Fall 2008 EE 410/510: Microfabrication and Semiconductor Processes
M W 12:45 PM – 2:20 PM
EB 239 Engineering Bldg.

Instructor: John D. Williams, Ph.D.
Assistant Professor of Electrical and Computer Engineering
Associate Director of the Nano and Micro Devices Center
University of Alabama in Huntsville
406 Optics Building
Huntsville, AL 35899
Phone: (256) 824-2898
Fax: (256) 824-2898
email: williams@eng.uah.edu

Course notes taken from LSU-CAMD, Sandia National Labs MEMS Course on LIGA, Link Jian’s Singapore Shortcourse on LIGA, and from JDW Research Programs
LIGA — Metal, Plastic and Ceramic Microparts
MEMS Fabrication

- Anisotropic bulk etching
- Deep reactive-ion etching
- Surface micromachining
- LIGA
- Wafer bonding
LIGA Acronym

**LIGA – Process**

LIGA = fabrication of high aspect ratio microstructures using

- X-ray lithography (LI = Lithographie) using SR to generate primary microstructures in PMMA or SU-8

- Electroforming (G = Galvanik) to produce microstructures in metal

- Molding (A = Abformung) of secondary microstructures in polymers, metals, and ceramics
LIGA: _Lithographie, Galvanoformung, Abformung_

- X-rays from a synchrotron are incident on a mask patterned with high Z absorbers. X-rays are used to expose a pattern in PMMA, normally supported on a metallized substrate.
- The PMMA is chemically developed to create a high aspect ratio, parallel wall mold.

- A metal or alloy is electroplated in the PMMA mold to create a metal micropart.
- The PMMA is dissolved leaving a three dimensional metal micropart. These microparts can be separated from the base plate if desired, or the electroplated part can be used as a mold insert.
LIGA Efforts Are Focused on Achieving More Precision and Smaller Size

- **LIGA**
  - Materials: Polysilicon and limited metal coatings
  - Processing: Parts produced at wafer level
  - Assembly: Pre-assembled through standard processing
  - Geometry: Two-dimensional, multi-level

- **SMM**
  - Materials: Limited metals, ceramics, and polymers
  - Processing: Parts produced at wafer level
  - Assembly: Precision assembly or non-standard processing for multi-levels
  - Geometry: Deep two-dimensionality or multi-level

- **Precision Machining**
  - Materials: Most metals, alloys, and superalloys & most polymers and ceramics
  - Processing: One piece at a time
  - Assembly: Hand assembly
  - Geometry: Full three-dimensionality

![Diagram showing depth and lateral dimensions](image-url)
Key Features of LIGA MEMS

- Arbitrary cross-sectional shape
- Smallest structures of some micrometer
- Vertical and smooth sidewall
- Extreme structure heights up to some millimeters
- Sub-micrometer structural details
LIGA Processing Capabilities: Lithographie (2)

LIGA X-ray Synchrotron Beam Lines:

**United States**
- Lawrence Berkeley National Laboratory, ALS
- Stanford Synchrotron Radiation Laboratory, SSRL
- Brookhaven National Synchrotron Light Source, NSLS
- Louisiana State University, CAMD
- Argonne and Univ. of Wisconsin have lines but they are not generally accessible

**Germany**
- ANKA, ELSA, BESSY

**Taiwan**
- SSRC

**Japan**
- AURORA, ...

**France**
- DCI

**Singapore**
- Helios2
Synchrotron Light Sources

Light Emitted by Relativistic Electrons

Electron Energies: 1.3/1.5 GeV
Photon Energies: IR – 15 keV X-rays

Electron beam in ring
Vacuum chamber

Photon beam emitted tangentially from dipole magnet
Intensity of Synchrotron Radiation
Making Use of Synchrotron Radiation
Arrhenius Absorption of X-rays Occurs in All materials

Absorption of X-rays

\[ I_2 = I_1 \cdot e^{-\mu_{\text{filter}_2} \cdot d_{\text{filter}_2}} = I_0 \cdot e^{\sum_i^{-\mu_{\text{filter}_i} \cdot d_{\text{filter}_i}}} \]
LIGA Processing Capabilities: Lithographie (3)

**LIGA X-Ray Scanner:**

Synchrotron radiation usually is emitted as a slit, so the LIGA mask and photoresist must be scanned vertically in order to achieve full wafer exposure

- 4 Beamlines at CMAD (1.3/1.5 GeV), 1 at SSRL (3GeV), 2 at ALS (1.9 GeV)
- Exposure width limited by the emittance port at the base of the beamline
- Typically capable of scanning 100 mm
- Alignment and tilted exposures available
- Low energy exposure (mirror) also available

