Microfabrication Using Polymers

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Microsystems Principles
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Polymers for Microfabrication

- Examples diverse
  - PDMS
  - PMMA
  - Polyurethane
  - Polyimide
  - Polystyrene
- Disadvantages
  - Low thermal stability
  - Low thermal and electrical conductivity
  - Techniques for fabrication on microscale not as well developed

Can We Measure Everything?

Can we measure everything?

PDMS

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

Soft Lithography

- Developed by Whitesides, et. al. at Harvard
- Microcontact printing
  - Elastomeric stamp
  - Patterns of self-assembled monolayers (SAMs) and proteins
  - SAMs allow a variety of surface modifications
    - Thickness variation by changing tail length
    - Modification of tail group changes surface properties
    - Variety available for different substrate materials
  - Other SAM advantages
    - Self-healing and defect rejecting
    - Ultrathin resists and seed layers
    - Do not require clean room facilities
    - Low cost
  - Fabricated using a PDMS mold of “photoresist” structure

Micro Contact Printing
Micro Contact Printing

Soft Lithography: MIMIC
- Polyurethane or other material wicks into capillaries formed in PDMS stamp

Soft Lithography Used To Fabricate Transistors On Curved Substrates

Microtransfer Molding
- A filled mold is reversed and liquid material is cured

Soft Lithography: Replica Molding
- Similar to fabrication of PDMS stamp, but another material is used
- Flexible mold easily removed
- PDMS non reactive and low surface energy
Rapid Prototyping

- How do we get around turn-around times associated with MEMS?
- Chrome masks are expensive >$400 (the more detailed, the more expensive)
- The answer: high resolution printing on polymer films (overheads)
- Idea to prototype time can be reduced to 1 day
- Typical cost about $10
- Other advantages
  - Polymer masks can be used for non-planar substrates
  - Multiple masks can be stacked to achieve modular patterns
- Disadvantages
  - Limited use
  - Limited to about 10 micrometer resolution

Other Polymer Techniques

- Embossing
  - Low cost
  - High throughput
  - Structures as small as 25 nm
- Injection molding
  - Features less than 500 nm
  - Useful for metals, ceramics, etc
- Laser ablation
  - Removes material
  - Resolution down to 6 microns
- X-ray lithography
- LIGA
Molding of High-Aspect Ratio Microstructures

Acceleration Sensor Made using LIGA

Typical Dimensions
- Height: 150 µm
- Min. Width: 3.3 µm
- Min. Detail: 0.2 µm
- Aspect Ratio: 45

Optical Lithography and Etching

- SU-8 Approach
  - Low AR (>5) capable
  - Structure height limited to 25 µm (to prevent bowing of sidewall)
  - Difficult to remove SU-8 after plating Ni
- DRIE Approach
  - Silicon used as mold insert. Surface conditioning to prevent stiction of polymer to Si is critical
  - Mold may not last many cycles
  - Si needs bead of epoxy around edge to prevent mold from being ripped apart during demolding

High Aspect Ratio Mold Inserts

LIGA Mold Insert Made from Electroplated Nickel
- 65 mm

Micromachined Mold Insert Made from Brass

Hot Embossing

An Alternative Molding Process?

- Extreme High Aspect Ratio Microstructures
- High Performance Material Properties

Examples of Molding Compounds:

<table>
<thead>
<tr>
<th>Compound</th>
<th>Abbreviation</th>
<th>Glass Transition Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymethylmethacrylate</td>
<td>PMMA</td>
<td>105</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>PE</td>
<td>120</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>PP</td>
<td>150</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>PU</td>
<td>130</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>PC</td>
<td>150</td>
</tr>
<tr>
<td>Polyetheretherketone</td>
<td>PEEK</td>
<td>270</td>
</tr>
<tr>
<td>Polyoxymethylene</td>
<td>POM</td>
<td>165</td>
</tr>
<tr>
<td>Polyvinylidene fluoride</td>
<td>PVDF</td>
<td>170</td>
</tr>
<tr>
<td>Polyamide</td>
<td>PA</td>
<td>180</td>
</tr>
</tbody>
</table>

High Aspect Ratio Molding

Mold Insert:
- LIGA Process; typical Materials are Ni, NiCo
- Micromachining; typical Materials are Brass, Al alloys
- Si Micromachining; typical Materials are Si, Ni
- Combination of Various Techniques
Followed by Electroplating Ni, NiCo

Mold Inserts

Basic requirements
- Low mechanical stiction and friction
- No deviation from vertical sidewalls (no undercuts)
- Avoid surface oxidation
  - Chemically inert
  - Smooth surfaces
  - Defect free sidewalls
  - Homogeneous material properties
Possible Applications for Molding Techniques

- Mass production of HARMS
  ⇒ Onto substrates up to 6 inch
  ⇒ Self supported structures
- Process integration enables construction of more complex µ-systems
  ⇒ Molding onto CMOS - wafers

