Polymer-Based Microfabrication

- Thick photoresist lithography
- Polymeric surface micromachining
- Soft lithography
Rigid Materials vs. Soft (Elastomeric) Materials

**Rigid materials**
Crystalline silicon, amorphous silicon, glass, quartz, metals

**Advantages:**
- Photolithography process is mature and well developed (e.g. PR against etching)
- Bulk-etching for forming two- and three-dimensional shapes
- Batch process – compatible with IC process
- Silicon dioxide: good quality, stable chemically and thermally

**Disadvantages:**
- Expensive
- Brittle
- Opaque (for silicon) in the UV/Vis regions
- Surface chemistry is difficult to manipulate

**Packaging/Bonding:**
- Anodic bonding (Si-Glass)
- Fusion bonding (Glass-Glass; Si-Si)
- Polymer bonding
Rigid Materials vs. Soft (Elastomeric) Materials

**Soft materials**
PDMS, PMMA, SU-8, AZ4000 series, Polyimide, Hydrogel, etc..

**Advantages:**
- Inexpensive
- Flexible
- Transparent to visible/UV
- Durable and chemical insert
- Surface property easily modified
- Improved biocompatibility and bioactivity

**Disadvantages:**
- Low thermal stability
- Low thermal and electrical conductivity

**Packaging/Bonding:**
- Through surface modification – easy but not robust
Thick Resist Lithography

**Polymethylmethacrylate (PMMA) Resist**
- e-beam, deep UV (220-250nm) and X-ray lithographic processes

- **LIGA process:** x-ray lithography + electroplating

- Deposition of PMMA on a substrate
  - Multiple spin-coating
  - Prefabricated sheet

- Structuring of thick PMMA requires collimated X-ray (0.2 nm -2nm), which are only available in synchrotron facility.

- Require special **mask substrates** such as beryllium and titanium; the **absorber** material can be gold, tungsten, etc.

- The limited access and costs of a synchrotron facility is a major drawback; although very high aspect ration can be achieved, it has been gradually replaced by other thick PR such as SU-8.
SU-8 Resist (Microchem)

SU-8 is a negative photoresist based on EPON SU-8 epoxy resin for the near-UV wavelengths from 365 nm to 436 nm. At these wavelengths the photoresist has very low optical absorption, which makes photolithography of thick films with high aspect ratios possible.

<table>
<thead>
<tr>
<th>Product Name</th>
<th>Viscosity (cSt)</th>
<th>Thickness (µm)</th>
<th>Spin Speed (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>3000</td>
</tr>
<tr>
<td>SU-8 2</td>
<td>45</td>
<td>2</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
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<tr>
<td></td>
<td></td>
<td>5</td>
<td>3000</td>
</tr>
<tr>
<td>SU-8 5</td>
<td>290</td>
<td>7</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>3000</td>
</tr>
<tr>
<td>SU-8 10</td>
<td>1050</td>
<td>15</td>
<td>2000</td>
</tr>
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<td></td>
<td></td>
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<tr>
<td></td>
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<td>15</td>
<td>3000</td>
</tr>
<tr>
<td>SU-8 25</td>
<td>2500</td>
<td>25</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40</td>
<td>3000</td>
</tr>
<tr>
<td>SU-8 50</td>
<td>12250</td>
<td>50</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>3000</td>
</tr>
<tr>
<td>SU-8 100</td>
<td>51500</td>
<td>150</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>250</td>
<td>1000</td>
</tr>
</tbody>
</table>

1 St(Stroke) = 1 cm²s⁻¹
**Steps**

- Substrate Pretreat
- Coat
- Soft Bake
-Expose
- Post Expose Bake (PEB)
- Develop
- Rinse & Dry
- Hard Bake (optional)

**Spin speed:**

- 65-95 °C
- 365-436 nm
- 65-95 °C

**Baking times (min):**

<table>
<thead>
<tr>
<th>Product Name</th>
<th>Thickness (µm)</th>
<th>Pre-bake @ 65°C</th>
<th>Softbake @ 95°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU-8 50</td>
<td>40</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>6</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>SU-8 100</td>
<td>150</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>30</td>
<td>90</td>
</tr>
</tbody>
</table>

(Microchem, Inc.)
AZ4562 (Clariant)

- Positive PR
- Thickness up to 100 μm
- High resistance to plasma, good adhesion properties, high-resolution capability
- Typically used as a mold for subsequent metal electroplating or as master templates for micromolding. No reports of using AZ4562 directly as structural material.

