Micro-Nano Fabrication Research

Technical Education Quality Improvement Programme

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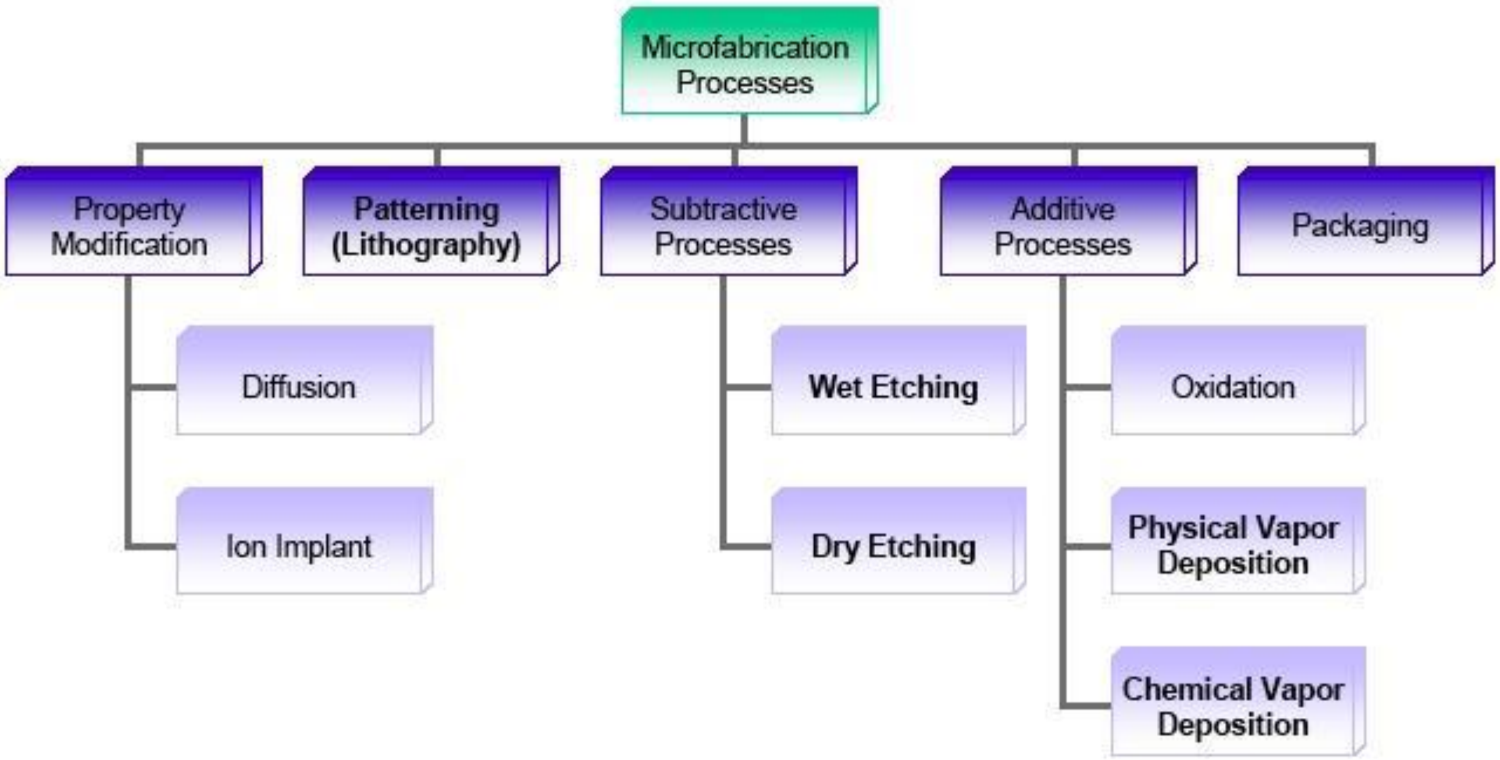
Micro/Nano Fabrication

- **Overview of Lithographic Techniques**
  - Photolithgraphy
- **Overview of Direct Machining**
  - Focused Ion Beam (FIB)
- **FIB Applications to micro-optical structures**
  - Milling
  - Depostion
  - Self organization
- **FIB Applications to tool fabrication for ultra precision machining**

Micro/Nano Fabrication Techniques

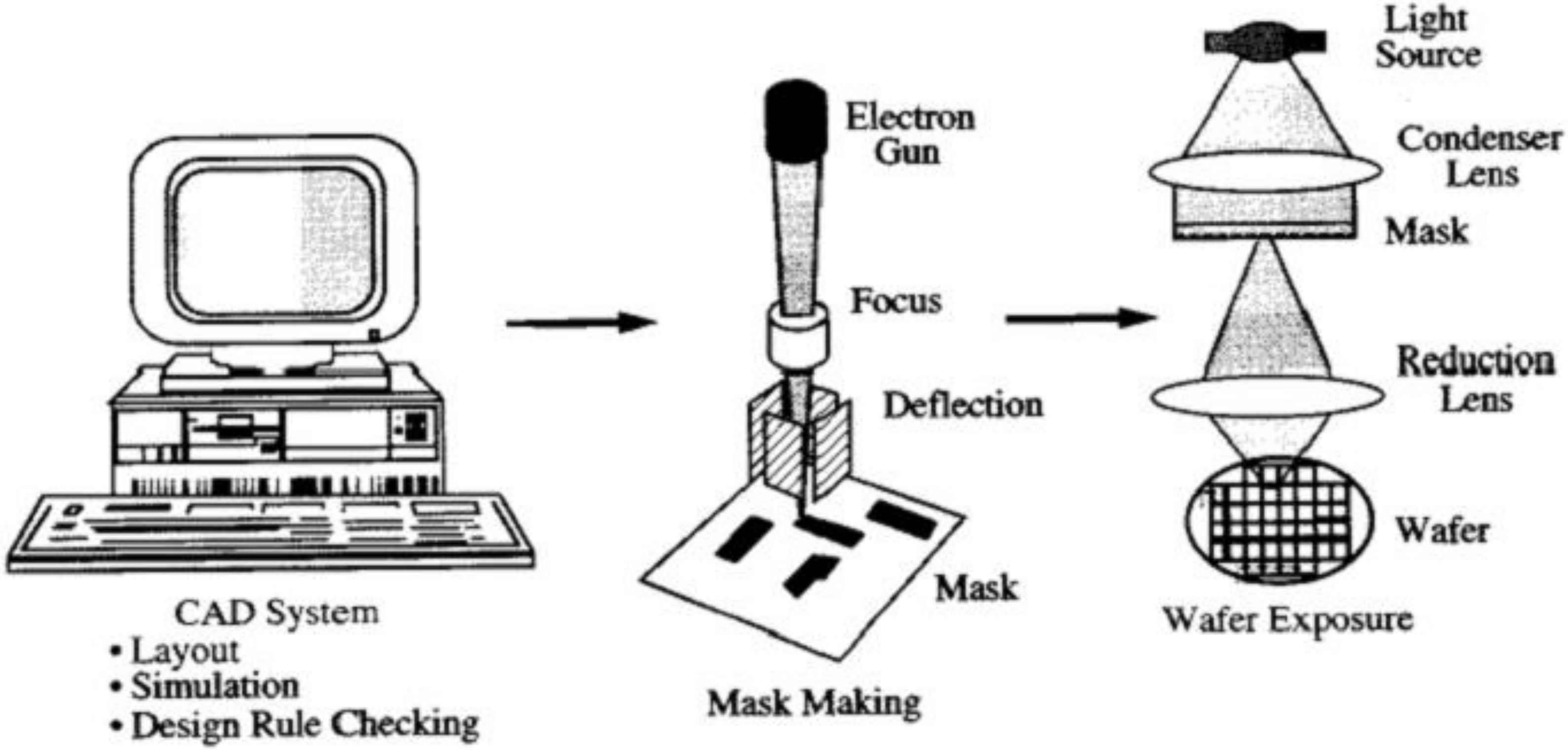
- **Lithographic Techniques**
  - Binary Mask Method (~ 300 nm)
  - Direct Writing (< 20 nm with e-beam lithography)
  - Interferometric Exposure (~ 300 nm)
  - Gray-scale Lithography
  - Near Field Holography
- **Direct Machining**
  - Focused Ion Beam (FIB) Milling (< 20 nm)
  - Laser Ablation
- **Replication**
  - Injection Molding
  - Thermal Embossing
  - Casting and UV embossing
  - Soft Lithography (< 100 nm)

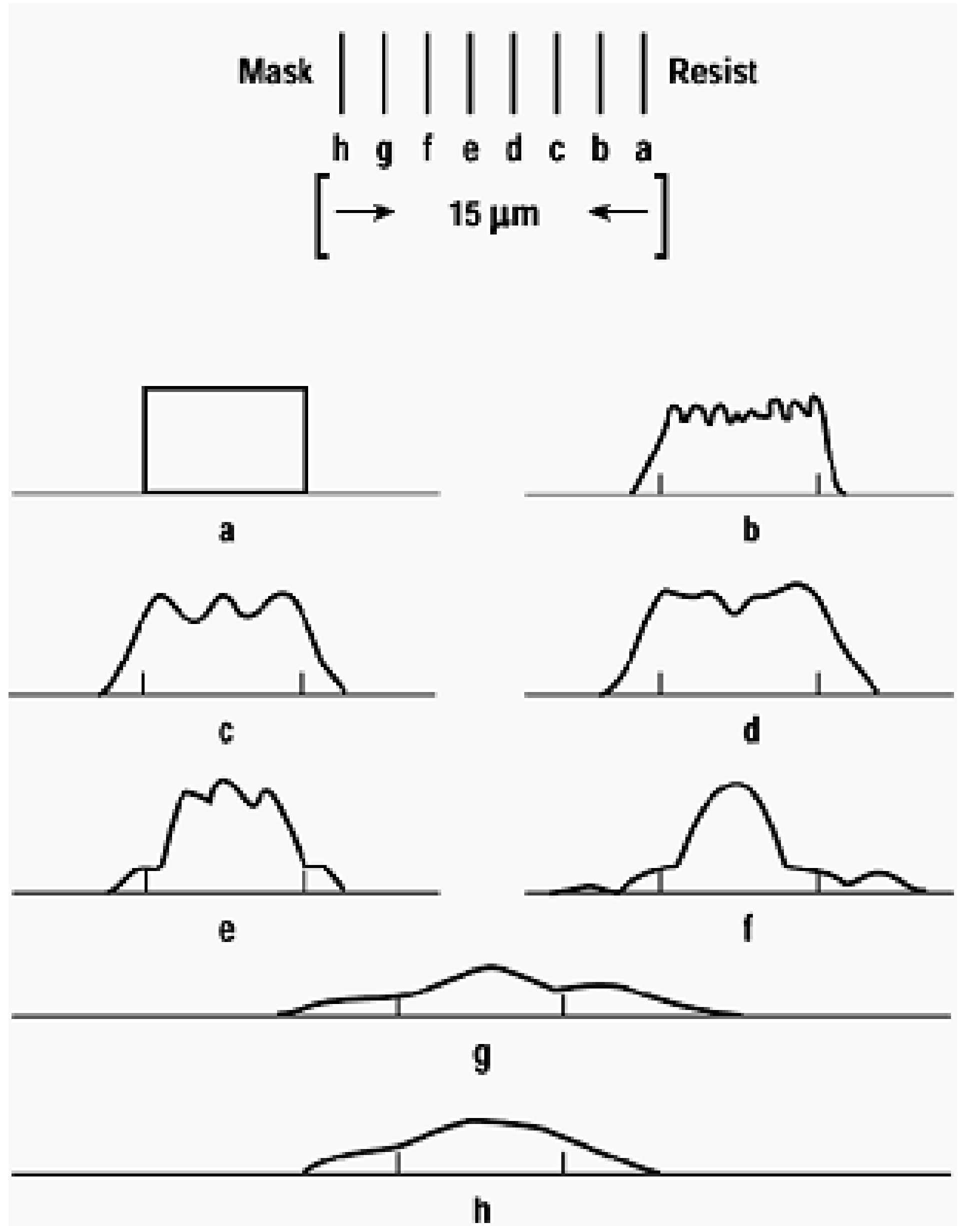
Micro - Fabrication Techniques



Lithography Process

- Optical Lithography / Photolithography
  - Parallel Writing
- E-beam Lithography
  - Serial Writing

