Microfabrication Techniques for Accelerators

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Symposium in Memory of Robert H. Siemann
and ICFA Mini-Workshop on Novel Concepts for Linear Accelerators and Colliders
Outline

- Terminology
- Microfabrication methods and tools
- DXRL at APS
- Summary
**Terminology and relative sizes**

![Terminology and relative sizes diagram](image)

- **Log scale**
  - Dimension: $10^{-10}$ m, $10^{-9}$ m, $10^{-8}$ m, $10^{-7}$ m, $10^{-6}$ m, $10^{-5}$ m, $10^{-4}$ m, $10^{-3}$ m, $10^{-2}$ m, $10^{-1}$ m, 1 m
  - Terminology: Angstrom, nm, 10 nm, 100 nm, 1 µm, 10 µm, 100 µm, 1 mm, 10 mm, 100 mm, 1000 mm

- **Examples of objects**
  - Atom, Molecule, Virus, Bacteria, Human hair, Human tooth, Human hand, Dalmatian (average length)

- **Terminology**
  - Nanotechnology, Microsystem technology, Traditional eng. linear dimensions

- **How to observe**
  - X-ray techniques/STM, Optical techniques, Magnifying glass, Naked eye

- **Fabrication methods**
  - Molecular engineering, Silicon layer technologies, LIGA process, Precision machining, Conventional machining
  - Nanofabrication technologies, Precision engineering
Microfabrication methods and tools - MEMS

Basic idea is to find a way to circumvent the limitations imposed by normal machining.

- **MEMS** (Micro-electrical-mechanical systems)
  - Fabricated at micron to millimeter sizes using a single silicon substrate
  - Used to fabricate sensors, motors, actuators, mirrors
    - *Wide range of industrial and consumer applications*
      - MEMS accelerometers for automobile airbag systems
      - MVED applications
    - **MEMS-based reflex klystron (JPL)**

A salient-pole electrostatically actuated micromotor made from polycrystalline silicon using surface micromachining techniques.

A mechanical gear which is smaller than a human hair.
MEMS fabrication process

- **Wet Etching**
  - Isotropic wet etching uses solutions of hydrofluoric, nitric, and acetic acid, HNA.
  - It produces hemispherical shaped cavities below the mask aperture.
  - Lateral etch rate is about the same as vertical etch rate.
  - Anisotropic wet etching of silicon is done using either potassium hydroxide, KOH, or a solution of ethylene diamine and pyrocatechol, EDP.

- **Dry Etching**
  - It provides a better control and faster etch rates than either isotropic or anisotropic wet etching.
  - It refers to the process of reactive ion etching (RIE)
    - *Ionization of fluorine-rich reactive gas in a plasma chamber*
    - *Energetic fluorine ions attack the silicon surface*
Microfabrication methods and tools – Laser Ablation

- Laser ablation micromachining uses the very high power density and very short pulse of the laser to vaporize the surface of a material without transferring heat to the surrounding area.
- It can be applied to a wide variety of materials including metals, ceramics, semiconductors and plastics.
  - The depth of the etch can only be done by knowing the material removal rate per pulse and counting pulses or by external measurement.

SEM images of an MgB$_2$ ablated at 193 nm @12 J/cm$^2$
Microfabrication methods and tools – EDM

- Electric Discharge Machining uses large electric field arcs across the gap between the two metal surfaces.
- The arc raises the local surface temperature to between 8,000°C and 12,000°C and melts a roughly hemispherical volume on both the electrode and the work piece.
- Since the surface is formed by millions of small craters, it has a very poor surface finish.
- This can be improved considerably with finishing cuts, smaller wire diameter, lower electric fields.
- It needs additional treatment for low RF loss applications.
- Dimensional accuracy for EDM is roughly the same as precision machining.
- EDM gains in accuracy from its noncontact material removal, compared to normal machining.
- Disadvantage: variation in height of the crater-defined surface.
- New wire-handling and tensioning systems have allowed EDM wire diameters to ~ 20μm (as compared to 0.3 mm – 0.03 mm), μEDM.
Microfabrication methods and tools – LIGA

