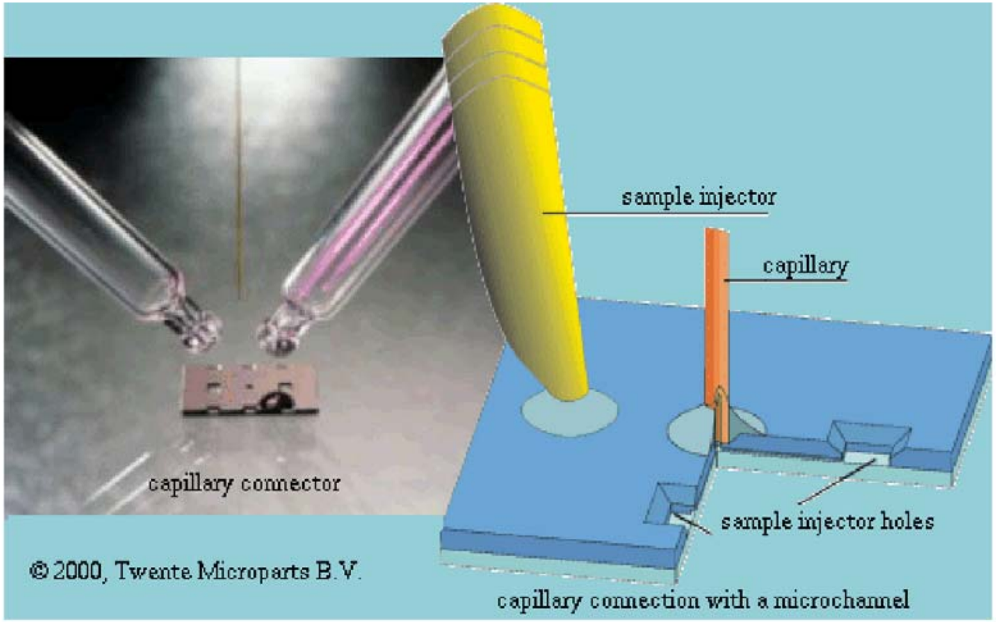


Fig. 4.40. Capillary connectors and sample injectors by Twente Microproducts B.V.

[N.J. Mourlas et al. Transducers ´99]

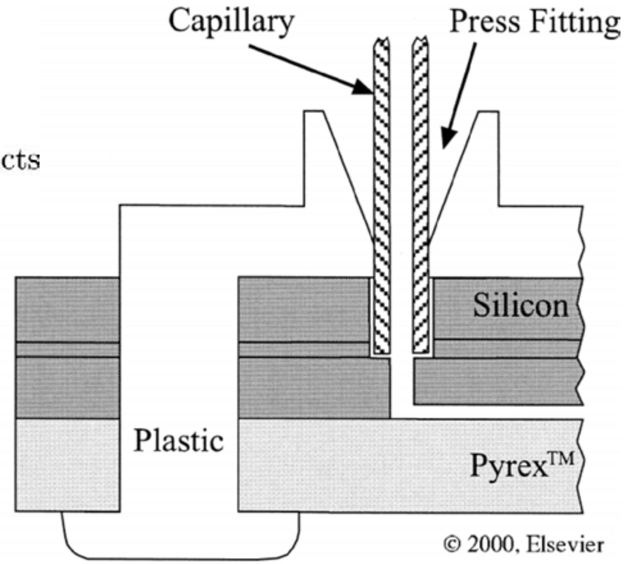


Fig. 4.37. Press-fitting system for capillaries into silicon fluidic chips

4. Microfabrication Technologies

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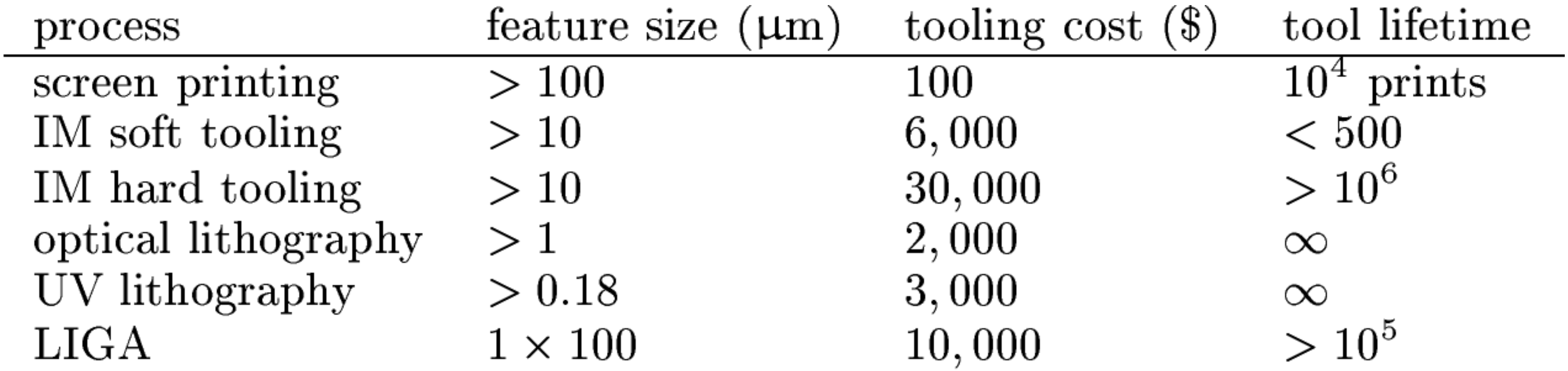
4.11 Ingredients for Commercial Success