<table>
<thead>
<tr>
<th>Resist</th>
<th>PMMA</th>
<th>SU-8</th>
<th>AZ4562</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure type</td>
<td>X-ray (0.2 – 2 nm)</td>
<td>UV (365, 405, 435 nm)</td>
<td>UV (365, 405, 435 nm)</td>
</tr>
<tr>
<td>Light source</td>
<td>Synchrotron facility</td>
<td>Mercury lamp</td>
<td>Mercury lamp</td>
</tr>
<tr>
<td>Mask substrate</td>
<td>Beryllium (100 μm)</td>
<td>Glass (1.5 –3 mm)</td>
<td>Glass (1.5 –3 mm)</td>
</tr>
<tr>
<td></td>
<td>Titanium (2 μm)</td>
<td>Quartz (1.5 – 3 mm)</td>
<td>Quartz (1.5 – 3 mm)</td>
</tr>
<tr>
<td>Mask absorber</td>
<td>Gold (10 –15 μm)</td>
<td>Chromium (0.5 μm)</td>
<td>Chromium (0.5 μm)</td>
</tr>
<tr>
<td>Max. height</td>
<td>1,000 μm</td>
<td>250 μm</td>
<td>100 μm</td>
</tr>
<tr>
<td>Aspect-ratio</td>
<td>~500</td>
<td>20 – 25</td>
<td>~10</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>2–3</td>
<td>4–5</td>
<td>-</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>-</td>
<td>0.22</td>
<td>-</td>
</tr>
<tr>
<td>Glass temperature (°C)</td>
<td>100</td>
<td>&gt; 200</td>
<td>-</td>
</tr>
</tbody>
</table>
Polymeric Surface Micromachining

• Polymeric surface micromachining is similar to silicon surface micromachining
• Polymers are used as structural or as sacrificial material

## Polyimide (PI)

• A single spin can result in a film thickness up to 40 µm.
• Photosensitive polyimide can be used for the same purpose as other thick PR
• Fluorinated polyimide is an interesting material because of its optical transparency and simple machining. In RIE processes of this material, fluorine radicals are released and act as etchants.

## Parylene

• Parylene is a polymer that can be deposited with CVD at room temperature. The CVD process allows coating with a conformal film with thickness ranging from several micrometers to several millimeters.
• Parylene can be used in microfluidic devices as a structural material, which offers low Young’s modulus. Such a soft material is needed in microvalves and micropumps.
**Electrodepositable Photoresist** (e.g. ED2100, PEPR 2400 (Shipley Europe Ltd.))

- The photoresist is an aqueous emulsion consisting of polymer micells.
- The photoresist is deposited on wafers by electrodeposition process. In an electric field, positively charged micells move to the wafer, which works as a cathode. The polymer micelles coat the wafer until the film is so thick that deposition current approaches zero.
- Typical thickness: 3 -10 um.

**Conductive polymers**

- Conductive polymers or conjugated polymers are polymeric materials, which has received growing attention of the MEMS community.
- Conjugated polymers have alternating single and double bonds between a carbon atom along the polymer backbone. This results in a band gap and makes the polymers behave as semiconductors.
- Doped conjugated polymers can be used as the material for electric device such as diodes, LED, and transistors.
- The doping level of polymers is reversible and controllable. In some polymers, the changes of doping level leads to volume change — can be as actuators. The most common and well-research conjugated polymer is polypyrrole (PPy).
Integration of Rigid and Soft Materials

1. Deposit and pattern nitride. Local oxidation.
2. Deposit and pattern PSG.
3. Deposit thick nitride and open etch holes;
   High concentrated HF removes oxide and PSG.
4. Seal cavities by depositing and patterning
   LTO/nitride.
5. Deposit, dope and pattern polysilicon.
6. Deposit thin nitride and open contact holes;
   Metallization.
7. Spin on, cure and pattern polyimide at 350°C.
8. Pattern backside: RIE etches nitride;
   DRIE etches Si to 70 µm thick.
9. DRIE etches away silicon between islands;
   RIE removes nitride.
10. Spin, pattern and cure polyimide on the backside.
    Electroless plate nickel/gold on backside pads.