- LIGA is a process in IC fabrication which involves lithography, electroplating, and molding on a given substrate. (Lithographie, Galvaniformung und Abformung)
- LIGA allows structures to have heights of over 100 μm with respect to the lateral size.
- LIGA fabricates High Aspect Ratio Structures (HARMS).
- The ratio between the height and the lateral size is the aspect ratio (e.g. 100:1)
- Ideal for fabrication of RF resonant cavities with frequencies from 30 GHz to 1 THz.
- Unlike semiconductor lithography, LIGA uses very thick resist films.
Deep X-ray Lithography and Electroforming

- Silicon wafer, 250-µm-thick
- Gold absorber, 45-60-µm-thick
- PMMA, 1-3-mm-thick
- Copper base, 50-mm-thick
- Copper plating

**SU-8 LIGA**
- An alternative to PMMA
- For X-ray LIGA applications, it has a significant advantage:
  - *About 200 times more sensitive to X rays than PMMA*
  - *This drops exposure times by two orders of magnitude.*
  - *Disadvantage: The etchants that attack the exposed SU-8 also attack the metal surface of the LIGA part.*
**X-ray Exposure Station at the Advanced Photon Source of Argonne National Laboratory**

APS Lithography beamline:

- 19.5 keV
- Highly collimated beam ( < 0.1 mrad)
- Beam size @exposure station: 100 (H) x 5 (v) mm²
- Using a high-speed scanner (100 mm/sec) for uniform exposure.
- Precision angular (~0.1 mrad) and positional (<1 micron) control of the sample.
- Exposure time:
  - 1-mm thick PMMA (100 x 25 mm²) ~1/2 hr
  - 10-mm thick PMMA ~ 2-3 hrs
Antiscatter Grid for Mammography

- Scatter
  - Produces slowly varying background fog
  - Reduces subject contrast
  - Reduces the ability to identify diseased tissues

Freestanding focused to the point copper antiscatter grid 60 mm x 60 mm in size with 25-µm-wide septa walls and 550 µm period and 2.8 mm tall (grid ratio 5.3).
Unique benefits of ANL

- APS is one of the very few light sources worldwide suitable for micromechanics with a unique possibility of dynamic exposure for very tall (1-3mm) structures.
- Knowledgeable and experienced staff provides excellent user support.
- X-ray lithography station in Sector 10 is fully operational on a shared bend magnet beamline.
- Long experience in fabricating copper high-aspect ratio microstructures.
**3-D Conceptual Planar Structure**

- Alignment Slots & Bonding Fibers
- Vacuum + HOM
- Beam Axis
- Coolant

Lower half of a Side-coupled planar SW Structure

Lower half of an on-axis planar SW structure
PMMA Masks with DXRL: 94 GHz CG

- Long structure (66 cells)

\[ \text{Magnification 40X} \]

\[ \text{Magnification 40X} \]

\[ \text{Magnification 40X} \]

\[ \text{Magnification 40X} \]

\[ \text{Magnification 40X} \]

### Constant impedance cavity

#### Muffin-tin cavity RF parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>$f = 120$ GHz</td>
</tr>
<tr>
<td>Shunt impedance</td>
<td>$R_0 = 312$ MΩ/m</td>
</tr>
<tr>
<td>Quality factor</td>
<td>$Q = 2160$</td>
</tr>
<tr>
<td>Operating mode</td>
<td>$TW = 2\pi/3$</td>
</tr>
<tr>
<td>Group velocity</td>
<td>$v_g = 0.043c$</td>
</tr>
<tr>
<td>Attenuation</td>
<td>$\alpha = 13.5$ m⁻¹</td>
</tr>
<tr>
<td>Accel. Gradient</td>
<td>$E = 10$ MV/m</td>
</tr>
<tr>
<td>Peak power</td>
<td>$P = 30$ kW</td>
</tr>
</tbody>
</table>

Multi-beam Planar Klystron

1 Y. W. Kang (ORNL/SNS): private communication
Accelerator on a Substrate

- Accelerating Structure
- Load
- Directional Coupler
- Collector
- Output Waveguide Cavity
- Directional Coupler
- Directional Coupler
- Input Waveguide Cavity
- Gun
- MULTIBEAM PLANAR KLYSTRON
- Circulator
- Vacuum Tank
- Beam
Comparison of Microfabrication Methods for RF Structures

