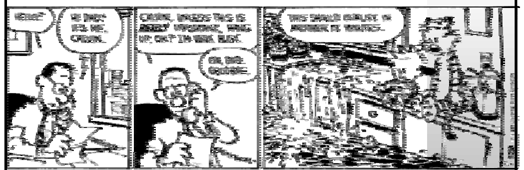
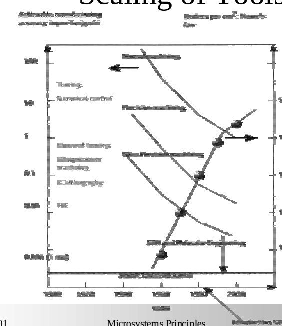
Nontraditional Microfabrication Techniques

Dr. Bruce K. Gale
Microsystems Principles
ENGR 494C and 594C

Emergencies



Scaling of Tools



Other Micromachining Techniques

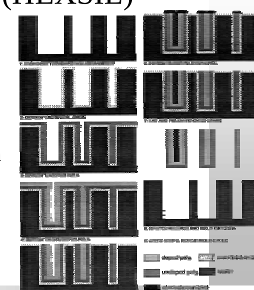
- Template replication
- Sealed cavity formation
- Surface modification
- Printing
- Stereolithography (3-D)
- Sharp tip formation
- Chemical-mechanical polishing
- Electric discharge machining
- Precision mechanical machining
- Thermomigration
- Photosensitive glass
- Focused ion beam
- SCREAM

Template Replication

- Injection molding
  - Metal or silicon structures used as mold
  - Plastics, metal and ceramic components with plastic “binders”
  - Often done with LIGA or etching in silicon
- Plating-based template replication (Electroforming)
  - Form mold or template
  - Plate into mold
  - Release structure
- Ceramic slurry templates
- Preformed, above substrate templates
  - Hollow microspheres

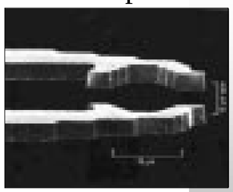
CVD-based Template Replication (HEXSIL)

- Structures made of polysilicon
- Formed on mold covered with oxide
- Oxide removed releasing polysilicon
- Can be multilayer process



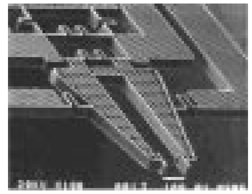
HEXSIL Example

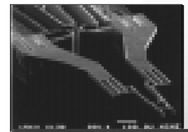
Micro-Grippers



Source: Berkeley

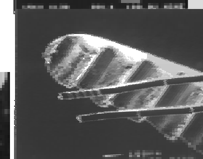
HEXSIL Example





Micro-Tweezers

Source: MEMS Precision Instruments

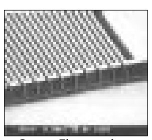


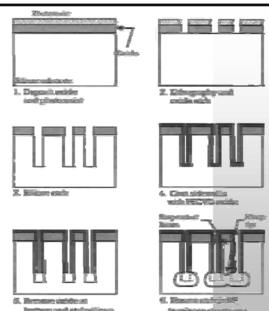
Sealed Cavity Formation

- Form structure using sacrificial material and small access holes
- Cover holes using one of three methods
  - Simple application of glues, plastics, photoresist, etc
  - Thin-film application such as sputtered, evaporated, and CVD films
  - Reactive sealing, i.e. thermal oxidation, etc
- Gettering- collect gases in cavity

SCREAM

- **Single Crystal Reactive Etching and Metalization**
- **CMOS compatible**
- **used by EG&G IC for accelerometers**





Source: Elwenspoek

Source: Maluf

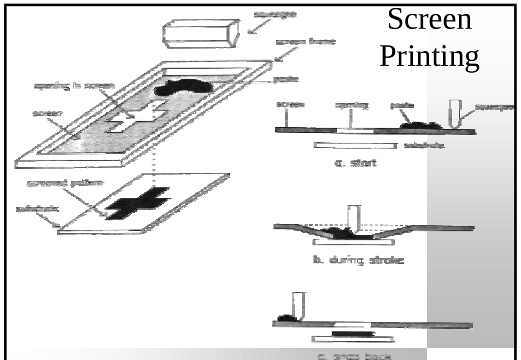
Surface Modification

- Used to change surface properties, especially in biomedical applications
- HMDS used to "methylate" surface and remove hydroxyl groups
- Self-assembled monolayers (SAMs) formed using $RSiCl_3$ (R is alkyl group)
- Often used to reduce wear and adhesion forces
- Apply dendrimers (hyper-branched polymers) for molecule recognition