A flexible shear stress skin for aerodynamic applications

(Tai)
Hydrogel Based Microfabrication

Hydrogel Fabrication

- Photosensitive (polarity like negative PR)
- Liquid-phase photo-polymerization
- Laminar flow-aided patterning
- Functional (stimuli-responsive) and non-functional materials
- Fabrication of fluidic channels, actuators, valves, pumps

A hydrogel jacket valve in a T channel (D. Beebe)
Fabrication of a valve in a Hydrogel Microchannel

2-D and 3-D micro fluidic network

1. Fabricate cartridge
2. Fill, expose and flush to create channels.
3. Flow in prepolymer mixture for functional hydrogel
4. Expose and flush to create autonomous valve
Geometry Control during Fabrication by Using Laminar Flows
Soft Lithography

- Developed by Whitesides, et. al

A set of techniques incorporating lithography and micro-molding for fabrication of polymer(PDMS)-based devices.

![Images of soft lithography examples]
Soft Lithography Process

- A microfabrication process in which a soft polymer is cast onto a mold that contains a microfabricated pattern.
- Polymer materials: PDMS, PMMA, etc.
- Mold materials: SU-8, thick-film positive photoresist
- Advantages come with soft lithography:
  1. Capacity for rapid prototyping
  2. Easy fabrication without expensive capital equipment
  3. Forgiving process parameters

![Diagram of soft lithography process]
PDMS (Polydimethylsiloxane)

- Deforms reversibly
- Can be molded with high fidelity
- Optically transparent down to ~300nm
- Durable and chemically inert
- Non-toxic
- Inexpensive

Upon treatment in oxygen plasma, PDMS seals to itself, glass, silicon, silicon nitride, and some plastic materials.
Soft Lithography Process

Advantages come with soft polymer
1. Excellent sealing between glass and PDMS
2. Easy for connecting a tubing adapter
3. Transparent material, great for microscopic observation
4. Permeable to gas but not to analytes or ions
5. Allow multi-layer process toward 3D networks
6. Biocompatible (?)
Quake’s Micromechanical Valve

Valve open:

Valve closed:

Flow channel is pinched-off.

Why semicircular shape?

Leakage! But…..
Fabrication: Two-Layer Soft Lithography Process

**Flow channel**

- Positive PR (~10 \( \mu \)m)
- Si wafer
- PDMS prepolymer (spin-coated)
- Reflow PR at 200°C
- 10~15 \( \mu \)m

**Control channel**

- SU-8 (30 \( \mu \)m)
- Si wafer
- PDMS Prepolymer (~5mm)

Final curing baking

Bonding to a cover slip
Fabrication: Two-Layer Soft Lithography Process

PDMS titration chip

Valve open and Valve close

Control line

Tubing

Cover slip

BioSensing
Properties and performance of Quake’s valve

Frequency response

- The geometry (width, height, and thickness) of the membrane determines the valve actuation pressure
- Valve experiences little hysteresis

Properties and performance of Quake’s valve

Driven pressure

12 flow channel widths X 12 control line widths

V. Studer et al., J. of Applied Physics, 2004
BioSensing & BioMEMS 530/580.672
Based on valves, what are the high-level components that have been developed?

**Peristaltic pump**

In LSI, subcomponents: memory, comparator, counter, multiplexer

- Flow
- Actuation pattern
  - 1 0 1 Trap
  - 1 0 0
  - 1 1 0 Push
  - 0 1 0
  - 0 1 1
  - 0 0 1 and prevent back flow

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**Linear region**
Based on valves, what are the high-level components that have be developed?

Rotary pump and mixer
Rotary mixing

Continuous-flow mixing

Fixed-volume mixing

Before

After

(a)

(b)

(c)

(d)

(e)

(f)