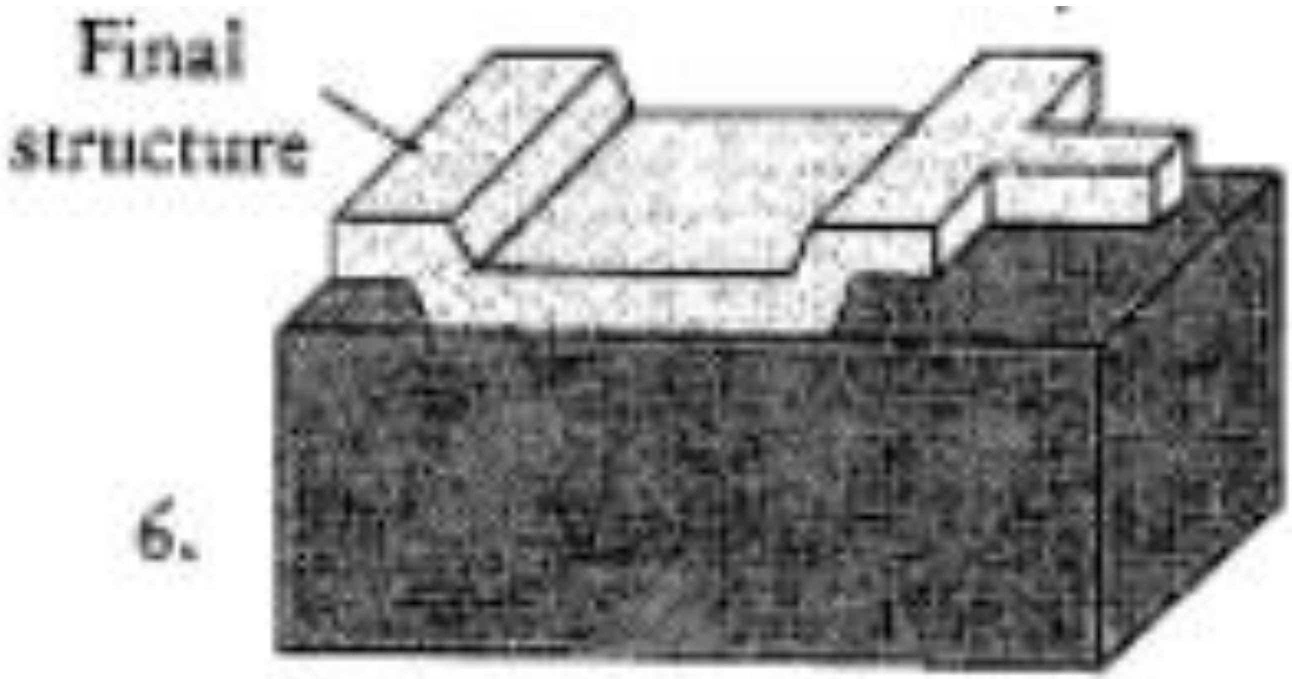



Mask
Resist
h g f e d c b a
15 µm
a
b
c
d
e
f
g
h

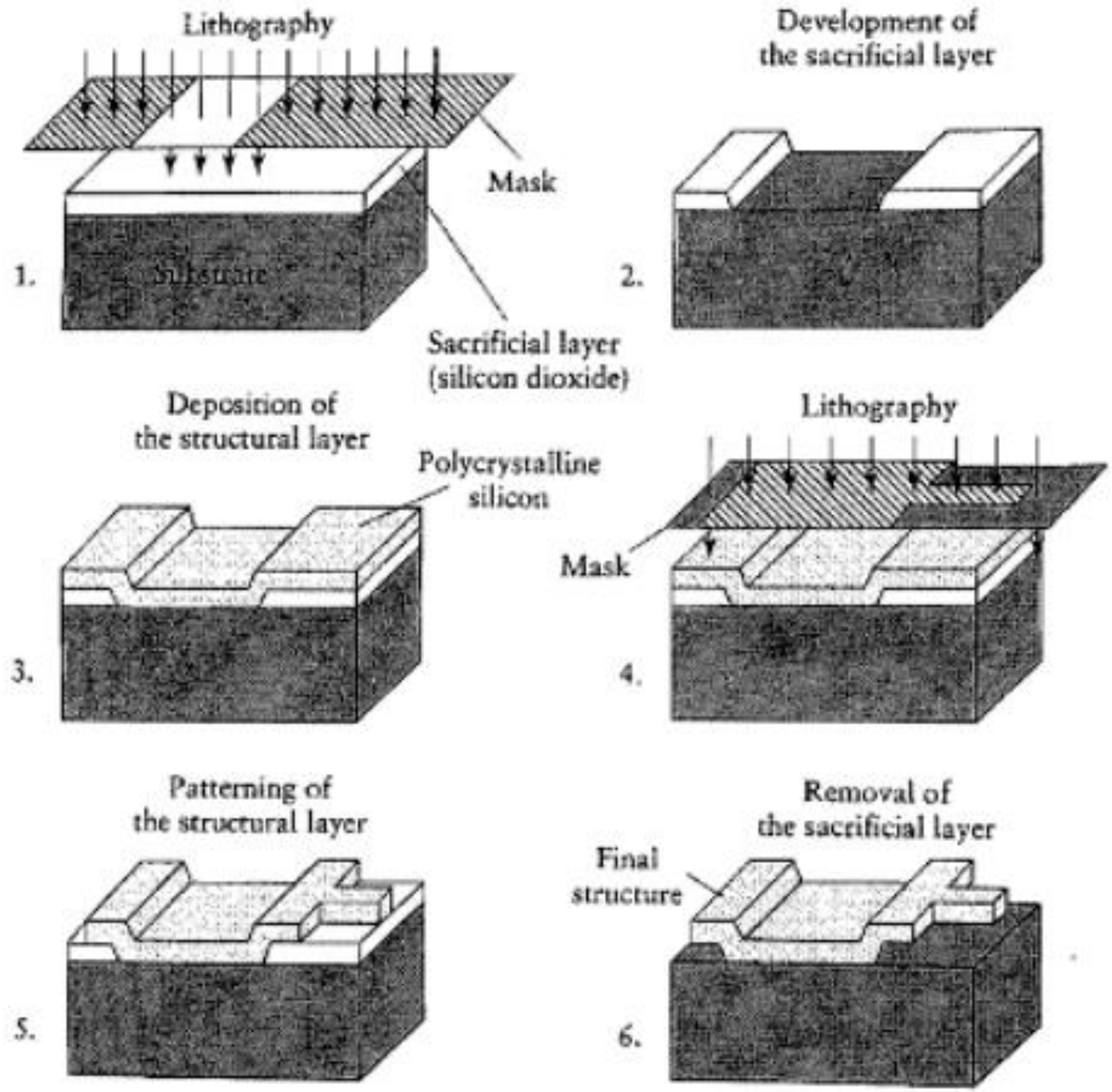
Lithography

- ✓ Litho means "Stone" and Graphy means "Writing"
- ✓ Pattern Transfer process from mask to wafer
- ✓ Optical Light/X-Ray is used to project pattern on mask onto surface of Wafer
- ✓ Wafer surface is coated with photosensitive material (photoresist) in case of photolithography
- ✓ Exposed area of photoresist gets softened/hardened depending on type of photoresist

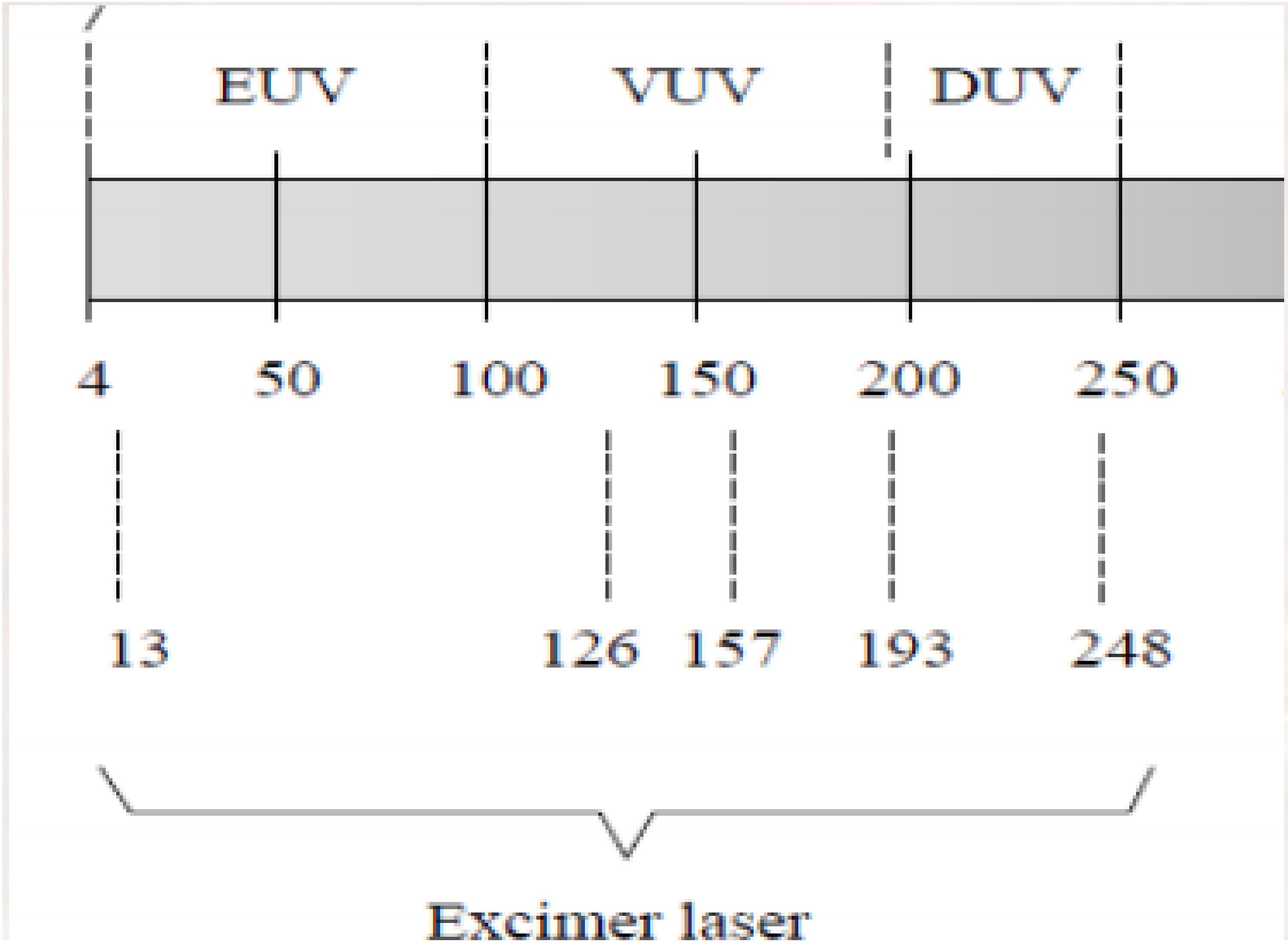
Lithography



Lithography

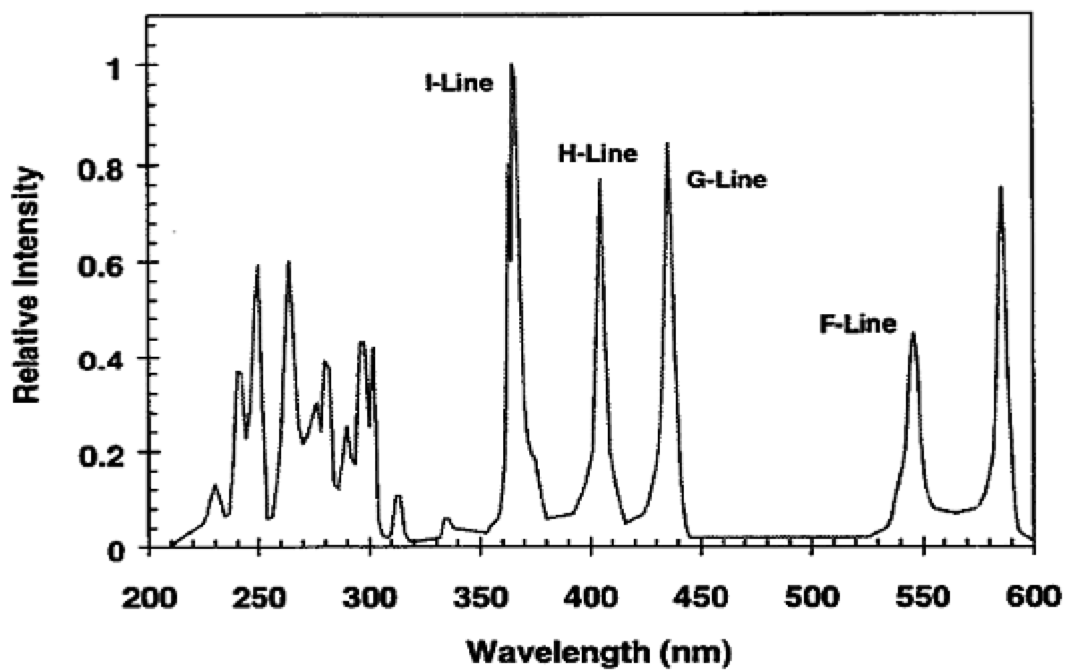


Photolithography



Photolithography

- Hg Arc lamps 436(G-line), 405(H-line), 365(I-line) nm
- Excimer lasers: KrF (248nm) and ArF (193nm)
- Laser pulsed plasma (13nm, EUV)



Photolithography

1.Begin with Doped Silicon Substrate (Electric Properties)

2.Grow Oxide Layer (Insulation)

3.Apply Photoresist Polymer (Photosensitive Coat)

4.Place Mask over Chip (acts as elaborate template)