Printing

- Useful for non-planar substrates
- Very low-cost
- Screen printing
  - Resolution limit of about 100 μm
  - Alignment more difficult
  - Great for patterning polymer layers in biosensors
  - One step process
  - Requires liquid form
- Transfer printing
  - Raised bumps used to transfer ink, etc
- Powder loaded polymers
  - Material properties dependent on material in plastic liquid that can be rolled on and patterned
- Ink jet

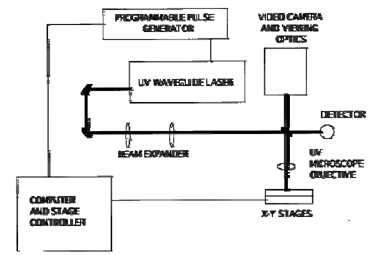
Screen Printing



Laser Microfabrication Processes

- Ablation
- Etching
- Deposition
- Photopolymerization
- Lithography
- Microelectroforming

Photoablation System



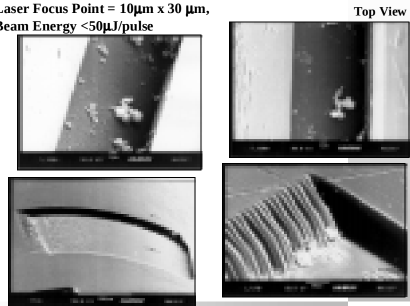
Laser Ablation

Laser Focus Point = 10µm x 30 µm,
Beam Energy <50µJ/pulse

Top View

Polysilicon, Tilt = 45º

Tilt = 65º



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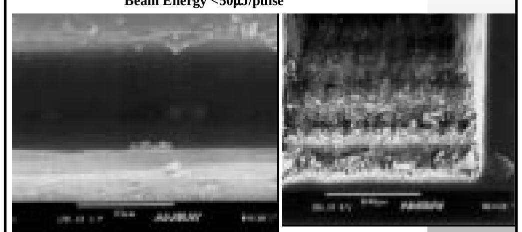
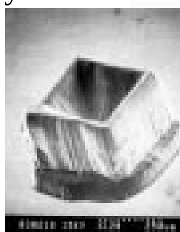


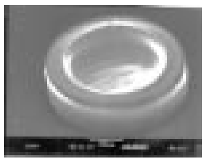
Laser Photopolymerization

Material:TMPTA+Ingracure 651
Laser: 248nm
PRR: 30 ~ 50 Hz
Feedrate: 100 :m/sec

Laser Photopolymerization



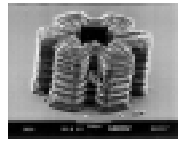
Initial *IfM* Results



Initial Japanese Results
Aisin-Cosmos R&D Co. Ltd.

Laser Photopolymerization

Material: TMPAT+Irgacure 651; Laser: 248nm

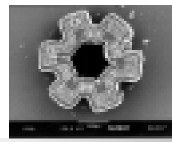


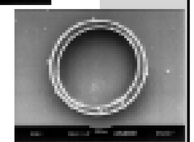
PRR:
20~30Hz

Feedrate:
80:m/sec

PPR:
20Hz

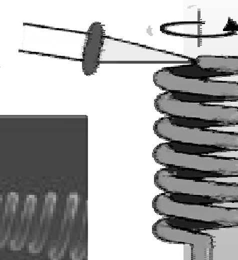
Feedrate: 100;m/sec

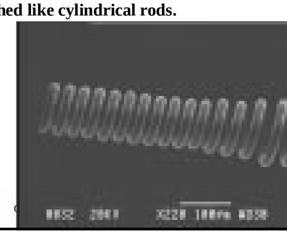




Laser CVD

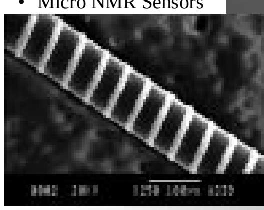
A rotating mandrel turns the deposit under the laser beam to form amorphous carbon helices. These can then be coated and etched like cylindrical rods.