- Each fabrication method discussed has specific advantages for different materials and geometries.
- Normal machining can produce RF structures up to several hundred gigahertz as long as surface finish and consequent surface losses are not important.
- In resonant structures where surface losses drastically degrade the performance, normal machining is limited to less than 100-GHz structures.
- EDM has similar issues regarding surface losses
  - Can handle hard-to-machine materials. Only conductive materials
- LIGA is effective in a range of frequency defined by
  - Depth to which the photoresist can be exposed
    - 6-mm thick PMMA “routine” \( f \geq 25 \text{ GHz} \)
    - 10-mm thick PMMA soon
  - Dimensional accuracy limits of the mask and the diffraction of the light source.
    - Smallest lateral size is 0.2 \( \mu \text{m} \).
    - Aspect ratios can range up to 500.
    - Surface roughness is small (~30 nm).
### Characteristics of Microfabrication Methods

<table>
<thead>
<tr>
<th></th>
<th>Dimensional Accuracy (μm)</th>
<th>Surface Finish (nm)</th>
<th>Compatible Materials</th>
<th>Litho or Serial Process</th>
<th>Cost per Part</th>
<th>Frequency Range (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIGA PMMA</td>
<td>±1</td>
<td>&lt; 200</td>
<td>Metals</td>
<td>Litho</td>
<td>Low</td>
<td>25 - 600</td>
</tr>
<tr>
<td>LIGA SU-8</td>
<td>±1</td>
<td>&lt; 200</td>
<td>Metals</td>
<td>Litho</td>
<td>Low</td>
<td>25 - 600</td>
</tr>
<tr>
<td>MEMS(WE)</td>
<td>±0.5</td>
<td>&lt; 50</td>
<td>Silicon</td>
<td>Litho</td>
<td>Low</td>
<td>300-3000</td>
</tr>
<tr>
<td>MEMS (DRIE)</td>
<td>±0.5</td>
<td>&lt; 50</td>
<td>Silicon</td>
<td>Litho</td>
<td>Low</td>
<td>300-3000</td>
</tr>
<tr>
<td>Laser ablation</td>
<td>±2</td>
<td>200-500</td>
<td>Almost any materials</td>
<td>Litho/Serial</td>
<td>High</td>
<td>100-300</td>
</tr>
<tr>
<td>EDM</td>
<td>±2</td>
<td>&lt;1000</td>
<td>Conductors</td>
<td>Serial</td>
<td>High</td>
<td>0-300</td>
</tr>
<tr>
<td>Normal machining</td>
<td>±8</td>
<td>&lt;1000</td>
<td>Almost any materials</td>
<td>Serial</td>
<td>Medium/High</td>
<td>0-100</td>
</tr>
</tbody>
</table>
**Can a “true” 3D structure be realized?**

- As attractive DXRL is, it can only fabricate microstructures with vertical wall, which limits their application.

- Although 3D structures can be realized by various LIGA techniques, structures have walls parallel to the incident X-ray.

- To overcome these limitations with the conventional lithography techniques, Two recently new techniques have been developed:
  - A moving mask deep X-ray lithography (M²DXL)\(^1\).
    - \(M²DXL\) is a technique to fabricate microstructures with controllable inclined or curve wall.
  - A double X-ray exposure technique\(^2\)
    - 3D is realized by controlling the propagation direction of the PMMA dissolution front. This is achieved by irradiating the whole PMMA surface again without the X-ray mask after the first exposure.

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\(^1\) Y. Hirai, et. al, J. Micromech. 17 (2007)

\(^2\) N. Matsuzuka, et. al, 17\(^{th}\) IEEE MEMS, 2004
Summary

- Technology for a fully integrated design in not (yet) available and not likely in the near future.
- Hybrid design, ala hybrid integrated-electronic circuits, is closer to being available, requires considerable R&D.
- Fabrication challenges of RF structures and circuits
  - Vacuum-sealing and vacuum pumping of circuit with sub-millimeter beam apertures
  - RF losses due to surface roughness
    - $\delta = 200 \text{ nm} @ 95 \text{ GHz} \text{ and } 66 \text{ nm} @ 1 \text{ THz for copper}$
    - Need surface roughness less that the skin depth
  - Dimensional accuracy of cavities/circuits and alignment
    - Dimensional accuracy required $\propto 1/BW$
  - Beam transport and magnetic focusing
  - Heat transfer and structure cooling (microchannel/nanotubes)
    - CW and pulse heating

Microchannel array formed by silicon DRIE

![Microchannel array formed by silicon DRIE](image)
Thank you.