5.Expose Areas to be Removed to Light

6.Remove Mask

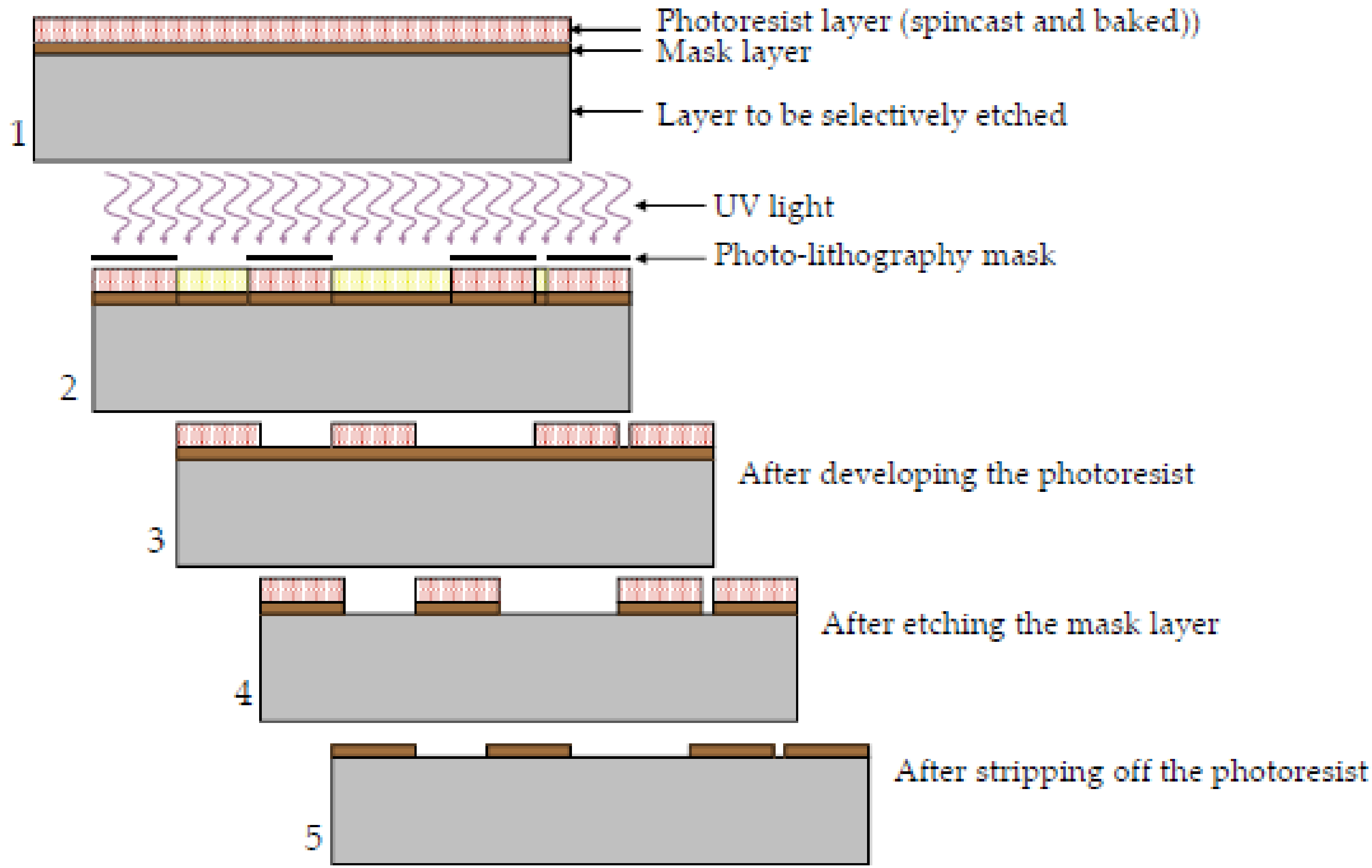
7.Wash Away Exposed Photoresist

8.Etch Oxide Layer

9.Deposit Next Layer

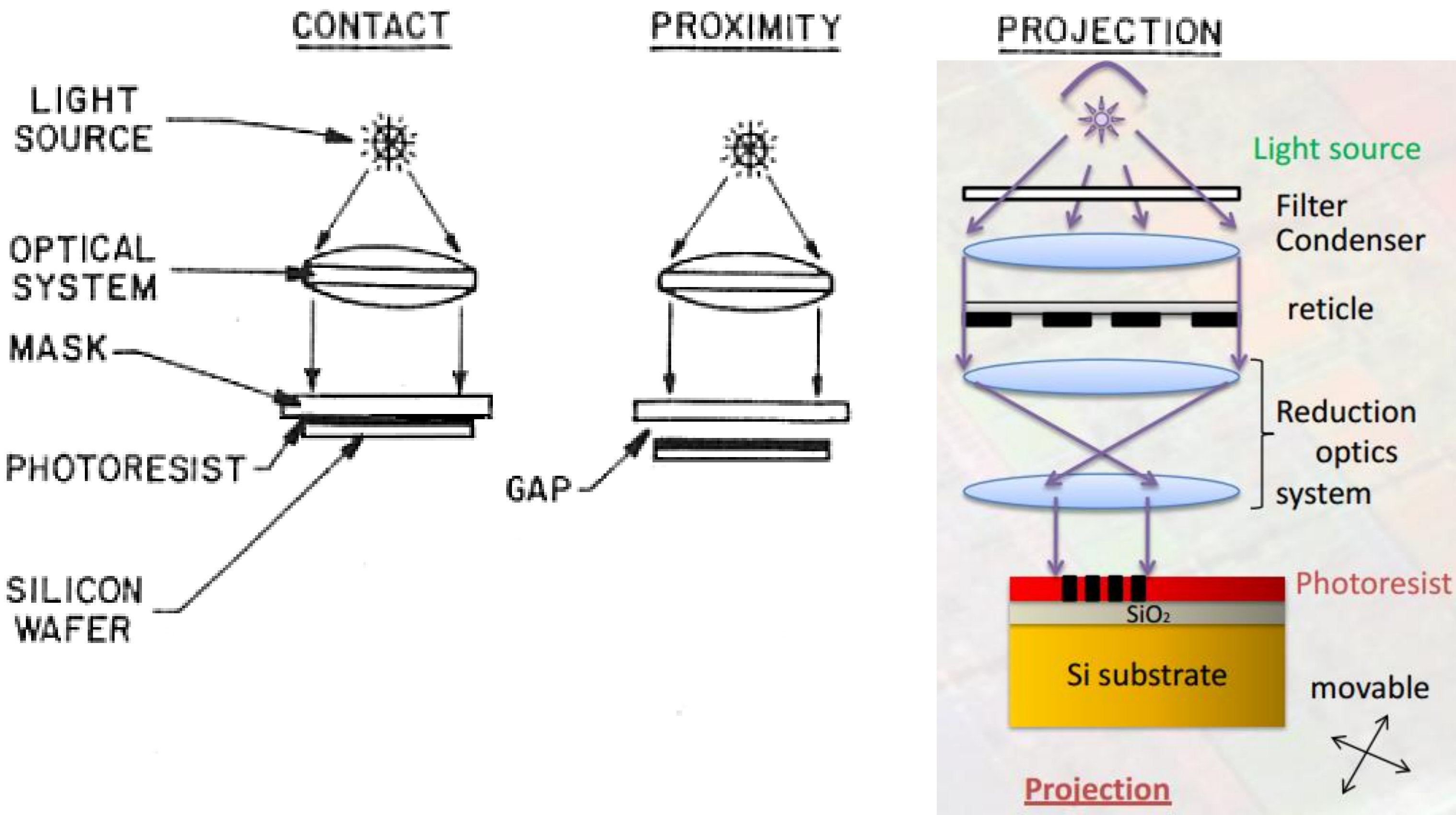
10.Remove Remaining Photoresist

Photolithography for patterning a mask layer



Photolithography

TYPES OF PHOTOLITHOGRAPHY



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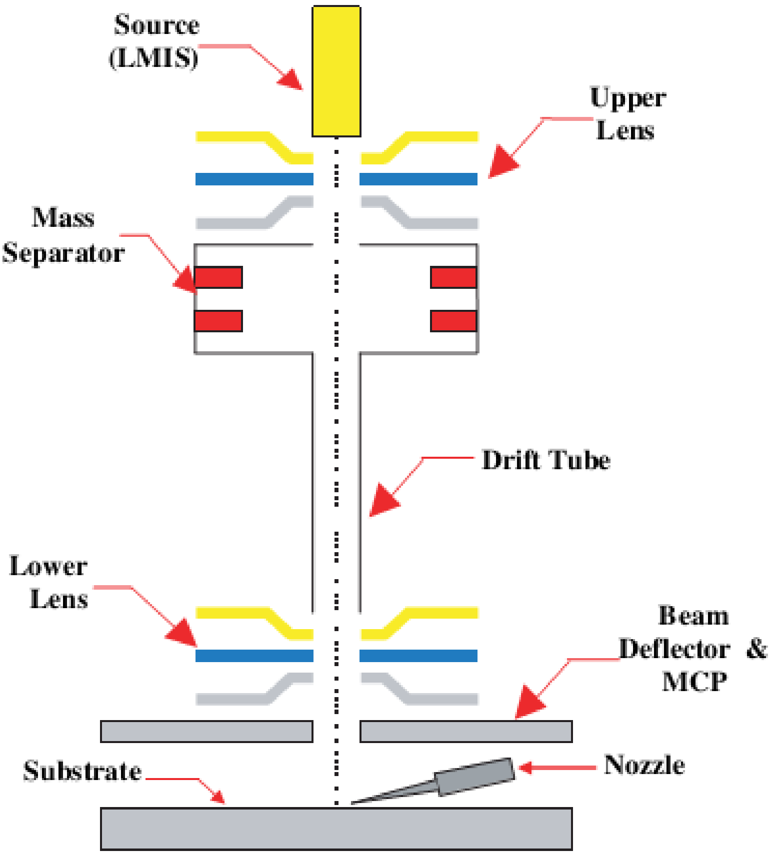
Focused Ion Beam (FIB)

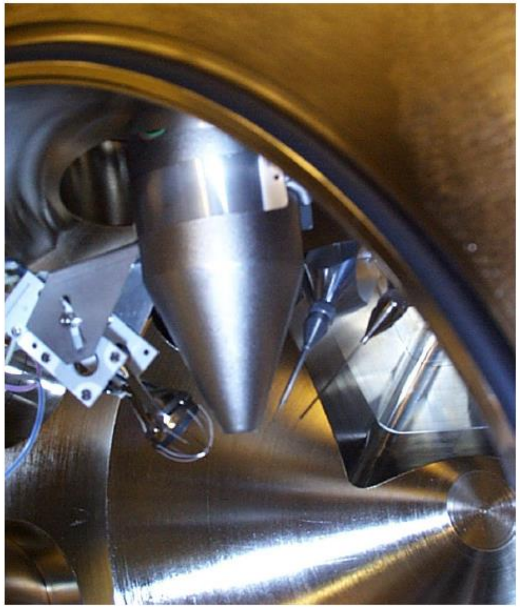
- Focused ion beam (FIB) microscopes are versatile tools enabling inspection, characterization, structuring or manipulation for a broad range of materials.
- The basic concept is very similar to scanning electron microscopes (SEM) but uses charge atoms (ions) instead of electrons.
- Typically, a fine tungsten pin covered with liquid Gallium is used as ion source from which Ga atoms are extracted and ionized via high tensions.
- Such Ga+ ions are then accelerated in the range of 0.5 - 30 keV and focused on the sample via electrostatic lenses.

Focused Ion Beam (FIB) System



FIB system
(Tseng 2004)

FIB-SEM Dual Beam System
(Nova 200 Nanolab, FEI Inc)



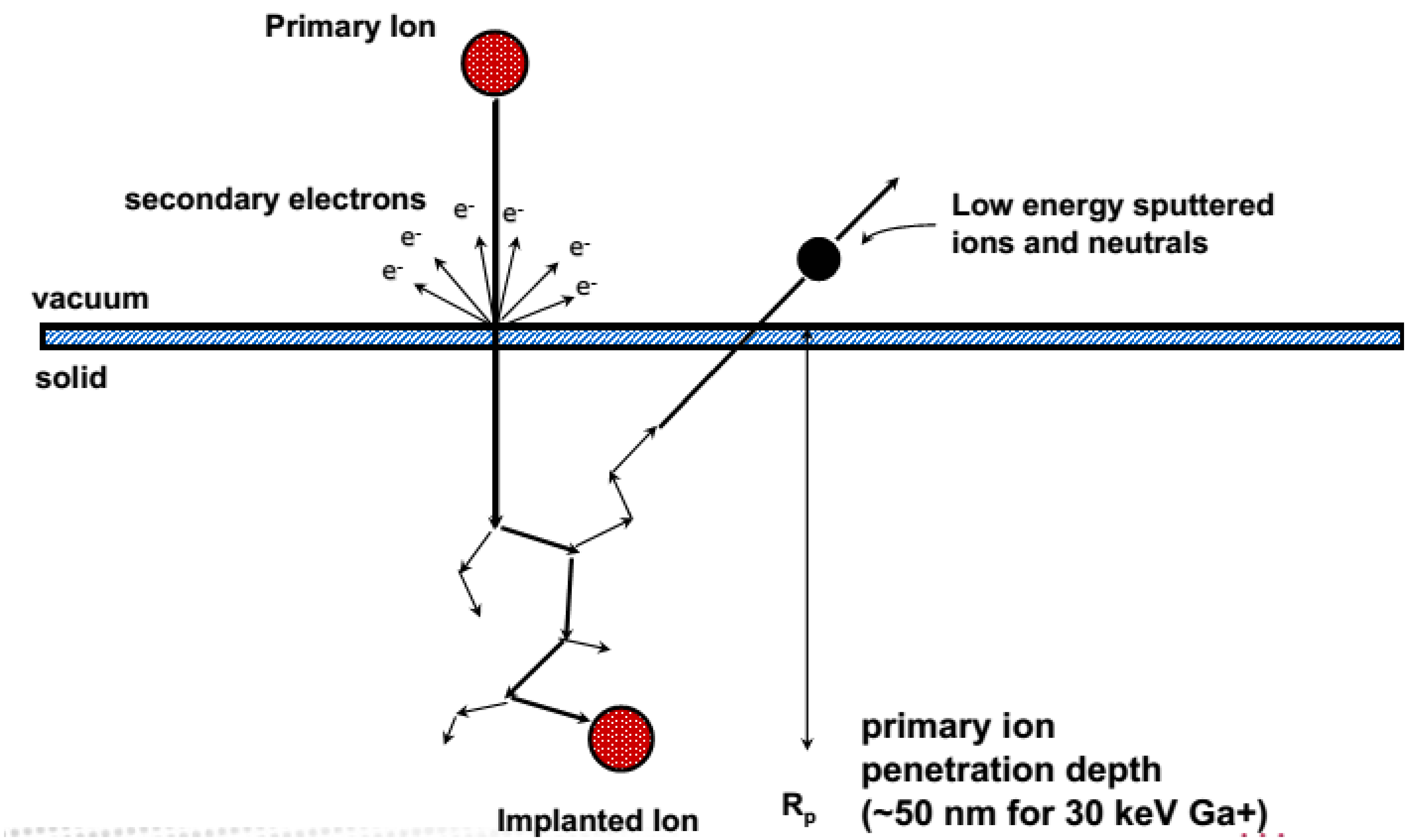
Ion Column in the Chamber
(FEI Inc)

Ion Sources

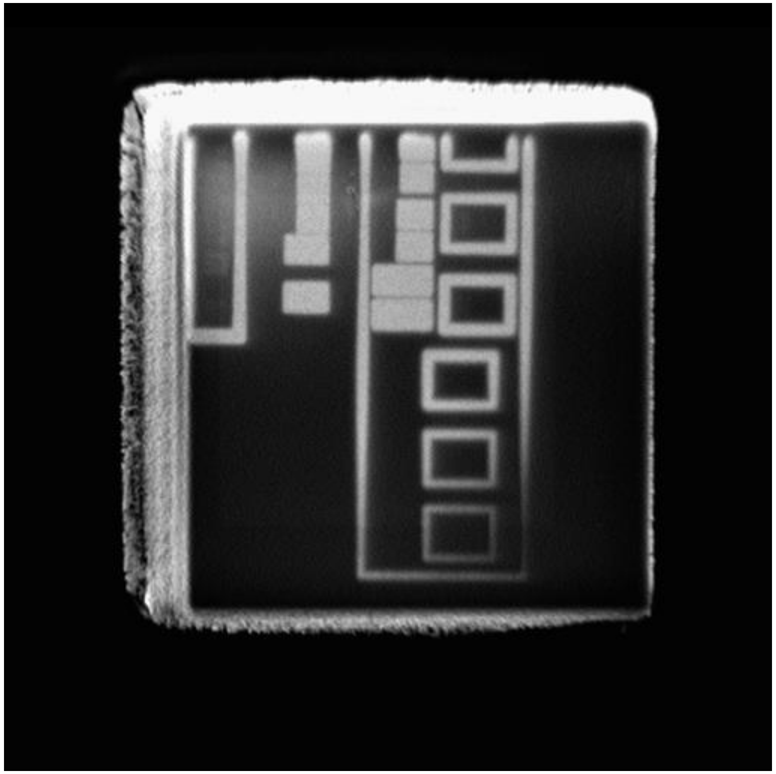
- *Gallium* as an ion source:
  - *Ga* has a low melting point (T_m = 29.6°C).
  - Lower melting point minimizes any reaction or inter-diffusion between the liquid and the tungsten needle substrate.
  - About 99% of the ions in the beam are singly charged. Therefore, no mass filter is needed and the ion column design becomes easier
  - *Ga* can be focused to a very fine probe size (10 nm in diameter)

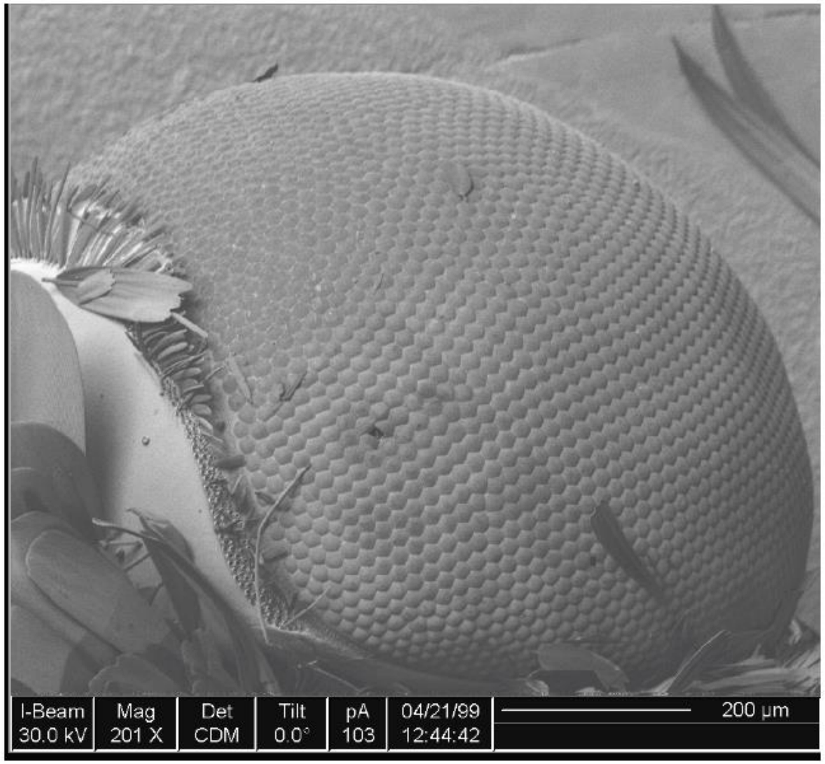
Focused Ion Beam (FIB) System

Sputtering mechanism (Nastasi et al. 1996)