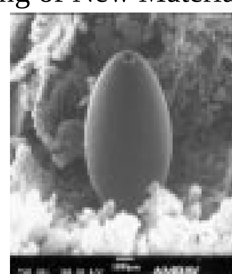
Laser CVD

- Microelectromagnets
- Magnetometers
- Micro NMR Sensors



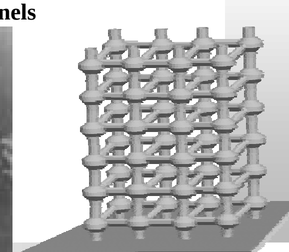
Fundamental Research in Prototyping of New Materials

- **Laser-Induced Growth of:**
  - **Refractory Materials**
  - **Intermetallics**
  - **Alloys**



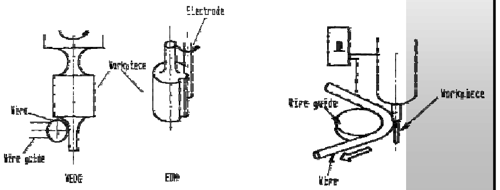
Laser CVD

- **Tissue Engineering Lattices with integral microfluidic channels**

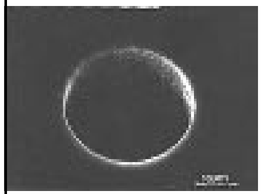


Micro Electrical Discharge Machining (University of Tokyo)

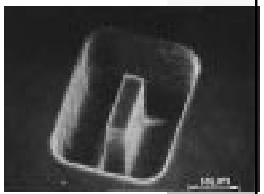
- **Electrical discharge from sharp tip erodes substrate faster than tip**
- **5 µm resolution, but serial and slow**



Micro Electrical Discharge Machining (University of Tokyo)



p-type Si, <1,1,1>
50µm dia, 330 um thick



p-type Si, <1,1,1>
15µm (w), 50µm (l), 50µm (h)

Micro Electrical Discharge Machining (University of Tokyo)

rotating electrode ram-type

400µm diameter, stainless steel

Sharp Tip Formation

- Useful for field emission devices, scanning microscopes
- Self-occluding masks
  - Perpendicular deposition (e-beam)
  - Atomically sharp
- Micromasking in plasmas
  - Etching in plasmas and RIE leaves sharp tips in spots where small particles lie on surface
  - By controlling gases, size, shape, and density of tips can be controlled
- Wet etching small squares until removal

Chemical-Mechanical Polishing

- Roughness less than 2 nm
- Alkaline, silica containing slurry
- Mechanical force increases etch at high spots

Abrasive Powder Machining

- Also called sandblasting, number of resists allow precise control

Scanning Probe Machining

- Uses scanning probe microscope to maneuver materials

Thermomigration

- At high temperature, with small differential, metals alloy with silicon and move through wafer leaving wire in wake

Photosensitive Glass

- Can be patterned using photolithography and etched using HF

Stereolithography

- 3-D lithography or printing
- Use of X-Y stage and Z-positioning lens for UV light
  - Forms box or "voxel" which can be moved to from 3-D structures
- Printing done in multiple layers

Micromechanical Machining - An Option to Lithography

- Can produce extremely smooth, precise, high-resolution structures
- Expensive, non-parallel, but handles much larger substrates
- Precision cutting on lathes produces miniature screws, etc with 12 µm accuracy
- Chip Processes
  - diamond machining, tools ~100 µm thermal surfaces, fluid microchannels
  - microdrilling, tools > 25 µm manifolds, fiber optics, molds
  - micromilling, tools ~22 µm, features < 8 µm molds, masks, thermal surfaces

Micromechanical Machining - An Option to Lithography

- Energy Processes
  - microEDM, tools > 10 :m microturbines, tools-electrodes, stators
  - focused ion beam (FIB), atomic-scale machining, micromilling tools, probes, etc.
  - laser, micron-scale spot ablate hard materials, polymerization

Micromechanical Machining Characteristics

- Relative tolerances are more typically 1/10 to 1/1000 of feature or part dimensions
- Absolute tolerances are typically similar to those for conventional precision machining (micrometer to sub-micrometer)
- Feature is often inaccessible by conventional metrology techniques (high aspect ratio boolean negative features)
- Like conventional machining, in-process, on-line metrology is preferred over post-process or off-line metrology

High Precision Drilling/Milling/EDM

Work table positional resolution - 1.25 nm
Spindle positional resolution - 20 nm
Milling/drilling spindle speed - 0 to 38,000 rpm
Total height - 2.2 meters (7ft. 2 in.)
Total mass - 1820 Kg (4000 pounds)
Joint project of IfM, National Jet Company and Dover Instruments