Commercially Available

- Jenoptik Mikrotechnik ([www.jo-mikrotechnik.com](http://www.jo-mikrotechnik.com))
- Oxford Danfysik ([www.oxford-danstik.com](http://www.oxford-danstik.com))
LIGA: Deep X-ray Lithography, Electroforming, Molding

1.3 GeV Synchrotron

Patterned gold on nitride membrane
PMMA resist on metalized substrate
X-rays
Mask and substrate fixed together
Scanned vertically across the beam

Develop Resist
Electroplate Metal
Strip Resist

DXRL performed at LSU-CAMD
Remainder of work performed at SNL, NM
**LIGA Processing Capabilities: Lithographie**

**LIGA masks:**
- Supported by a thin low Z membrane
- 4-inch diameter
- 1 to 20 micron gold in pattern for X-ray absorption to produce mask contrast

**LIGA resist:**
- CQ grade Goodfellow PMMA
- Adhered to metallized silicon wafer or metallic substrate
- Fly cut to about 50 microns over desired final metal thickness
Substrate Preparation

• PMMA can be spin coated to approx. 25 um
• SU-8 can be spun to approx. 1.5 mm
• Other Standard Methods:

**Application of Thick PMMA Resist Solvent Bonding**

Solvent bonding of a PMMA disk on a Si wafer

(Patent: H. Guckel)

Properties of Bonding/Gluing of Thick PMMA Sheets

• Low stress, well-defined material properties (Mw, uniformity,...)
• Fly cutting to desired height necessary
• Potential for mass production
Direct Casting of PMMA

Application of Thick PMMA Layer Casting 1

Casting material: PMMA/MMA viscose syrup + initiator (BPO, DMA)

Polymerization causes shrinkage and stress

=> technology limited to ~ 200μm height
X-ray Mask – Membrane Materials

• Good X-ray and optical transmission
• Good mechanical stability, low internal stress
• Radiation resistant
• Compatible with established mask making processes and equipment
• Compatible with plating of Au absorber

=> Thin membranes from Silicon, Silicon Nitride, Titanium, Diamond
=> Low Z “sheets” from Graphite, Beryllium, and Silicon (UDXRL)

X-ray masks are important for a successful LIGA fabrication
General Concept for DXRL Mask Fabrication

1. Design a pattern
2. Create/write an optical mask
3. Copy pattern onto an x-ray mask
4. Writing the pattern into a thin resist
   Using an Optical Pattern Generator or Electron Beam Writer
5. X-ray Mask
DXRL Masks Fabricated w/ Optical or e-beam Lithography

Electron beam lithography in thin resist layers (3-4 μm)
Intermediate X-ray mask for 2-3 μm of Au, 0.1 - 0.2 μm details, rounding below 100 nm, vertical sidewalls

Electron beam lithography in thick resist layers (20 μm)
Working X-ray mask for up to 15 μm of Au, no sub-μm details (proximity effect), rounding ~3 μm, vertical sidewalls

Optical lithography in thin resist layers (3-4 μm)
Intermediate X-ray mask for 2-3 μm of Au, ~0.5 μm details, rounding ~1 μm, vertical sidewalls

Optical lithography in thick resist layers (20-80 μm)
Working X-ray mask for 15-50 μm of Au,….limits?

Smaller Size has its Price!
DXRL Mask Fabrication

EB: E-Beam writing, PG: Pattern Generator, PL: Photo-Lithography, XRL: X-ray Lithography
**X-ray mask: Silicon Nitride Membrane**

Plated Gold Pattern

Source: Sandia National Laboratories, NM

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**X-ray Mask – Thin Film membrane**

Pattern area (6.5 x 2.5 cm²)

Ti mask: FZK IMT

Source: FZK IMT

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**X-ray Mask – Silicon Substrate**

100 μm thick Si wafer, 30 μm of Au absorber

Source: Sandia National Laboratory/California

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**X-ray Mask – Graphite Substrate**

200 μm thick graphite wafer, 20 μm of Au absorber

Source: LSU-CAMD
**X-ray Mask – Membrane Materials**

**Beryllium**
Best transmission, thick sheets possible, good thermal conductivity
but: toxic, no optical transparency, price

**Diamond**
Acceptable transmission, good thermal conductivity, optical transparency
but: free-standing in bigger format critical, price

**Silicon Based (Si, SiC, Si₃N₄)**
Acceptable transmission, optical transparency, established MEMS material
but: thin membrane, poor cooling properties

**Titanium**
Acceptable transmission
but: thin membrane, poor cooling properties, no optical transparency

**Rigid Graphite**
Acceptable transmission, thick sheets possible, good thermal conductivity, cheap
but: poor surface roughness, no optical transparency, striations?