FIB Imaging

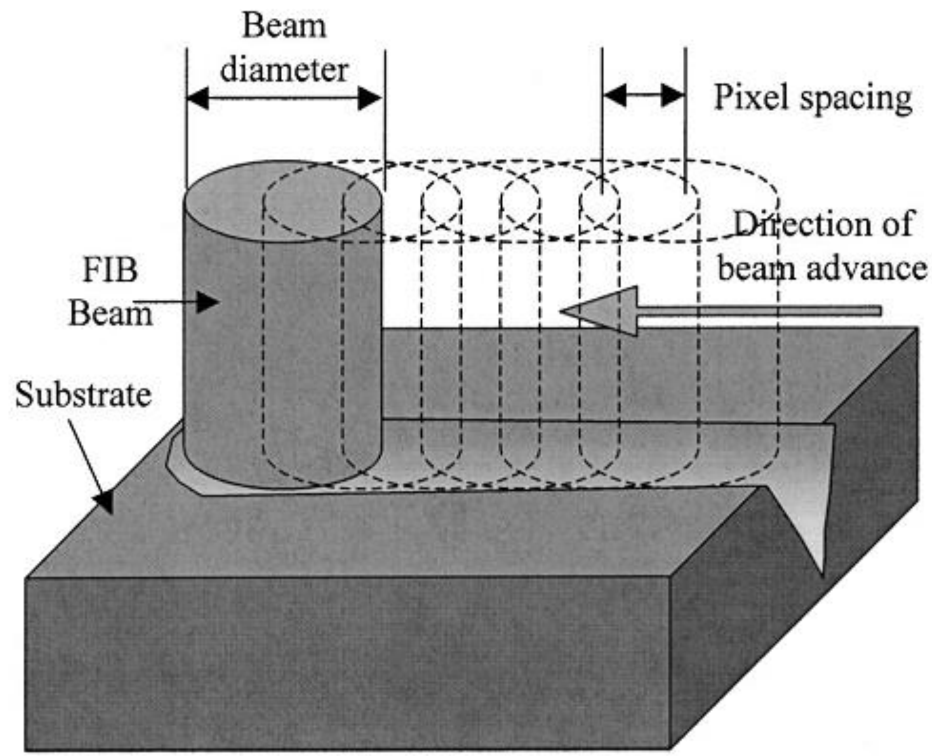




Voltage Contrast like Imaging of N-Wells

FIB Milling

- Simple milling in FIB refers to the sputtering phenomenon due to energetic impingement of focused ion beam on the target material.
- Maskless etching: It is possible to process several tens on nanometer level area without using a mask.
- In addition, provision to observation of processing condition under microscope makes very accurate and high precise results possible

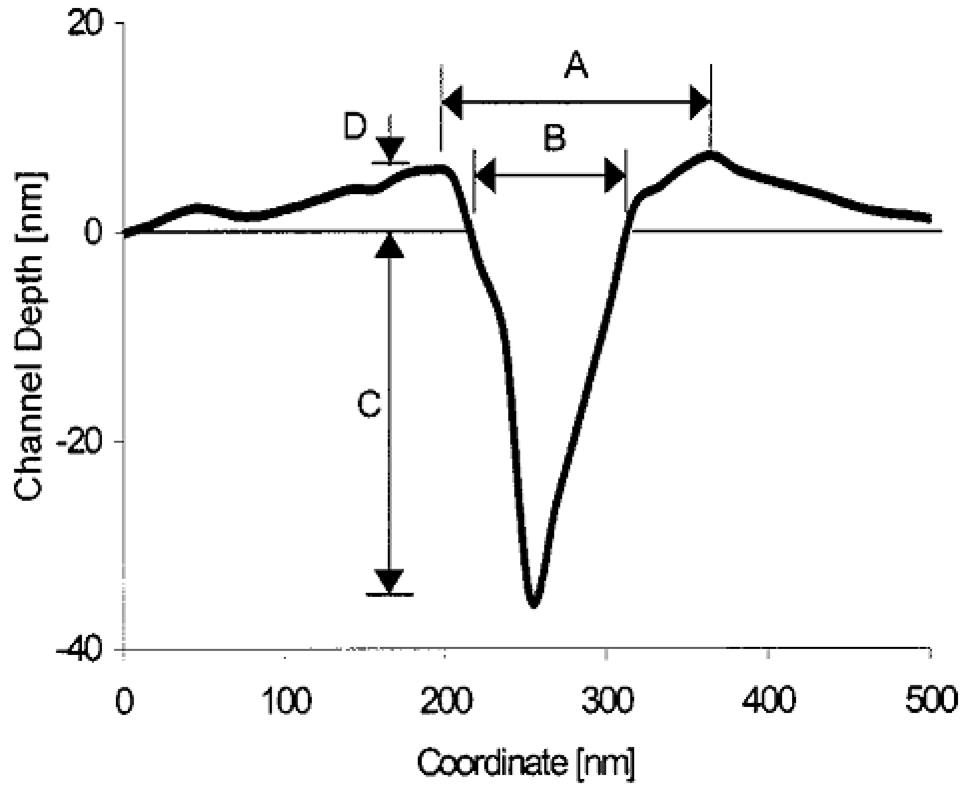


FIB Milling
Micro Channel

- A: Ridge width

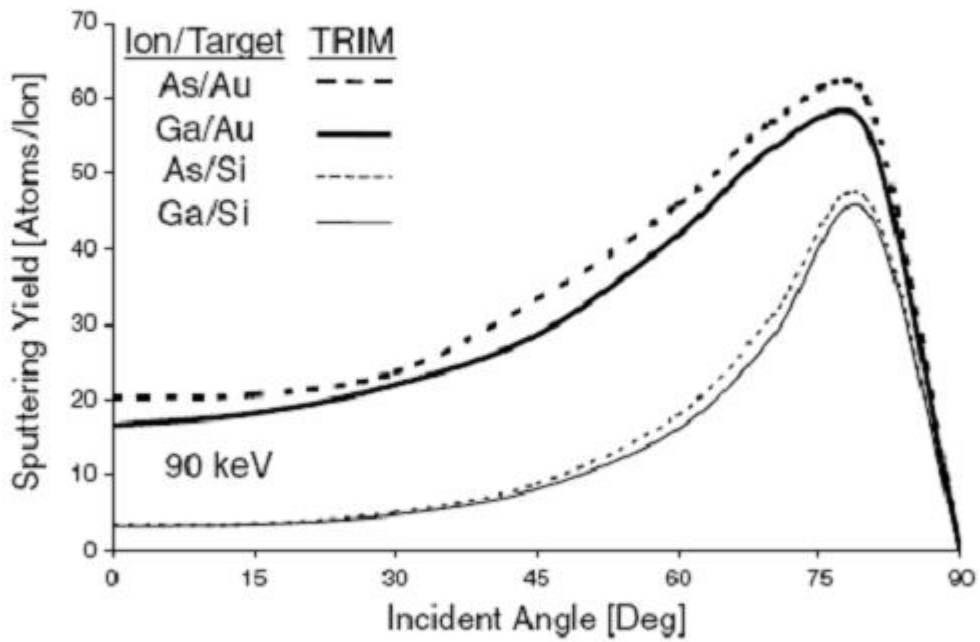
  the distance between the ridge peaks
- B: Mouth width

  the channel width w.r.t. the original surface,
- C: the depth from the original surface,
- D: Ridge height.



FIB Milling
Process Parameters

- Beam Current
- Angle of Incidence



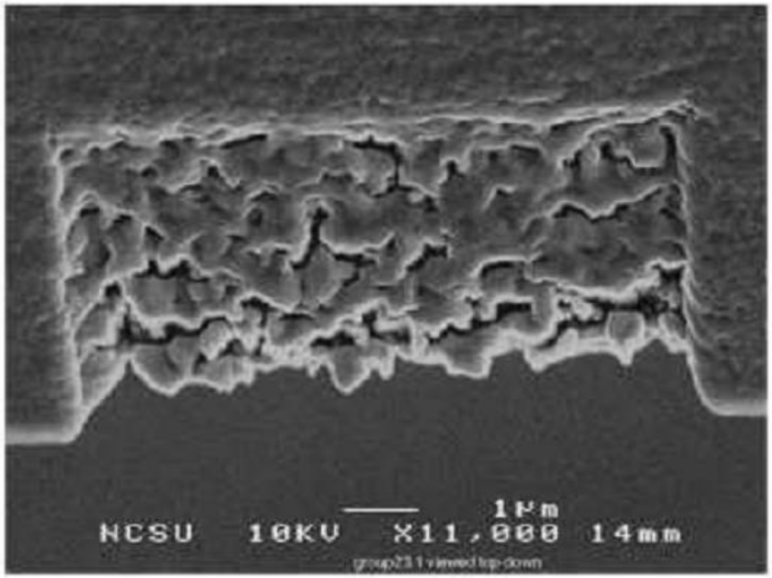
FIB Milling
Process Parameters

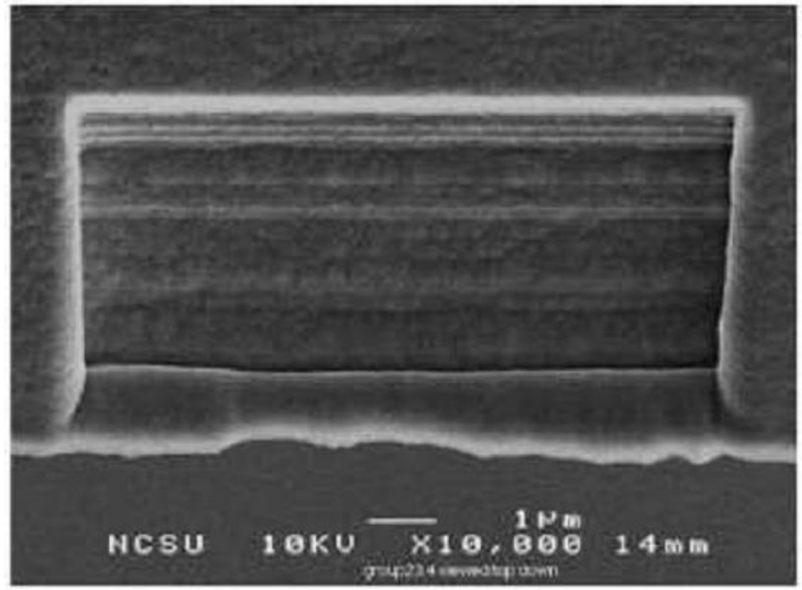
- Ion Energy (~ 1-60 KeV)
- Dwell Time (or Ion Dose)
- Number of Passes
  - Single vs Repetitive passes
  - Redposition

FIB Milling
Enhanced Etch

- Gas Assisted Etching (GAE) or Chemical Assisted Focused Ion Beam Machining (CEFIBM)
- Chemical enhancements of material removal rates result from chemical reactions are initiated by impinging Ga^+ ions.
- These reactions involve a chemical injected into the vacuum which then adsorbs to the sample surface and the surface constituents of the material being micromachined
- Ideally, these reactions both increase the material removal rate and result in a volatile reaction product, thus reducing redeposition of micromachined material.

FIB Milling
Enhanced Etch





Free edge micromachining of Permalloy
(a) without chemical enhancement and (b) using C_2Cl_4

Russell et al, JVSTB (1998)

FIB Milling – Gas assisted Enhanced Etch

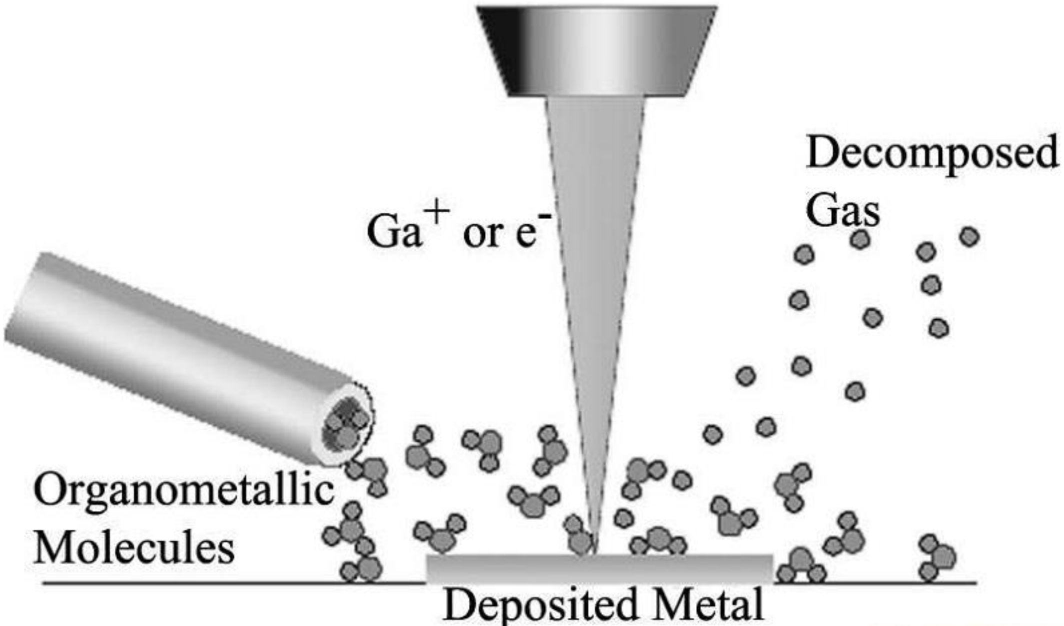
Gas	Target	Etch rate ($\mu m^3/nC$)	Enhancement factor
Cl_2	Silicon	2.6	11.8
	Aluminum	0.6	3
	GaAs	6.9	10
	Silver	1.1-2.8	< 2
H_2O	Diamond	1	7
	PMMA	7.5	15
	Polyamide	8.5	17
XeF_2	Silicon	---	7-12
C_2Cl_4	Permalloy	0.78	7.8
I_2	PMMA	0.9	2

FIB Chemical Vapor Deposition
FIB-CVD

- A gas carrying the element to be deposited is delivered through injection nozzles
- Deposition requires that gas molecules delivered to the surface are adsorbed in adequate numbers and their binding energy to the surface is sufficiently large
- Binding Energy vs Decomposition Energy
- Wide range of metals can be deposited:

  W, Pt, Al, Ta, C, SiO_2, etc

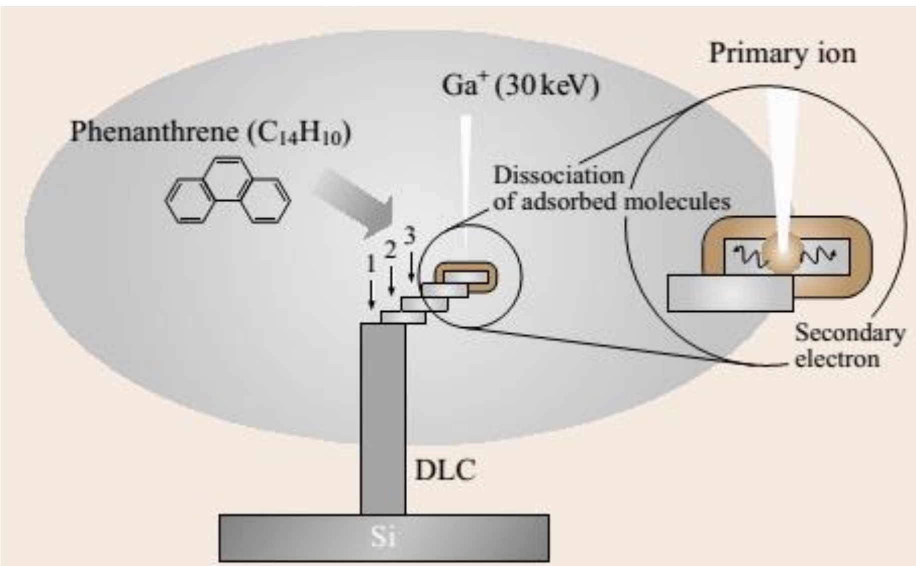
FIB Chemical Vapor Deposition FIB-CVD



FIB Chemical Vapor Deposition FIB-CVD

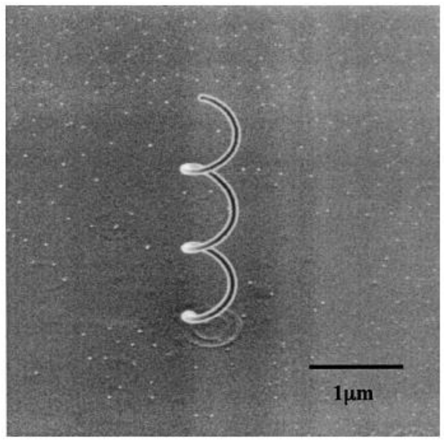
Element	Precursor gas	Deposit
W	Tungsten hexacarbonyl [$W(CO)_6$], WF_6	W:C:Ga 60:20:20
Pt	Methylcyclopentadienyl(trimethyl) platinum [$C_9H_{16}Pt$], $C_7H_{17}Pt$, Trimethylcyclopentadienyl-platinum [$(CH_3)_3CH_3C_5H_5Pt$]	Pt:C:Ga 30:60:10
Au	$C_7H_7F_6O_2Au$	Au:C:Ga 80:10;10
Al	$Al(CH)_3$, $(CH_3)_3NAlH_3$	Al:O:Ga:C 37:27:26:10
Si, SiO_2	Siloxane compound TEOS: $Si(C_2H_5O)_4$, Silane TMOS: $Si(CH_3O)_4$, O_2	Si:O:C:Ga 11:64:11:13
C	Phenanthrene $C_{14}H_{10}$	---

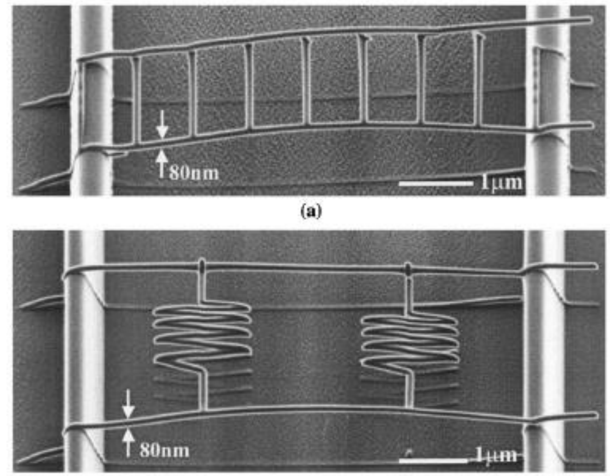
FIB Chemical Vapor Deposition FIB-CVD - 3D Structures

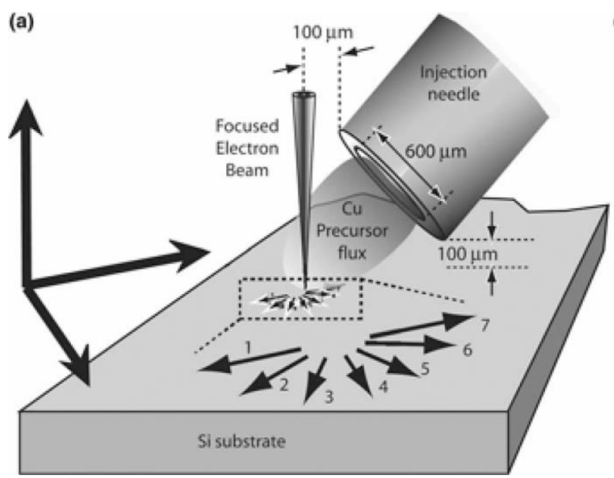


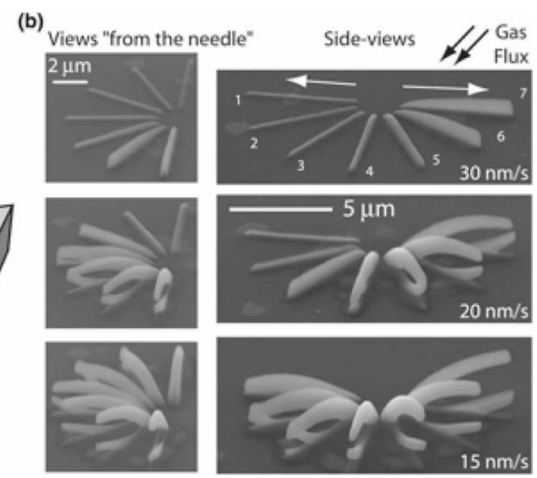
The key point to making 3D structures is to adjust the beam scan speed so that the ion beam remains within the deposited terrace, which means that the terrace thickness always exceeds the range of the ions.

FIB Chemical Vapor Deposition
FIB-CVD - 3D Structures









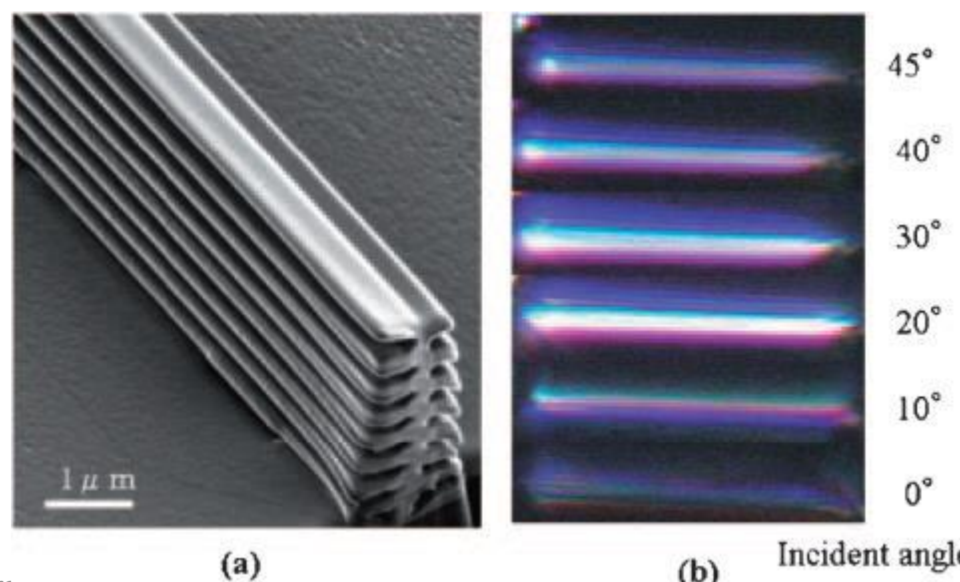
Jun et al, Nano Lett. (2010)

FIB Chemical Vapor Deposition FIB-CVD - 3D Structures

Due to an intriguing optical phenomenon, the scales reflect **interfered brilliant blue color** for any angle of incidence of white light.
This color is called a **structural color**, meaning that it is not caused by pigment reflection

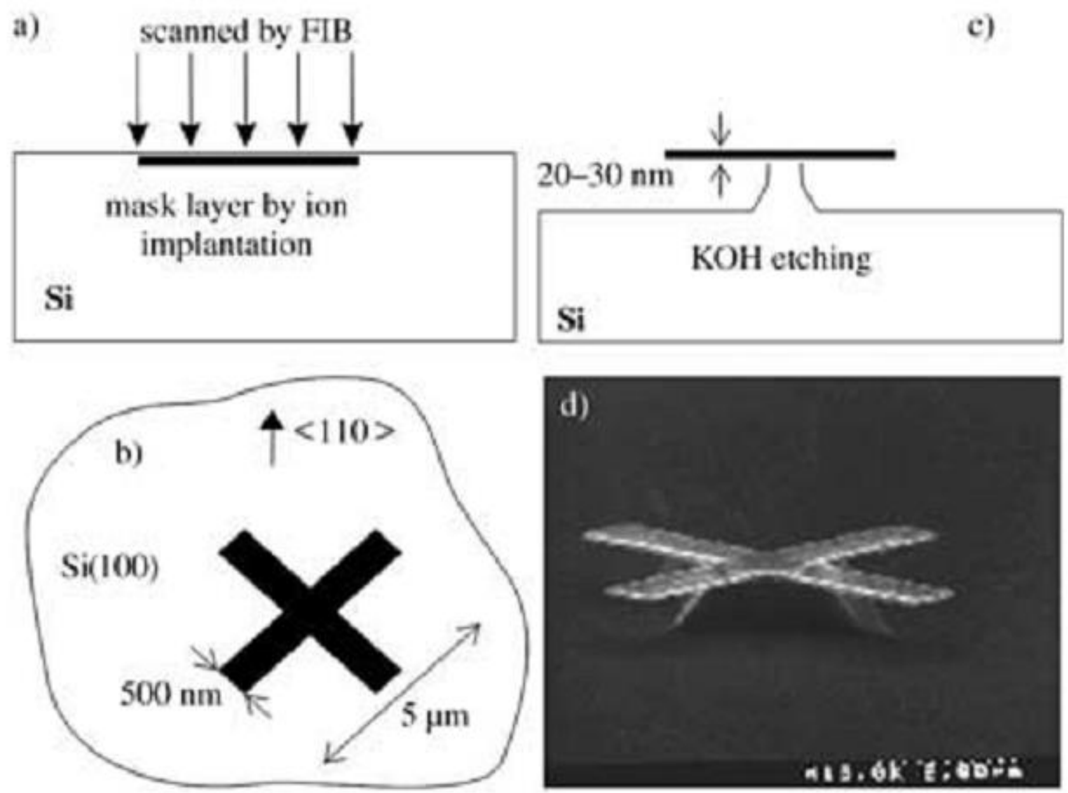
SIM image of the Morpho butterfly quasistructure of DLC fabricated by FIB-CVD using *phenanthrene* ($C_{14}H_{10}$) as a precursor

Watanabe et al, Jpn. J. Appl. Phys., 2005



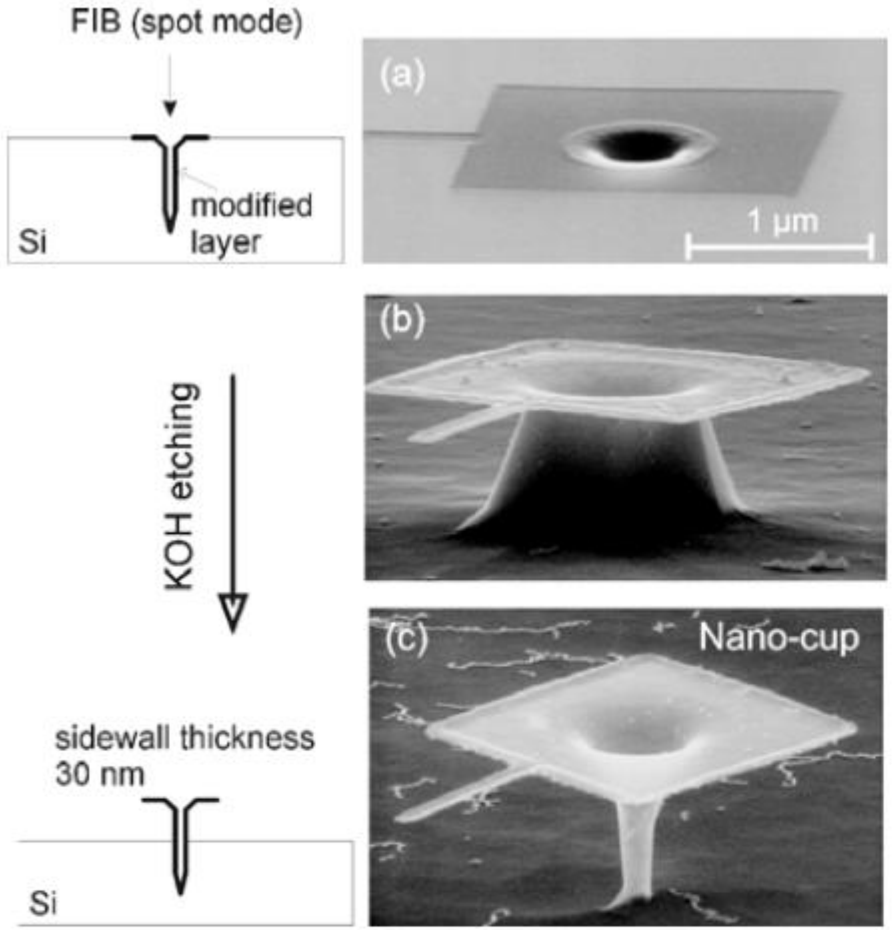
FIB Implantation
Micro-cantilever fabrication

a) Implantation or modification by FIB scanning (cross section),
b) Top view of a FIB-scanned surface with a quad-cantilever layout,
c) KOH etching for a non-implanted substrate (cross section),
d) SEM image of fabricated quad-cantilevers, which are 30 nm thick, 500 nm wide, and 5mm long



J. Brugger et al, Microelectron. Eng., 1997

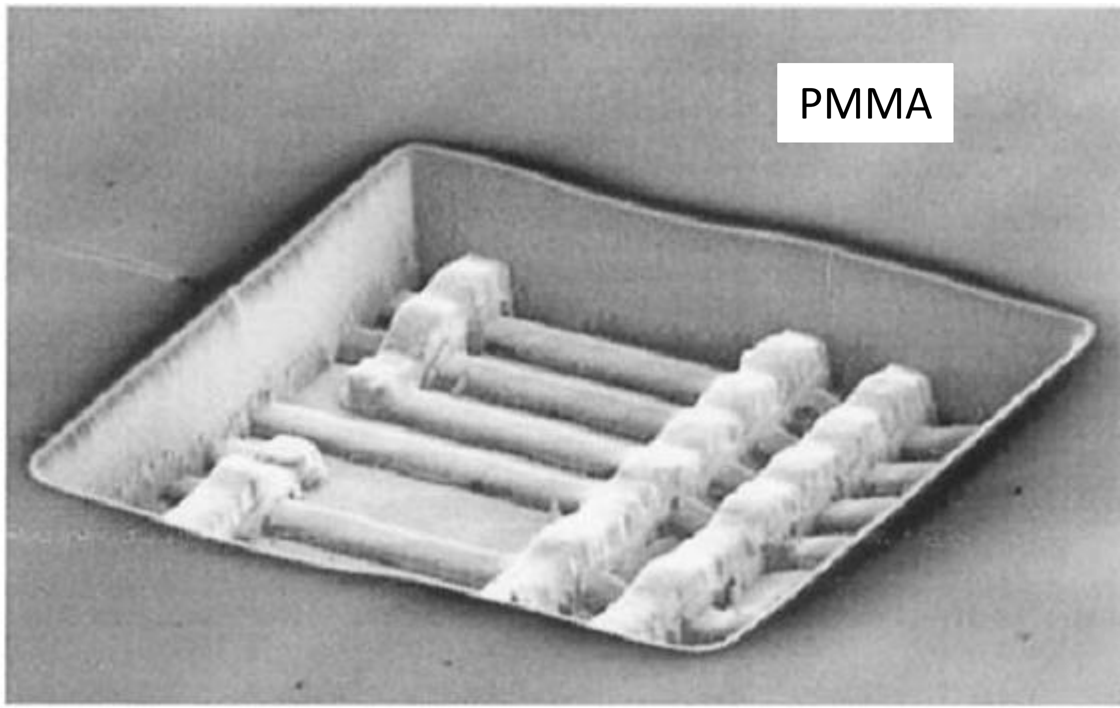
FIB Implantation
Maskless Nanocup fabrication