process	feature size (µm)	tooling cost ($)	tool lifetime
screen printing	> 100	100	10^4 prints
IM soft tooling	> 10	$6,000$	< 500
IM hard tooling	> 10	$30,000$	$> 10^6$
optical lithography	> 1	$2,000$	∞
UV lithography	> 0.18	$3,000$	∞
LIGA	1×100	$10,000$	$> 10^5$

Table 4.3. Tooling costs in MEMS technology

- Commercial success
  - Contribution to creation of value
- Costs of technology
  - Feature size
  - Tooling costs
  - Tool lifetime

4.11 Ingredients for Commercial Success

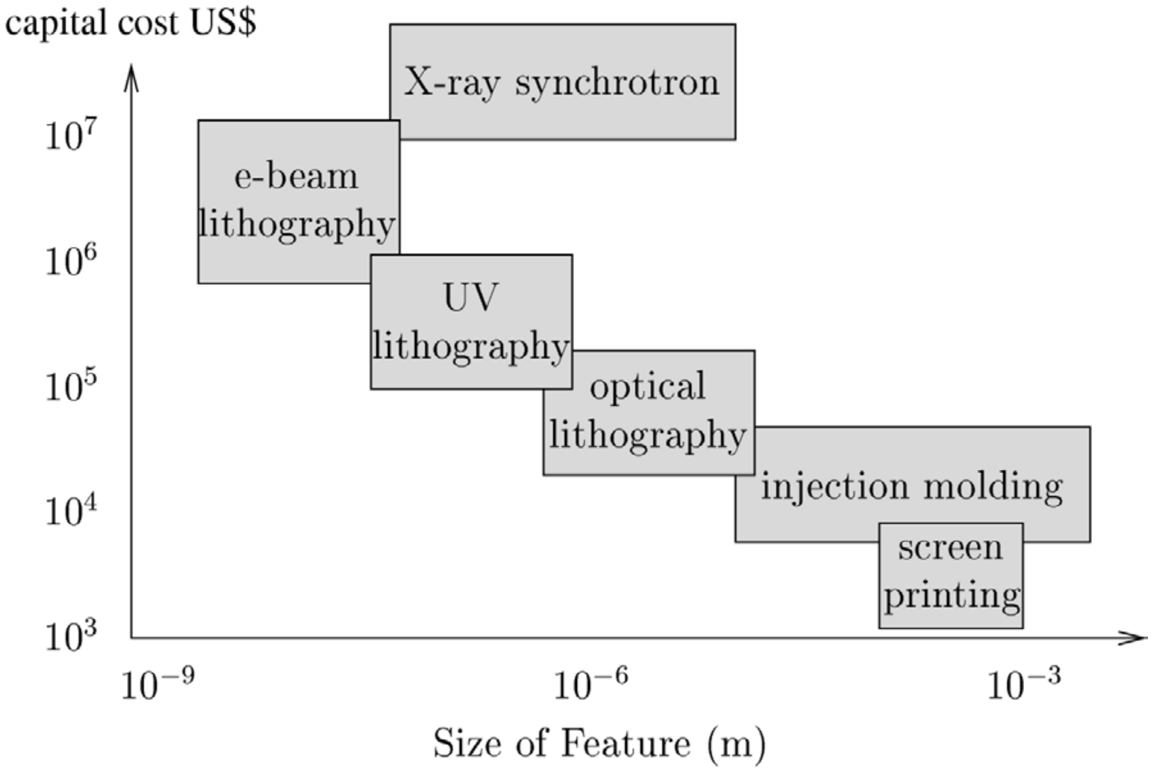


Fig. 4.45. Capital cost versus feature sizes attainable with the associated technology