**X-ray Mask and Filter - Transmission**

**Properties desired**
- Low losses or high transmission
- Stable (thick) membrane
- Good thermal conductivity

=> Low Z materials
Power Spectra after Transmission through Window, Mask, and Resist

- CAMD white light power spectrum
- Spectrum after passing 150\(\mu\)m Be vacuum window
- Spectrum after passing 300\(\mu\)m Be mask
- Spectrum after passing 250\(\mu\)m PMMA resist
**Characteristic Doses, Definition and their values for PMMA**

**Threshold dose** ($D_{th}$): maximum dose underneath absorber to avoid development (Critical dose)
For PMMA, $D_{th} = 100 \text{ J/ccm}$

**Damage dose** ($D_{dm}$): maximum dose allowed at top of resist before bubble formation occurs (Top dose)
For PMMA, $D_{dm} = 20,000 \text{ J/ccm}$

**Development dose** ($D_{dv}$): minimum dose needed at resist-substrate interface to completely dissolve the resist (Bottom dose)
For PMMA, $D_{dv} = 3,500 \text{ J/ccm}$
Dose Profiles for Both Major DXRL Resist

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Resist</th>
<th>SU-8</th>
<th>PMMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development dose</td>
<td></td>
<td>20 J/ccm</td>
<td>3500 J/ccm</td>
</tr>
<tr>
<td>(Bottom dose)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Threshold dose</td>
<td></td>
<td>0.05 J/ccm</td>
<td>100 J/ccm</td>
</tr>
<tr>
<td>(Critical dose)</td>
<td></td>
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</tr>
<tr>
<td>Damage dose</td>
<td></td>
<td>α*</td>
<td>20,00 J/ccm</td>
</tr>
<tr>
<td>(Top dose)</td>
<td></td>
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</tr>
</tbody>
</table>
Pattern Accuracy of DXRL

Ph.D. Thesis Jürgen Mohr, IMT/FZK, 1987

Ph.D. Thesis Sven Achenbach, IMT/FZK, 2000
Simulated and measured sidewall profile

Ph.D. Thesis Andreas Schmidt, IMM, 1996
Secondary Radiation Effects Leading to Pattern Changes

Fluorescence radiation as photo- and Auger electrons:
- Mask
- Absorber
- Substrate

Thermal Effects:
- Heating of resist
- Mask distortion

Ph.D. Thesis Dieter Muenchmeyer, IMT/FZK, 1984
Successful Development of High Aspect Ratio Structures Is Very Dependent on Geometry and Geometric Variations

- Transport differences in small and large features can lead to significant variations in development times
- Development defects lead to tolerance and electrodeposition problems
  - incomplete development
  - undercutting in large features
- Megasonic development increases mixing and reduces diffusion limiting effects
Intentional Break

• LIGA without X-rays
UV LIGA Lithographic Techniques

• Thick UV resists
  – Relies on i-line, DUV, or broadband contact lithography
  – Commercially available resists
  – Typical thickness of resist is up to 100 microns
  – Aspect ratios typically limited to 10:1
  – Extremely high aspect ratios have been obtained
  – Solvent development required
  – Megasonic development available
  – Sandia is currently developing the capability to expose up to 1500 microns in SU-8
  – Multi-layer projects are welcome
  – Electroplating and fusion bonding are available
  – Resist stripping of SU-8 is still problematic
Intentional Break
LIGA Processing Capability: Galvanoformung

**Development:**
- Three steps: GG developer, intermediate rinse tank, water
- Megasonic agitation
- Temperature control

**Electroplating:**
- Custom-designed system
- copper, nickel, permalloy, gold, platinum, 45/55 NiFe

**Planarization:**
- Lapped with diamond slurries to desired thickness and surface finish
- 4 Separate polishing tools used to provide high surface finish
Transport Issues Are Combined With Electric Field Intensity Variations to Produce Non-uniform Plating in LIGA Molds

- When geometrical issues are combined with morphological and homogeneity concerns, LIGA electroplating is a complex problem to fundamentally understand.
LIGA Fabricated Metallic Structures: Materials Tailored for the Application

- High conductivity metals
  - Au, Cu, Pt
- Paramagnetic NiCu alloy
- Soft Magnets (\(m_{sat} \leq 1.5\) Tesla)
  - Ni, 80/20 NiFe, 45/55 NiFe
- Molded NdFeB, 0.45T hard magnets

Surface Metal MEMS using low stress gold

High surface area Platinum black

0.45 Tesla NeFeB permanent magnets micromolded into plastics, metals, or silicon
High Aspect Ratio Electroplated Microstructures