J. Brugger et al, Microelectron. Eng., 1997

Etch Selectivity

The ability to remove one sample constituent while leaving other sample constituents relatively unaffected

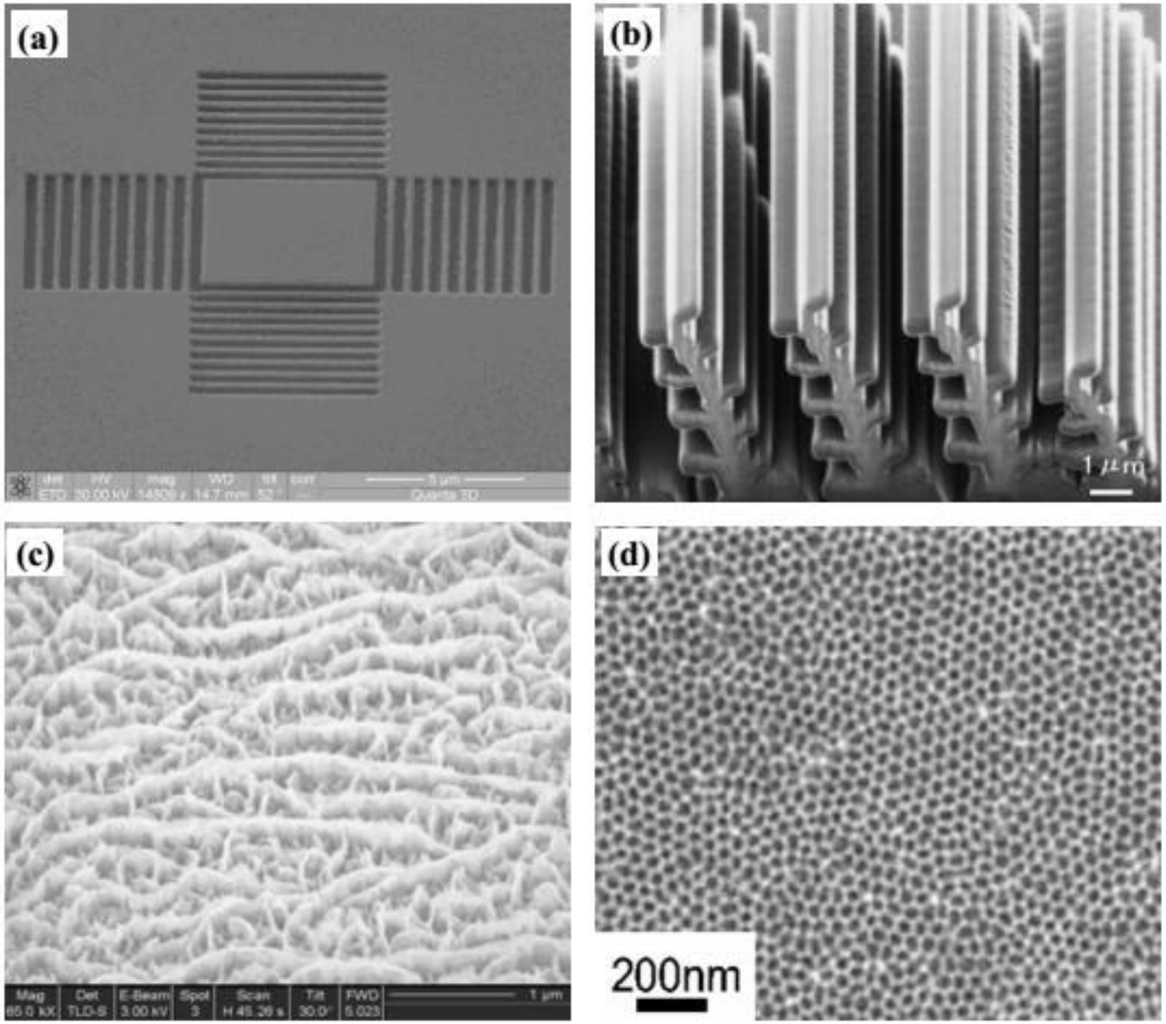


Stark et al, JVST, 1996

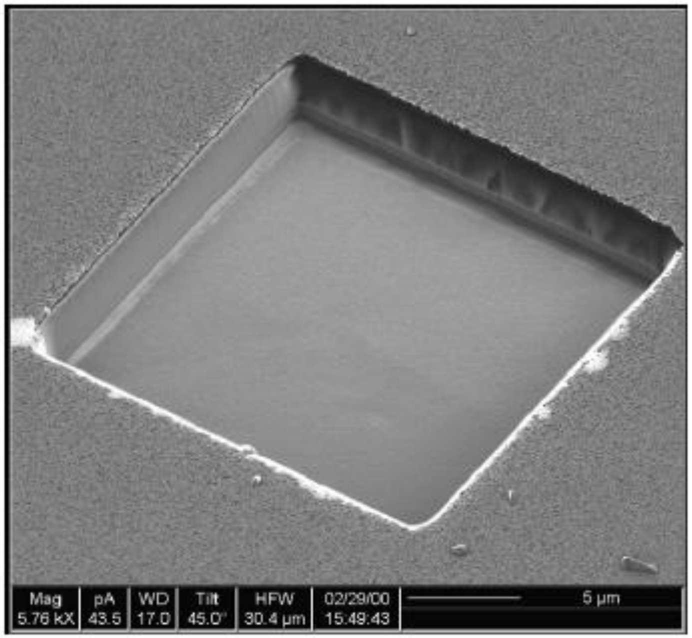
This feature was micromachined in 11 minutes.

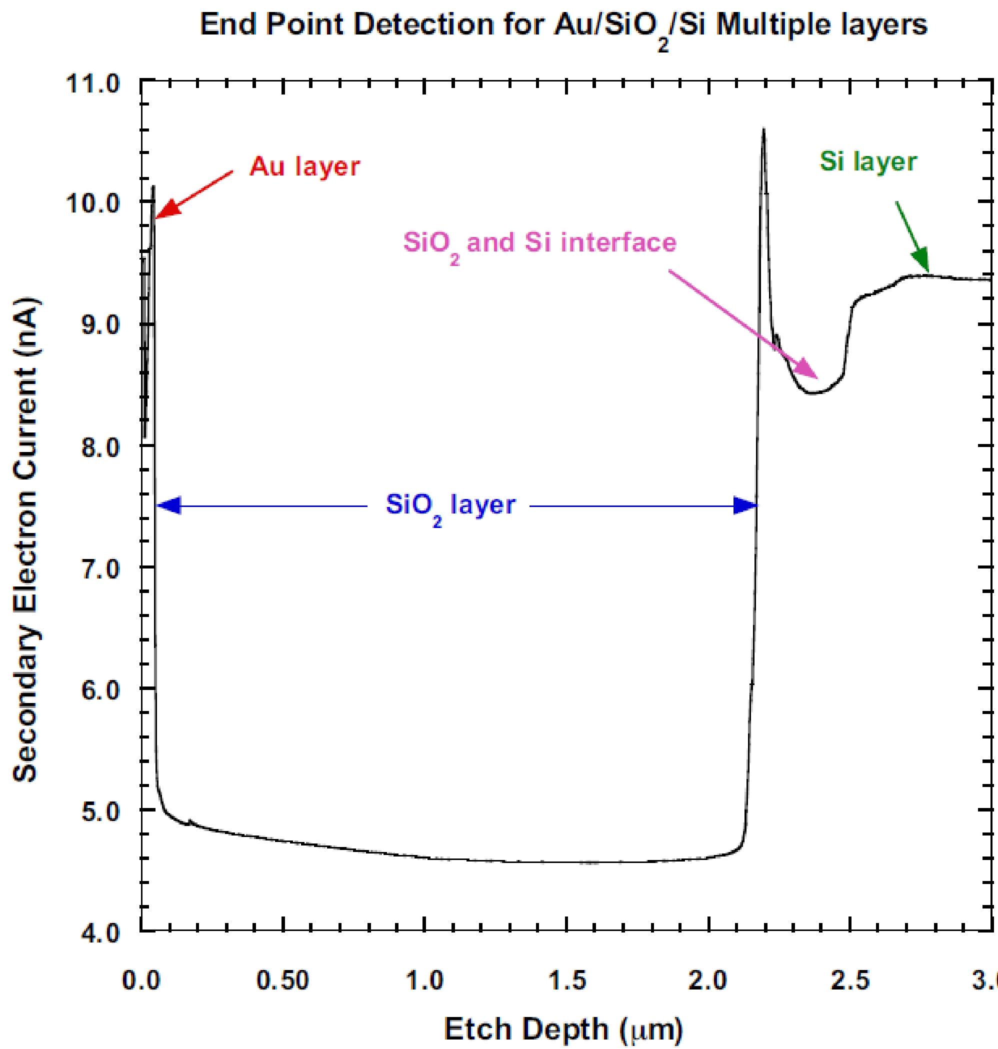
Using physical sputtering alone to remove the **PMMA** would have required 225 minutes and the ***Al* metallization** would be completely removed

Surface Structuring



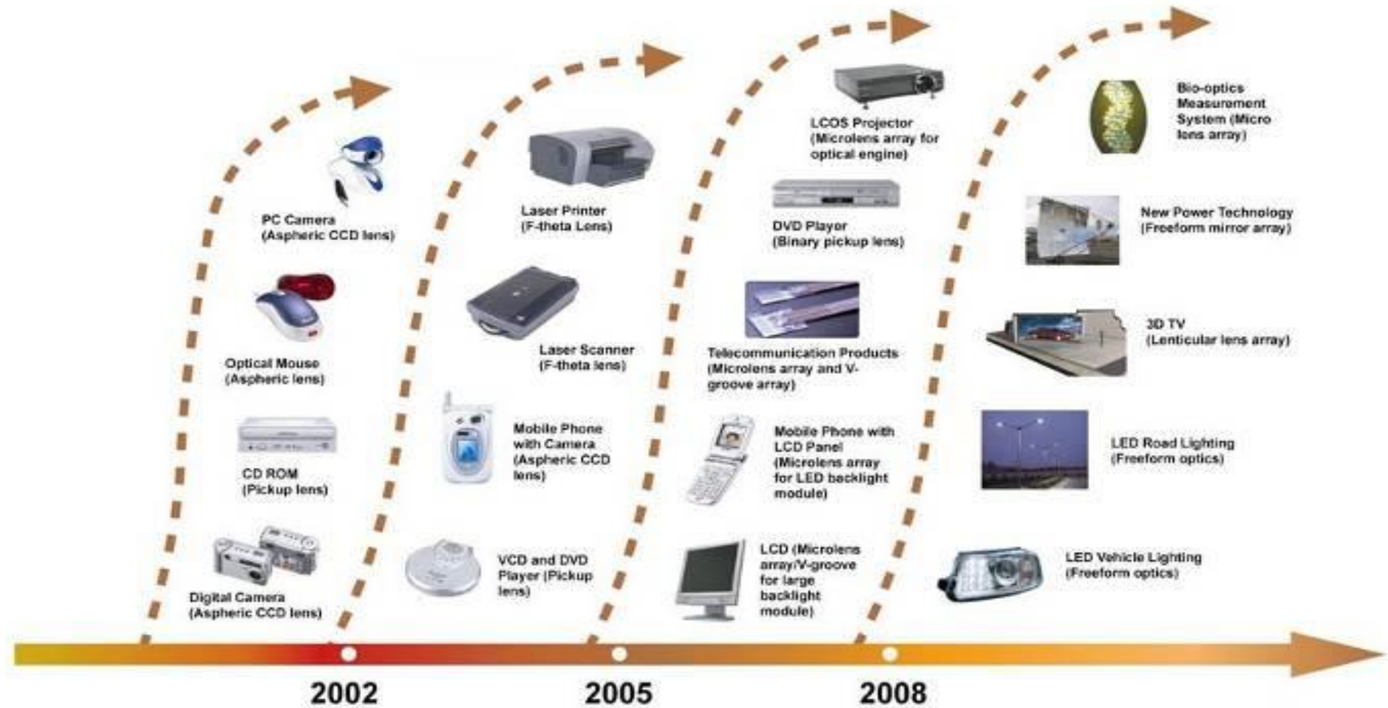
End Point Detection





FIB Nanofabrication of cutting tools for Ultra Precision machining

Roadmap for Precision Optical Components and Systems



“Ultraprecision machining is doing for light what integrated circuits did for electronics”.

- Blynsky, G, “Closing in on Perfection”, *Fortune 2003*

Traditional Optical Fabrication vs Diamond Turning

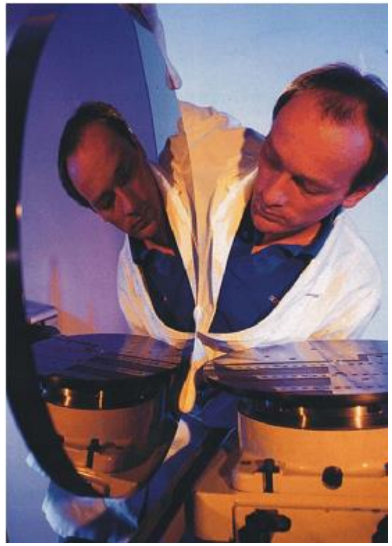
- **Traditional optical fabrication**: the final shape and surface of the optical element are produced by lapping and polishing with an abrasive loaded lap
- a *displacement - controlled vs* a *force - controlled process*
- **Lithographic techniques**: limiting devices to 2D and generally low-aspect ratio
- Unlike in electronics, 3D form accuracy is a necessity for optics, and precision assembly is critical to performance
- **Diamond turning**: the final shape and surface of the optical produced depends on the machine tool accuracy and the *cutting tool geometry and integrity*