General Micromachining Metrology

- Tool location
  - Endmills 8 µm x 2 mm
  - 22 µm x 3 mm
  - Drills 25 µm x 4 mm
  - Diamond 100 µm x 2 mm
- Part/fixture location for multiple processes in multiple machines
- Post processing of lithographic molds
- Post processing of electroplated structures

Complementary Processes (Direct Removal Processes)

- Chip making (force processes)
  - Diamond machining
  - Microdrilling
  - Micromilling
  - Grinding and polishing
  - Microsawing
- Energy beam (forceless processes)
  - Focused ion beam
  - Micro electrical discharge
  - Laser ablative and photo polymerization

Complementary Processes

- Often regarded as conventional precision procsses which have been “simply shrunk” for micromachining applications
- Does precision engineering have a mainstream place in MEMS, MST, Micromanufacturing, etc?
- Do complementary processes have a mainstream place in MEMS, MST, Micromanufacturing, etc?

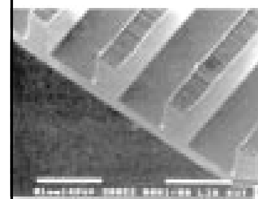
What is Precision Engineering

- "Working at the forefront of current technology"
- "Shooting after the next decimal place"
- "Those striving for the best possible product"
- "Engineering wherein the tolerances are 10^{-4} or less of a feature/part size"
- An attitude wherein there is no such thing as randomness, all effects have a deterministic cause

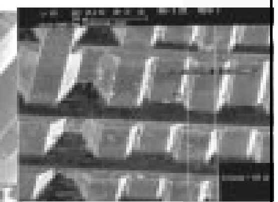
Brief History of Diamond Machining

- Diamond was apparently first used as a cutting tool material in 1779 for hardened steel threads
- In the early 1850's, a diamond-pointed pantograph could engrave legible characters 2.5 microns high
- Lord's prayer was engraved into an area 100 x 40 µm by 1920
- By 1926, it was claimed that 80 "bibles per square inch" could be engraved (3,556,480 letters/bible). This gives dimensions requiring SEM (late 1930's)
- By the 1960's diamond machining was pervasive at government research labs and moving into the optics industries (Perkin-Elmer)
- Cutting with very small (tens of microns) tools was developed by Japanese in 1980's and today

Micro Diamond Machining

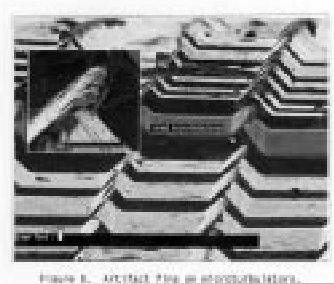


flow channels for micro heat exchanger (KfK)



microturbulators for surface enhancement (IfM)

Diamond-Machined Microturbulators and Microfins for Augmented Heat Transfer



Brief History of Energy Processes

- Electrostatically charges streams of liquid date to the 18th century by Rayleigh
- Liquid metal ion source (basic to focused ion beam) demonstrated 1978-1980
- Electrical discharge machining has been around since the first thunderstorm, but used to machine mid-20th century. Ram-type microEDM (to 75 microns) used in U.S. since 1960's
- Rotating spindle microEDM and wire electrical discharge grinding pioneered in Japan in late 1980's and to today
- Laser micromachining developed in late 1980's and to today with high pulse rate, waveguide excimer laser

Brief History of Chip Processes

- Microdrilling used for fuel injectors and textile spinnerettes since before 1950
- Vee-block, centerless spindle patented by John Cupler (basis of microdrilling/milling/EDM spindles)
- Micromilling done with micro spade drills since 1950's. Fluted end mills being developed at IfM
- Grinding and sawing developed for gem and lapidary industries, greatly improved for semiconductor applications

Brief History of Precision Engineering

- Precision engineering has roots in astronomy and sailing
  - Hipparchus in 2nd century BC and Ptolemy in 150 AD used “graduated” instruments
  - The angular diameter of Tycho’s star in Cassiopeia (1572) was measured to be from 4.5 to 39 arc minutes using the best instruments of the day
- During the middle ages and industrial revolution, many improvements were made in timekeeping
  - The founders of Browne and Sharpe, the maker of the first diffraction grating were clock makers
  - The first lathes and many other machine tools are rooted in watch/clock making

Brief History of Precision Engineering

- In modern times, precision engineering was pushed by nuclear programs
  - The laws of nature and physicist’s equations do not have provisions for tolerances
- Thermal control to +/- 0.1F was demonstrated as early as 1886 at Colby College in Maine