- Capital investment vs. feature size

4.11 Ingredients for Commercial Success

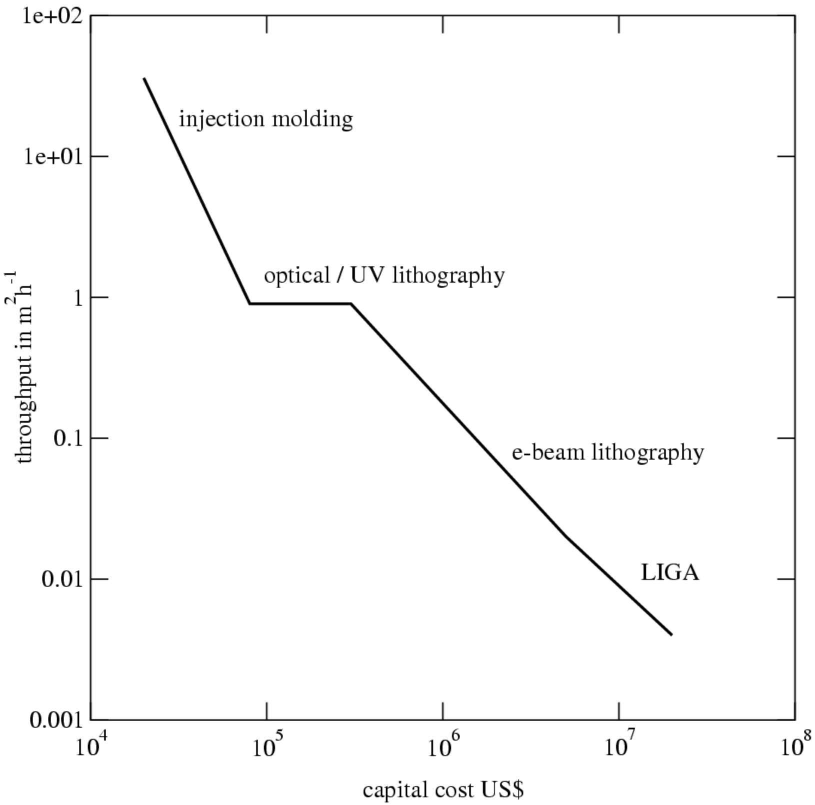


Fig. 4.46. Throughput as a function of capital costs for commonly employed processes in microfabrication

- Throughput vs. capital cost

4.11 Ingredients for Commercial Success

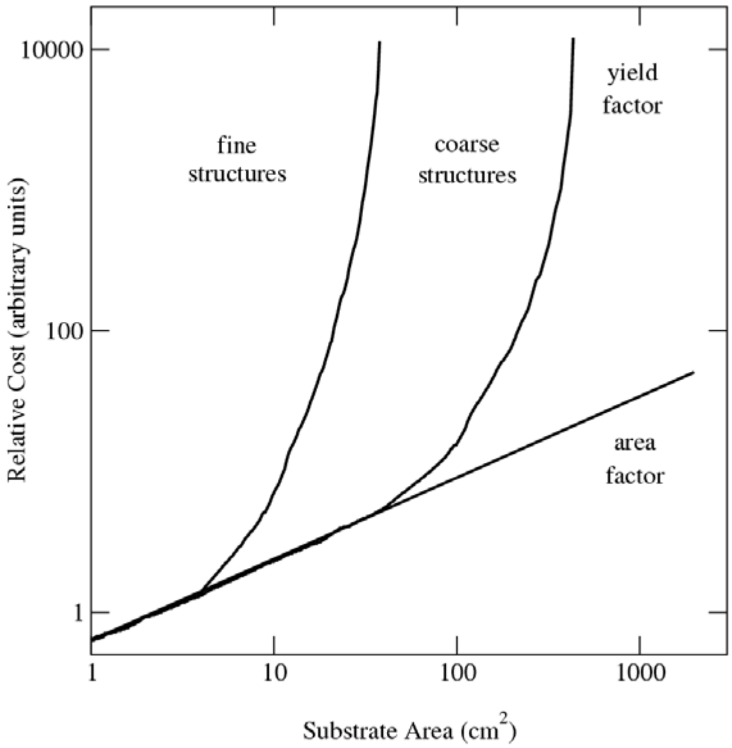


Fig. 4.47. Impact of yield on relative cost for a simple printed circuit board process

- Impact of yield on relative costs
  - ➢ Example: simple PCB

4. Conclusions

- There are several production technologies for microstructuring silicon (wet etching, dry etching) as well as for plastic materials (injection molding, hot embossing) which are well suited for mass production.
- The costs for micromachining of silicon devices increase with surface area and are hardly dependent on production volume.
- The costs for microfabrication of plastic devices are mainly determined by investments (machines, mold inserts etc.). They decrease with increasing production numbers.
- Which materials are to be used has to be determined according to the specific application, production numbers and necessary investments.
- For special applications and rapid prototyping there exist a wide variety of production technologies and materials. These are in general not suited for mass production.