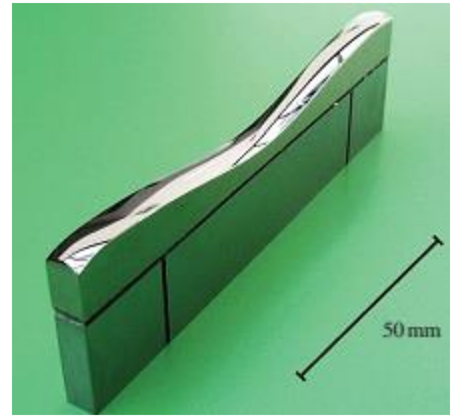
Micro/Nano Machining

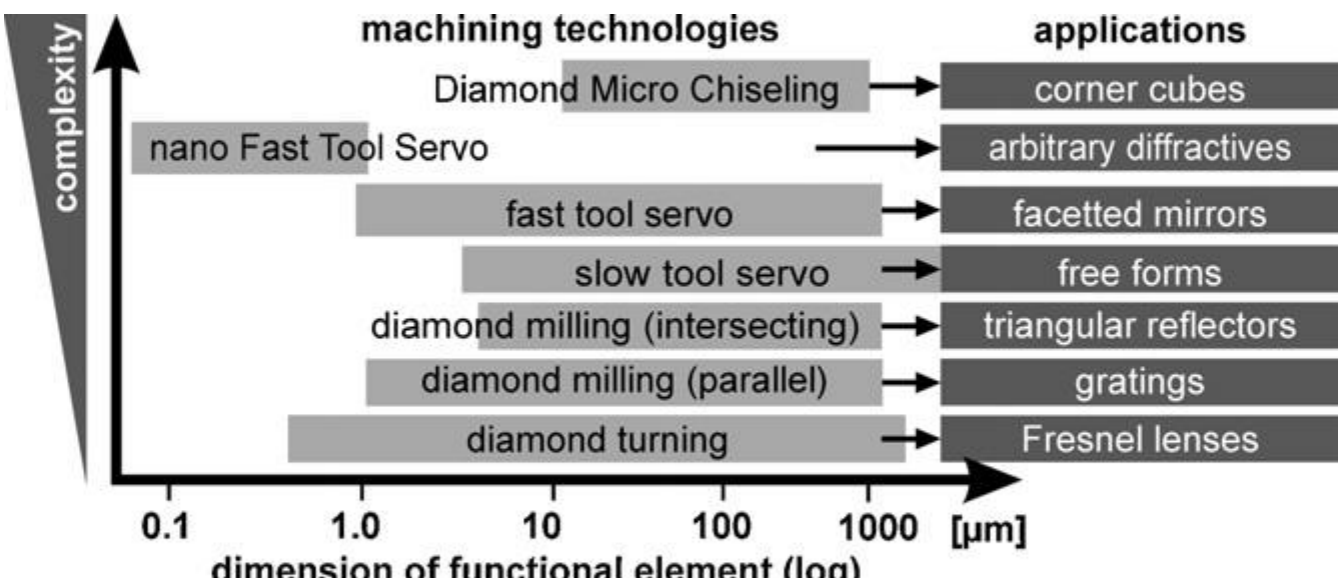
	nano-machining	micro-machining	macro-machining
size of machined area	1–10^5 μm^2	1–10^5 mm^2	1–10^5 cm^2
volume removal in one machining step	from 10^{-3} to 10^2 μm^3	from 10^{-3} to 10^2 mm^3	from 10^{-3} to 10^2 cm^3
material removal rate	from 10^{-5} to 1 $\mu m^3\,s^{-1}$	from 10^{-5} to 1 $mm^3\,s^{-1}$	from 10^{-5} to 1 $cm^3\,s^{-1}$
relative figure error	from 10^{-5} to 10^{-3}	from 10^{-7} to 10^{-5}	from 10^{-5} to 10^{-3}
surface roughness (S_a)	1–10^2 Å	1–10^2 nm	from 10^{-1} to 10 μm

symmetrical surfaces	freeform surfaces	structured surfaces
moulds for plastic lenses	non-telecentric imaging systems	automotive lighting
IR optics	head-up displays	lens arrays
UV optics	LED lighting systems	prism arrays
CO_2-laser mirrors	range finders	phase plates
ophthalmic lenses	F-theta lenses	Fresnel lenses
scanner polygons	flat panel backlight units	lab-on-a-chip

Micro/Nano Machining Techniques

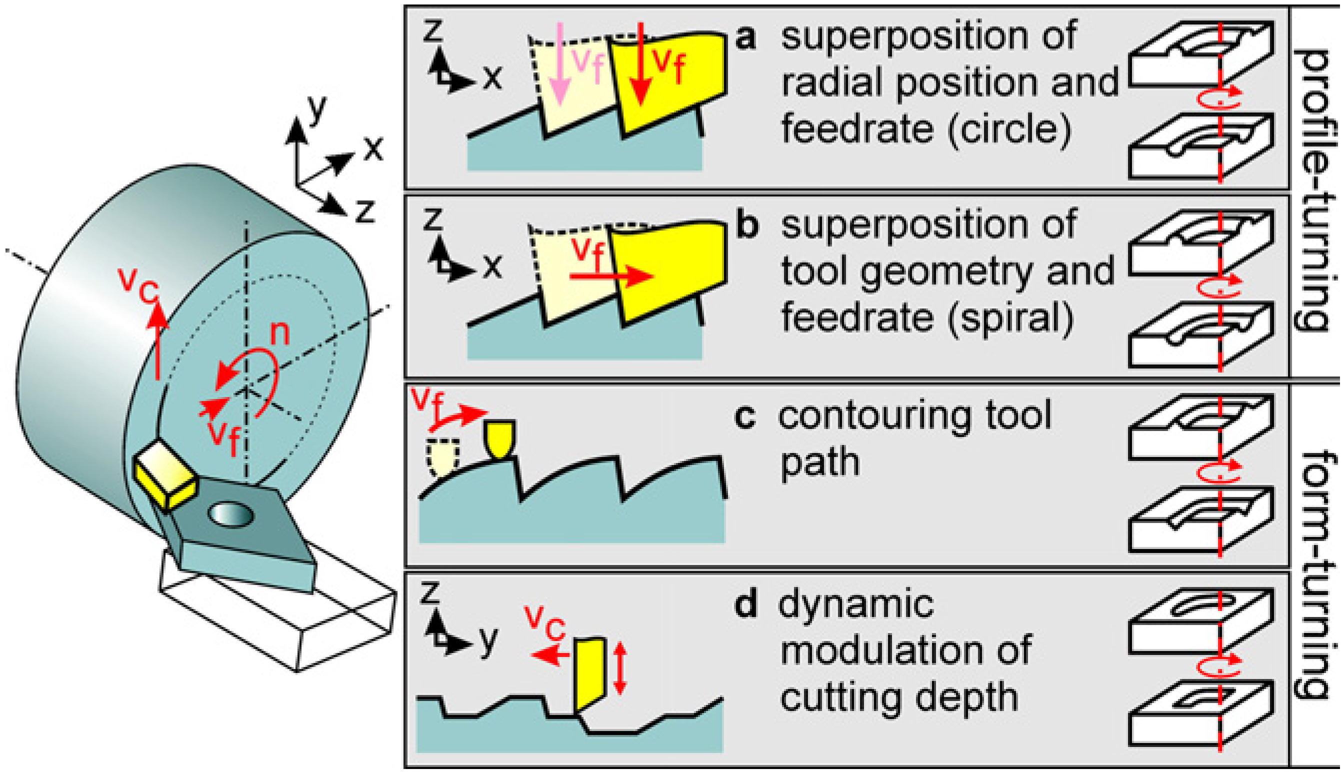






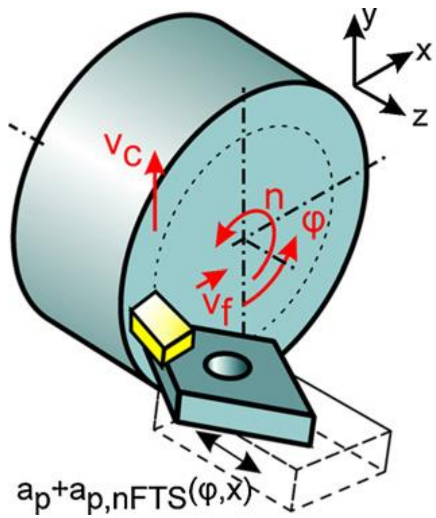
Standard Structuring Processes

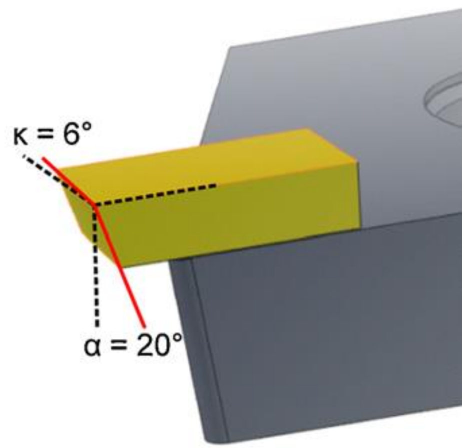
- Diamond Turning

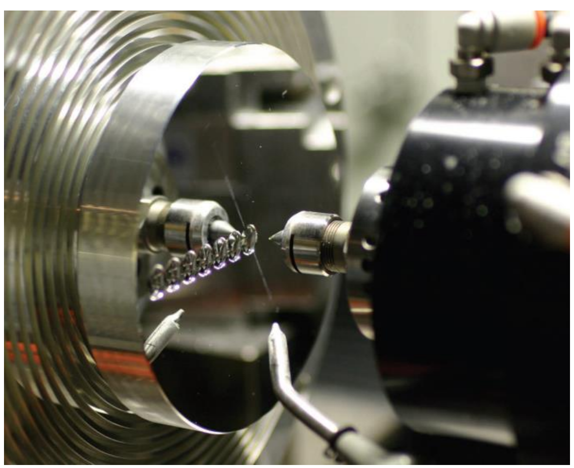


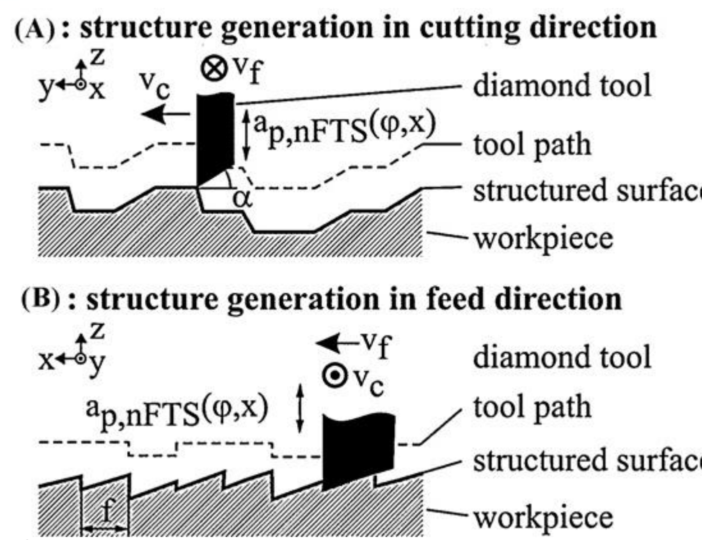
Standard Structuring Processes

- Diamond Turning – Fast Tool Servo (FTS)



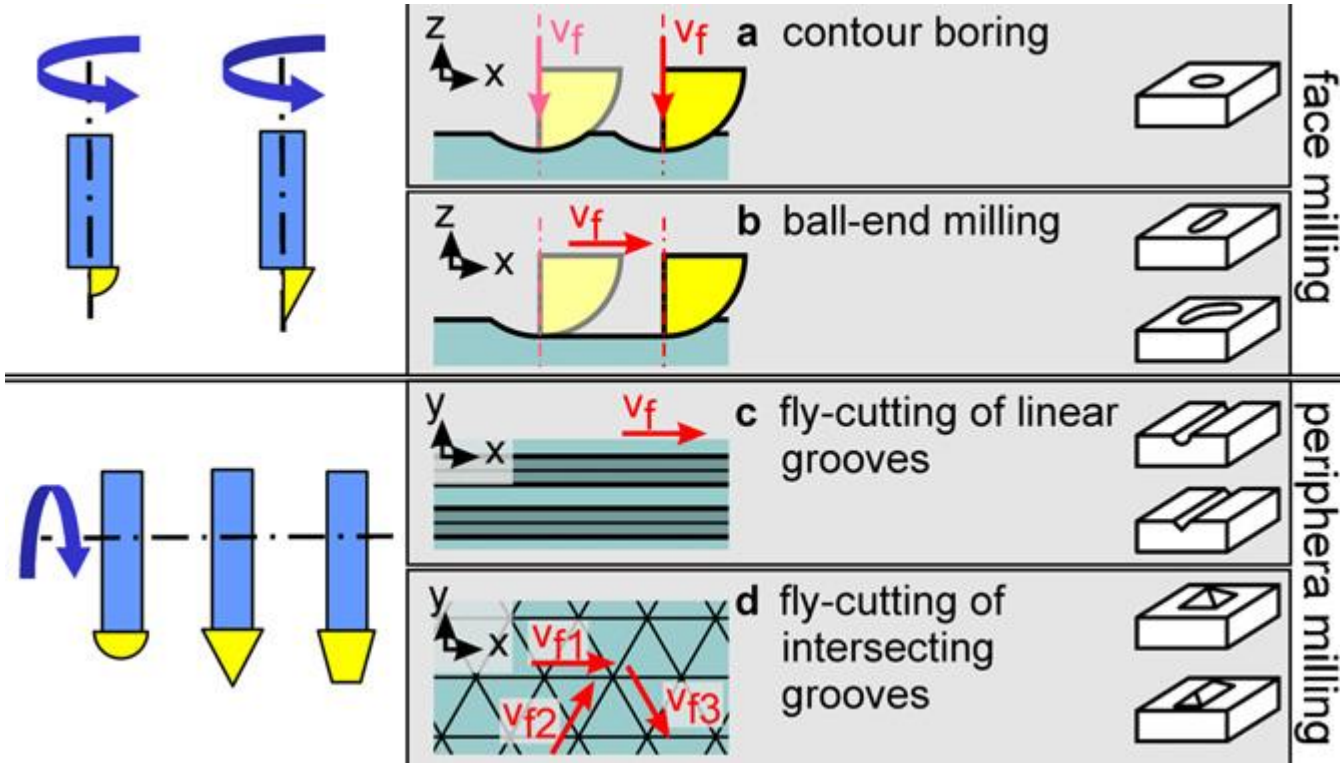






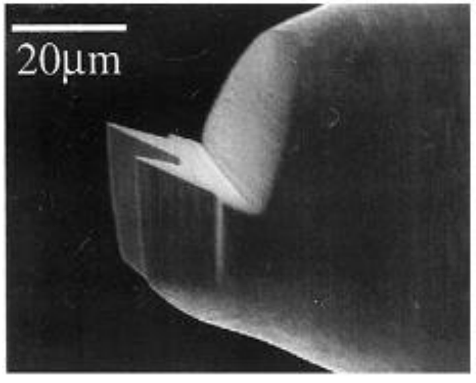
Standard Structuring Processes

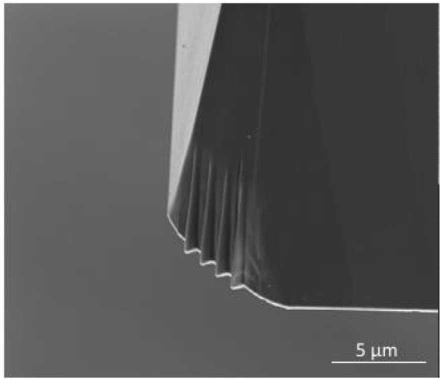
- Diamond Milling



FIB manufacture of microtools

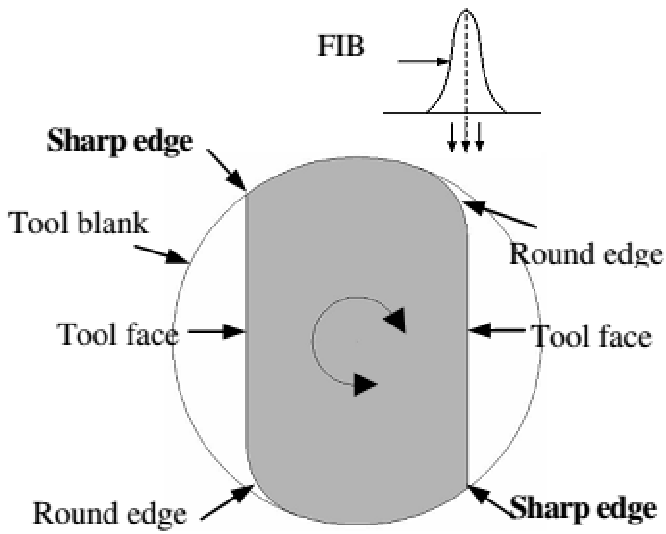
- The variety of tool shapes
- The control over tool geometry
- The nanometer dimensional resolution
- The observation of a tool during shaping
- Negligible mechanical force is placed on the tool during FIB fabrication.