Required Process Development to Support Rapid Microfabrication

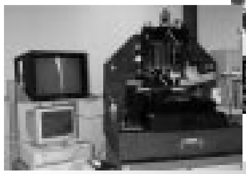
- Tool making
  - FIB might be too time consuming, but wear/tool very low
  - EDM of milling tools using external die as one pole and round (or other shape) electrode as other pole
- Machining parameters
  - Which speed, feed, etc. Give best results
  - Which speed, feed, etc. Give most throughput
  - Which materials give best results
- Finishing
  - What are the most effective deburring methods (chemical, mechanical, electrochemical)
  - What are the variable values required for effective deburring (concentration, voltage, electrolyte)

Required Process Development to Support Rapid Microfabrication

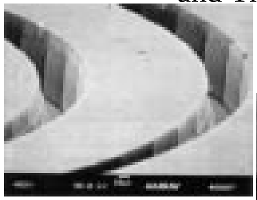
- Demonstration Will Be Required
  - Lithography community will be slow to accept this approach, industry is already interested
- Eventual “Ground Up” Machine Tool Re-Design
  - Why does it take a 5000 pound machine tool to fabricate parts where cutting forces are in the milli- to micro- Newton range?

Unique High Aspect Ratio Micromachining Tools

- Micromilling
- Focused Ion Milling
- Micro Water-jet Cuttin
- Micro EDM

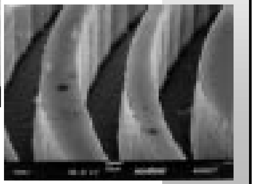



Micromilled Trenches with Thick and Thin Walls

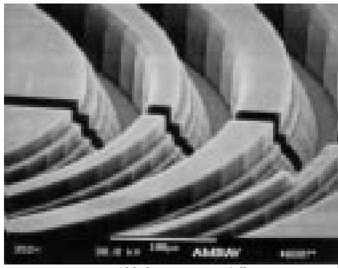


(scale bar =10 μm)
thinnest wall is 8μm wide by 62μm deep

(scale bar =10 μm)

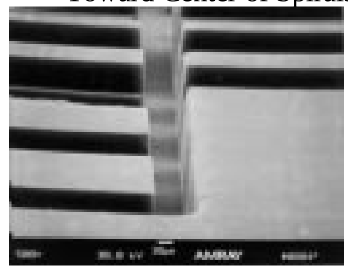


Straight and Stepped Walls



step width decays exponentially
wall facets are due to 5-degree increment used in spiral program

View of Straight Trench Looking Toward Center of Spirals



trenches are 62 µm deep with 89.5 degree sidewalls, tool had 0.4 degree front taper

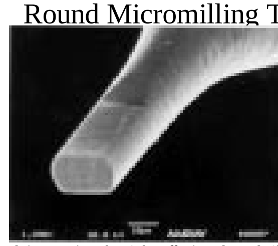
Trench Milled with 4-Fluted Tool

only 5 µm deep, sloped walls, rough bottom, rounded bottom-wall intersection

22 *µm* Diameter by 25 *µm* Long, Square Micromilling Tool

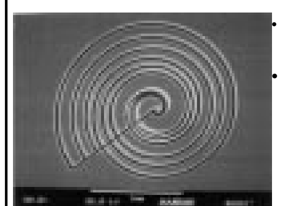
tool has clearance behind cutting edge but ability to withstand torsional shear stress is only one-tenth as round tool

22 *µm* Diameter by 77 *µm* Long, Round Micromilling Tool



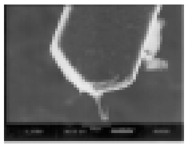
Macroscale rake angle is approximately -30° but effective rake angle (due to very thin chip) is -45 to -60 degrees and results in relatively large machining forces even though cutting edge radius 50 nm - 100 nm. No clearance behind cutting edge so round portion of tool burnishes trench walls.