Molding Process Options

- Accepted industrial process
  ⇒ Reliable, repeatable, reproducible
- Batch processing
  ⇒ Parallel using of several mold inserts
- Tailoring of structural properties due to flexible material choice
- Other than polymer materials are possible
  ⇒ Filed polymers e.g. conductive materials (particles, powder and fibers)
  ⇒ Metals
  ⇒ Ceramics

Common Molding Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Description</th>
<th>Processing Range</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMMA</td>
<td>Poly(methyl methacrylate), $T_g$ 100°C, $T_{proc}$ 170°C-210°C</td>
<td>Transparent, brittle, sensitive to cracks, lost mold for production of metallic microstructures</td>
<td>Optics, lost mold for production of metallic microstructures</td>
</tr>
<tr>
<td>POM</td>
<td>Poly(oxymethylene), $T_g$ 150°C (Copolymer), $T_{proc}$ 180°C</td>
<td>Low friction, good impact strength, critical decomposition into formaldehyde, critical cavitation due to crystallization</td>
<td>Mechanical applications (gear wheels)</td>
</tr>
<tr>
<td>PSU</td>
<td>Poly(sulfone), $T_g$ 190°C, $T_{proc}$ 200°C</td>
<td>Transparent, high strength for use at higher temperatures up to 180°C</td>
<td>Microfluidic pump</td>
</tr>
<tr>
<td>PC</td>
<td>Poly(carbonate), $T_g$ 148°C, $T_{proc}$ 180°C-200°C</td>
<td>Transparent, good hardness and impact strength</td>
<td>Optics, medical</td>
</tr>
</tbody>
</table>

Micro Metal Injection Molding (MIM)

Metal Microstructures are of Interest Because of

- Mechanical Properties (Hardness, E-Modulus,...)
- Electrical and Magnetic Properties
- Low Thermal Expansion Coefficient Compared with Polymers

But

- Can other than Electroplating Techniques be Used? (Electroplating is Limited to some Noble Metals and only Few Binary Alloys)
- Can they be Replicated from Molded (Polymer) Forms?

Ceramics FZK - IMF

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green Compact</td>
<td>Sintered $\text{Al}_2\text{O}_3$ Bench</td>
<td>Open: shrink control to better than 1 µm in all critical dimensions achievable?</td>
</tr>
</tbody>
</table>
Aligned Molding of LIGA Microstructures

IFM Hot Embossing machine

Benefits
- Fully programmable process
- Data acquisition (force, temperature, position and pressure)
- Short process time due to electrical heating and oil cooling

Limitation
- Manual substrate handling only

Hot Embossing Process

Pattern Transfer by ‘Controlled’ Stamping of a Mold Insert into a Polymer Sheet

Key Features
- Extremely Precise and Simple Process
- Well Controlled Embossing Force
- ‘Gentle’ Process due to Low Embossing and Demolding Velocity
- Uniform and Homogeneous Material Properties and Low Internal Stress Microstructures
- Compatible with other Technologies
- Simple Process Integration Allows the Fabrication of Complex Systems with Reduced Assembly Efforts
- Cost-effective Small Scale Series Fabrication Demonstrates Performance and Reproducibility of Microsystems

Hot Embossing Process Cycle

• Phase 1
  - Closing and evacuation of process chamber
  - Heating of mold insert and substrate
  - Plasticification of the polymer sheet

• Phase 2
  - Maximum temperature
  - Molding tool is pressed into the polymer
  - Applying the max. molding pressure

• Phase 3
  - Cooling of mold insert and substrate
  - Venting of the chamber
  - Demolding and taking out the molded micro parts

Hot Embossing - State-of-the-art

⇒⇒⇒⇒

A “perfect” µ-fab technology for

• University R&D environment
• Small scale series
  (prototyping, demonstration of manufacturing capability)

Applications

Plastic microstructures as

Semi finished structures
- onto substrates (e.g. Si, ceramics)
  • Fabrication of metal microstructures e.g. movable

Finished structures
- self supported
  • Separated structures like micromechanical devices e.g. gear wheels
  • Optical structures like lenses, spectrometers
  • Microfluidic devices like micro- and nanochannels

onto substrates (e.g. Si, ceramics)
- Optical benches
- Optical structures like lenses, spectrometers
- Microfluidic devices like micro- and nanochannels

Applications

Plastic microstructures as
General Design Rules for Mold

- Round the corners where the polymer will shrink onto the metal
- Avoid patterning numerous aspect ratios in one sample (i.e., use AR that deviate +/- 2 from the average AR in the pattern)
- Centralize the patterns that are most critical. Deviation further from center are more difficult to emboss

General Design Rules for Mold

- Sidewall quality is critical
  - Surface roughness > 500 nm
  - Perpendicularity > 85° with > 2° center bowing
- Bottom surface quality less critical
  - Surface roughness > 10 mm

Metal - Tool Insert

Silicon Wafer Used As Tool Insert