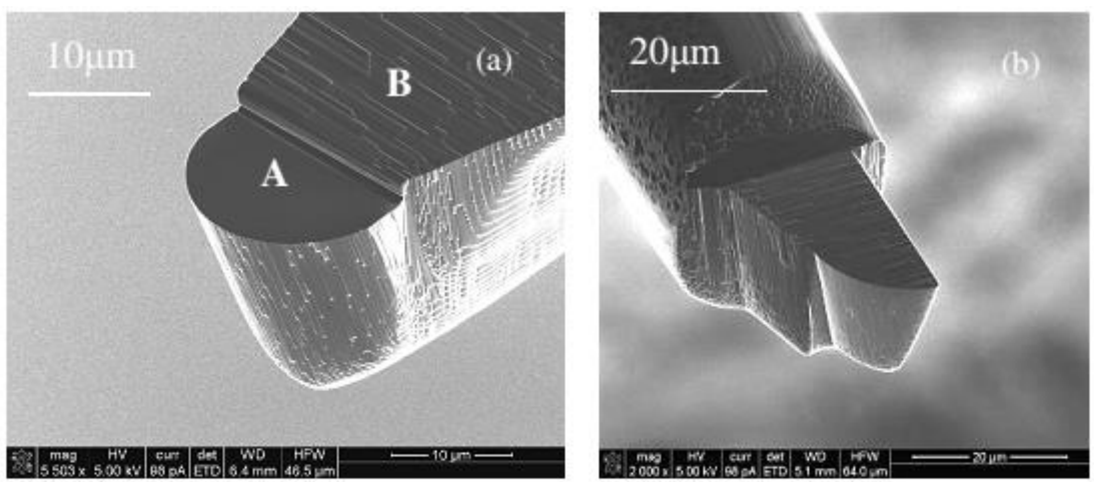




FIB fabrication issues

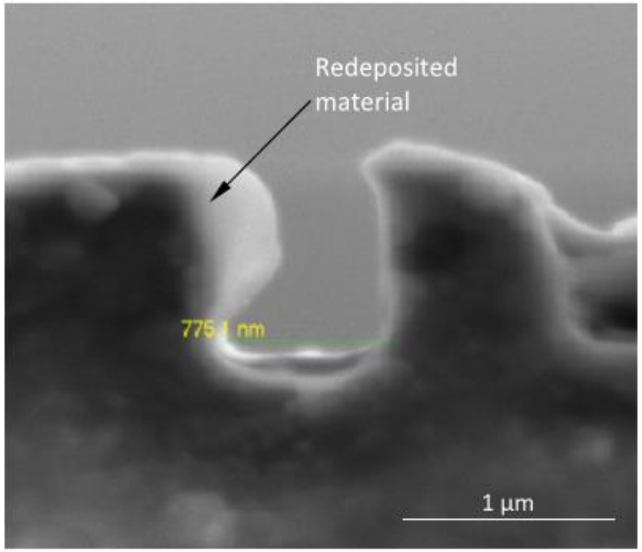
- *Formation of a sharp cutting edge*

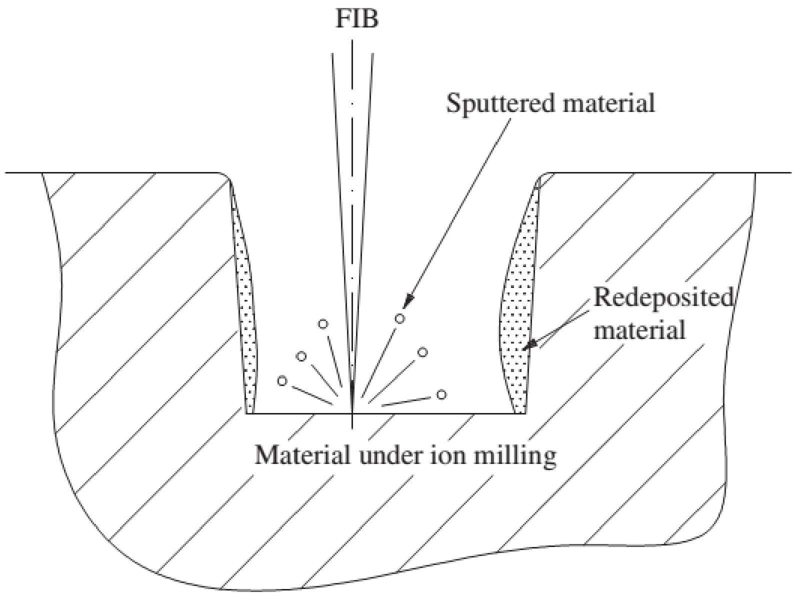




FIB fabrication issues

- *FIB induced redeposition effects during sputtering process*
  - The sputtered atoms get redeposited on the machined surface

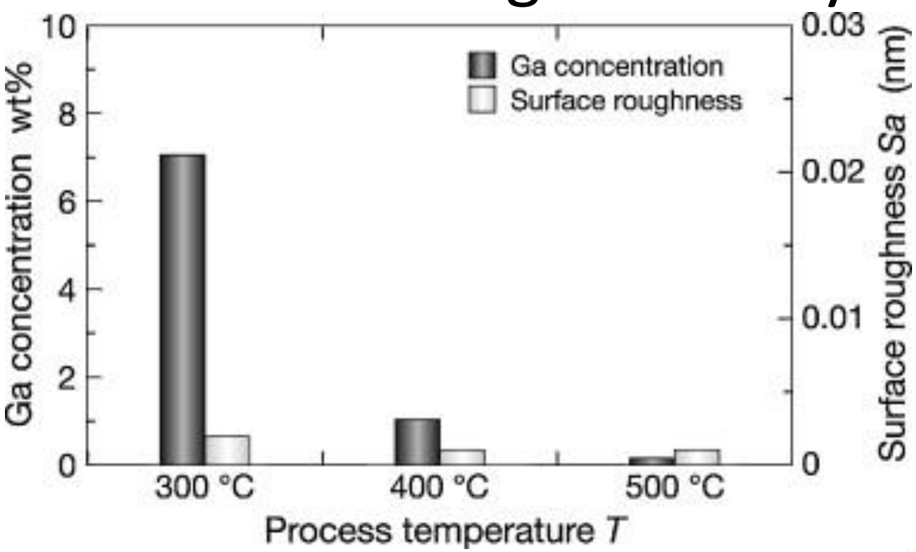


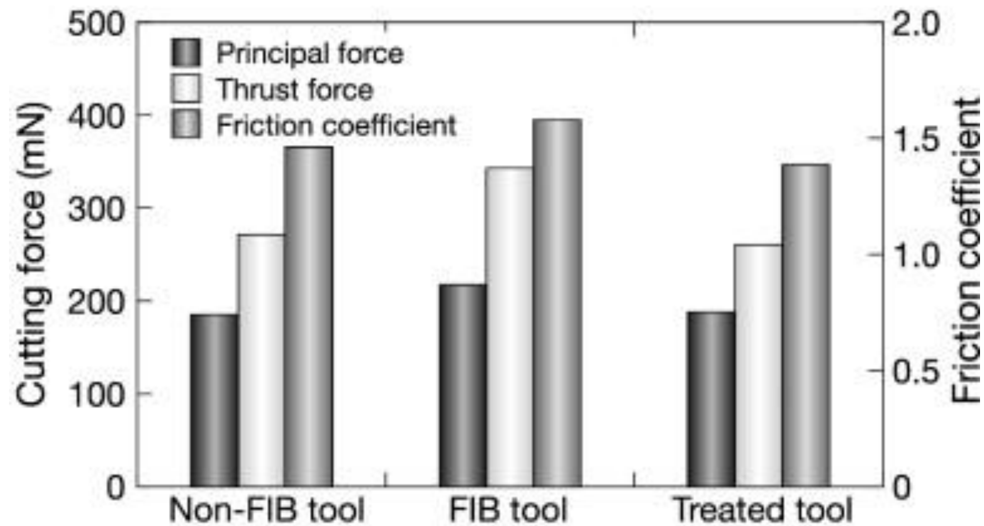


FIB fabrication issues

- *FIB induced damage:* Heat Treatment
  - Diamond surface was sputterted with an *Al* layer ~100 nm thick
  - Heating the diamond and maintaining there for 1h to allow Ga ions diffuse into the *Al* layer.
  - Cooling and *Al* layer removal

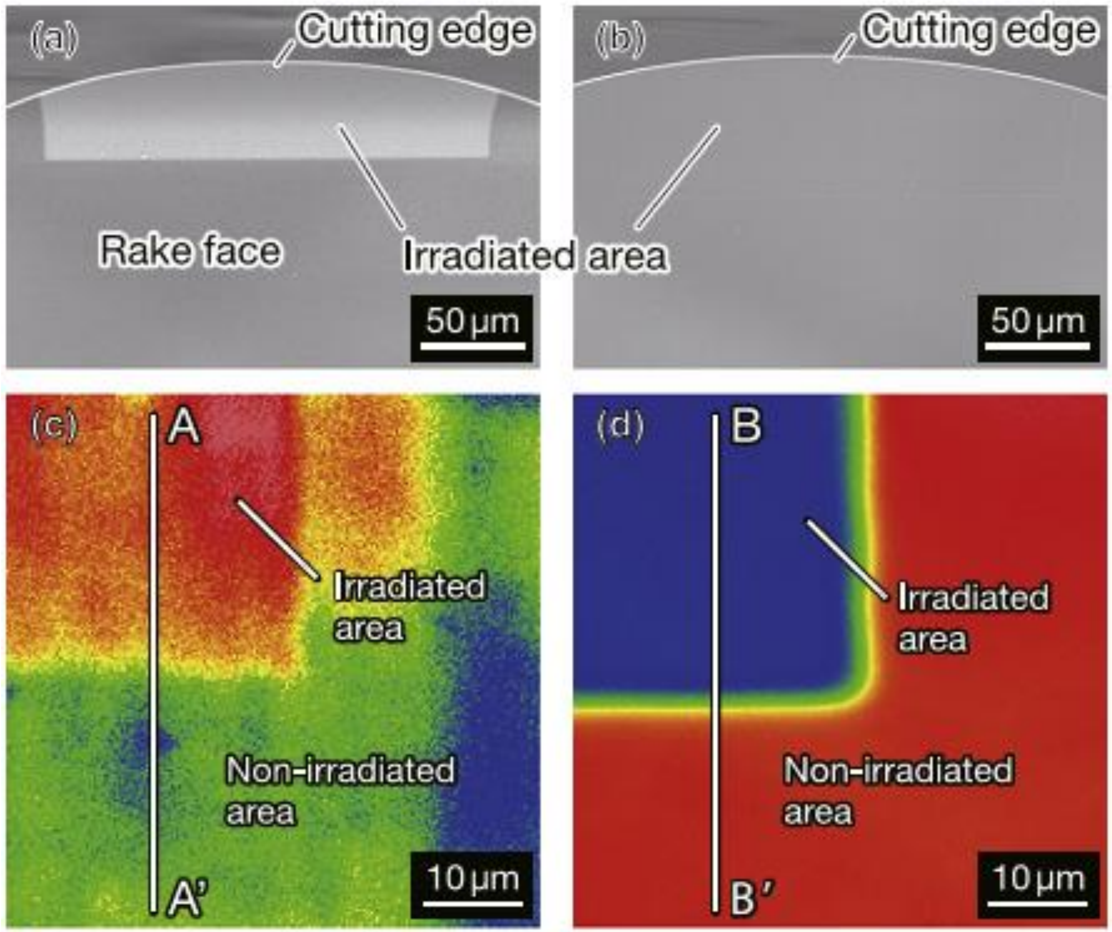
Kasegi et al, PE 2014





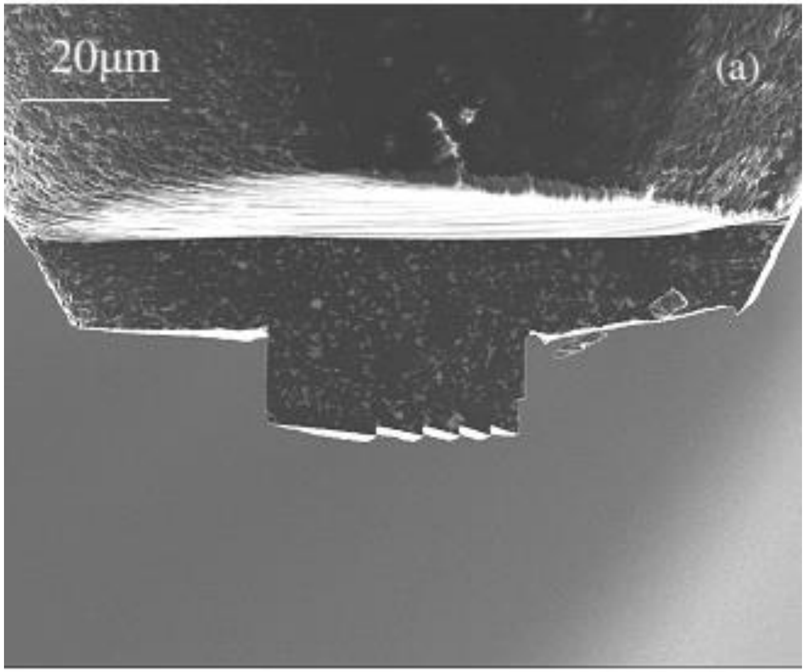
FIB fabrication issues

- *FIB induced damage:* Heat Treatment

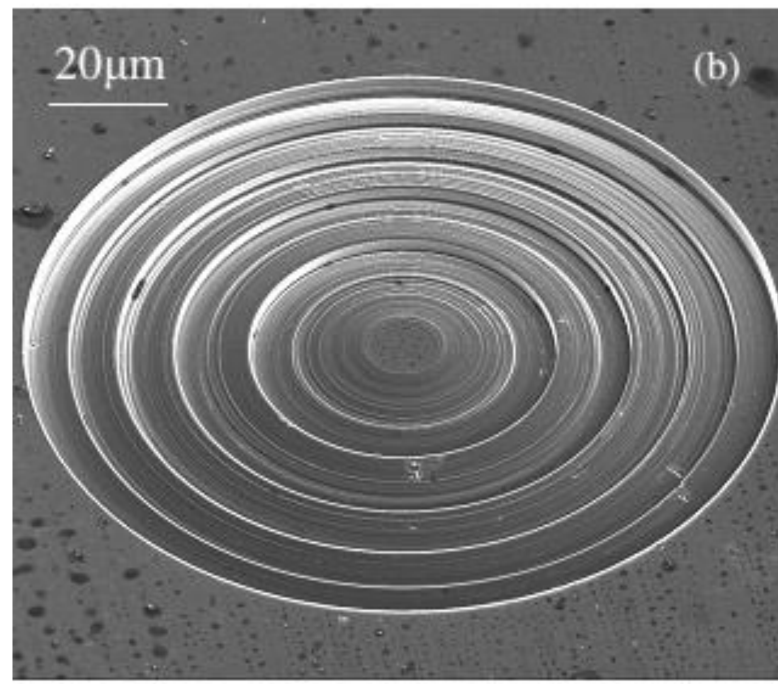


Kasegi et al, PE 2014

FIB Fabricated Diamond Tools



Xu et al, OE 2010



Thank you !!!

- Discussion …