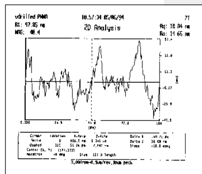
Example of Micromilling Process in PMMA



- Overall size is approximately 2 mm
- Machining parameters
  - 19,000 rpm
  - 2 µm axial depth per pass
  - Total depth is 62 µm
  - 35 µm/sec tool feedrate
  - Vegetable oil lubricant
  - Total machining time - 3 hrs
  - Removal rate- 3200 μm^3 /sec

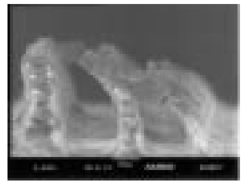
Micro Spade Drilling

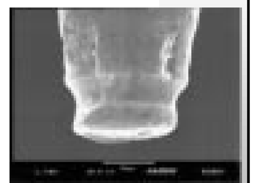




25 um diameter drill **PMMA wall roughness**

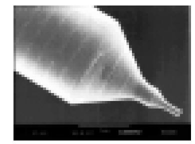
Closely Spaced Trenches in Aluminum (IfM First Results)

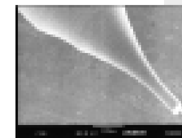




SEM photo **"tool"**

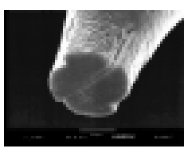
Diamond Machined Microshafts (Aluminum)

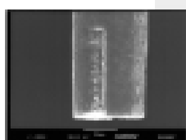




125 um diameter (IfM) **25 um diameter (IfM)**

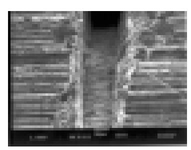
Micromilling Cutters (IfM - Focused Ion Beam)

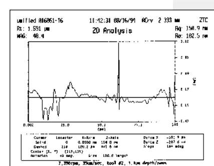




22 um diameter 4-fluted **22 um diameter 2-fluted**

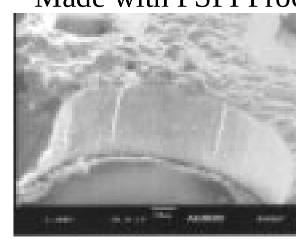
Micromilled Trench in Aluminum (IfM - First Results)





SEM photo **bottom roughness**

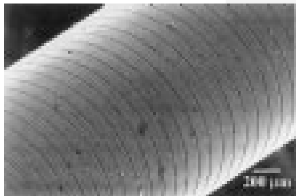
Hub Wall of Copper Microgear Made with PSPI Process



RMS roughness of plated gear is 416 nm (typical) over a length of 40 µm. Microdrilled hole wall in same material was 145 nm (typical) over a length of 104 µm

Machining Processes

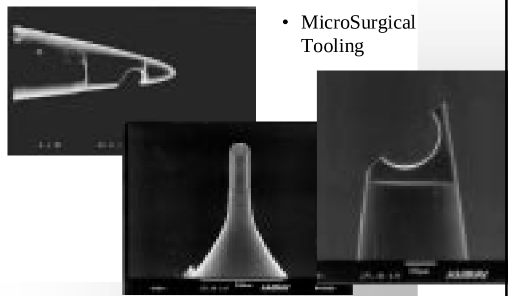
μTurning



FIB Machining: Detonator Linear Actuator

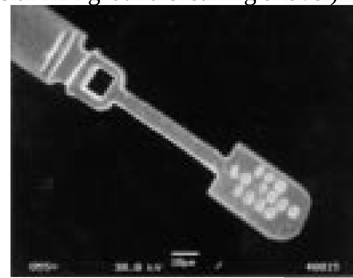
FIB

- MicroSurgical Tooling



Example of Focused Ion Beam Process (Official IfM ground breaking shovel)

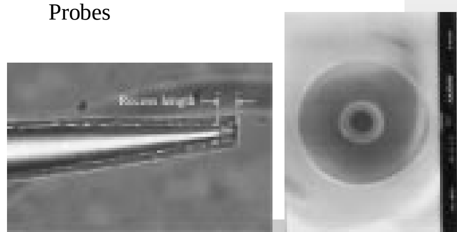
Focused highly reactive ions (F) get high resolution, i.e. 1-100 µm structures with 100 nm tolerance



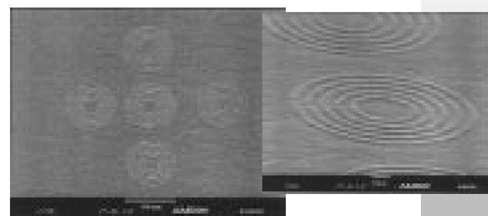
FIB Machining of ICF "Sphere": Just for Fun

Major Research Initiatives at the IfM

- Intra-cellular Oxygen Probes



Micro Forming/Molding Tools: Injection Moulding



Precision Machining: in Support of MicroMolding

- Micro Hot Embossing Masters
- Molds for Micro-Scale Casting