- 450 um tall plated nickel structures
- Minimum width of an isolated line
  - Mask Pattern: 4 um wide
  - Plated Metal: 3.5 um wide
  - Aspect ratio: 129
  - Structure plated with small notch at base and fell over during the final rinse and drying process
- Expect crosses would be capable of achieving these aspect ratios
- Cylindrical structures should achieve aspect ratios in excess of 80:1
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Aging and Reliability Studies of LIGA-based Microsystems Are Being Defined

- Mechanical property baselines and changes are being evaluated
- Tribological property baselines and changes are being evaluated
- Surface treatments being explored — “conformal” CVD, pulsed laser deposition, ion implantation, ...
- Fundamental influence of grain structure and impurities on changes are being explored
Assembly and Packaging with LIGA: Offering New Solutions for MEMS

- 3-D systems from 2-D parts
  - diffusion bonding (wafer level)
  - multilevel processing
  - robotic manipulation & assembly
- Actuation
- Allowing for Interconnects
- Atmospheric control

Poled micromagnets for use as actuators

LIGA fabricated micro manipulators

Multi-level LIGA parts achieved through wafer-scale diffusion bonding

Multi-level LIGA parts achieved through processing

Low temperature, hermetic, wafer level packaging for MEMS
Prototype Metal Microparts

**Millimotors:**

**Version 1**
- Linear drive
- 30 distinct LIGA elements
- Nickel, permalloy, and copper parts
- Precise thickness control required for proper assembly, thickness range 200-500µm

**Version 2**
- Variable reluctance motor
- Utilizes electrodischarge machined permanent magnet
- 8 mm dia x 3 mm deep
- 30 LIGA parts
- 4 materials (PMMA, copper, nickel, permalloy
- 3 week fabrication time

**Acceleration Sensor:**
- Smallest Dimension 6 microns
- Nickel and nickel-iron parts
- Assembly aided by commercial gauge pins
- 30 LIGA parts
- Mass of metal allows more inertia and lower acceleration sensing

**Tribology Test Vehicle:**
- Primary purpose to look at tribological behavior of materials
- Driven by Smoovy motor out of plane
- Nickel, nickel-iron, nickel-cobalt, ...

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Multilayer UV-LIGA process
Electrodeposition of the thick resist layer

- Reduced cross linking of SU-8 on electroplated nickel due to acid catalysis
- Electroplated nickel into selective high aspect ratio multilayered SU-8 resist patterns
- Polished the surface
- Electroplated a thin layer of copper over the polished nickel
Combining Positive and Negative Resist with LIGA
Making Photonic Crystals with the LIGA Technique

Two exposures with no alignment pattern the resist required to electroplate a 3-D photonic crystal

Plastic Micromolding

**Hot Embossing**

- Heating of Substrate and Tool to just above Tg
- Application of Embossing Force
- Cooling of Substrate and Tool just below Tg
- Deembossing

**Injection Molding**

- A molten polymer is injected into the evacuated cavity and then hydraulically compressed into mold features
- Hydraulic containment of the plastic is needed to afford higher aspect ratios and material options
- Replication of typical LIGA structures requires an injection shot size large enough to fill the features and also provide the backing disk (about 25-30 grams)
- The same equipment can also be used for compression molding of liquid thermosets or ceramic/metal powder filled formulations
Sandia Efforts in Hot Embossing

- Hot embossing of various materials has been investigated using a modified Instron machine with special fixtures
- Inserts with circular features (below) and Micro-ChemLab features have been used with a range of thermoplastic substrates
- High-flow resins often exhibit flow away from the insert. Low-flow resins can have difficulty filling in small feature

Topas 5013 COC polyolefin

Standard Lucite PMMA sheet

Vectra A950 liquid crystal polymer

Lexan 1010R high flow polycarbonate
Sandia Injection — Compression Molding
Nanocomposite Micromolding

LIGA PMMA Mold → Fill Mold → Planarize and Demold

MnFe$_2$O$_4$
Nanoparticle Results Have Been Obtained for Four Materials

- **Alumina**
  - Firing temperatures of 1350, 1375, and 1400°C
  - Shrinkage 17%

- **Zirconia**
  - Firing temperature 1200°C
  - Shrinkage 4%

- **Stainless Steel**
  - Firing temperature 1200°C
  - Shrinkage 9%

- **Nickel**
  - Firing temperature 900°C
  - Shrinkage TBD
Micromolding Microparts on Silicon Substrates

1. Dovetail
2. Photoresist
3. Pattern and seal
4. PMMA
5. Open up mold
6. Micromold

JDW, Electrical and Computer Engineering,
UAHuntsville