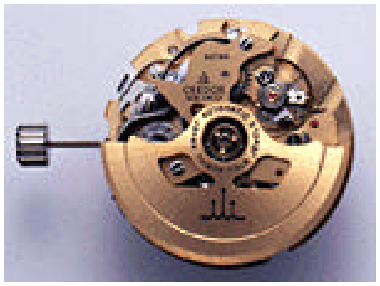
II. Fundamentals of Micromachining

- Two Different Approaches of Micromachining
- Bulk or Surface
- Fundamental Four Techniques of Micromachining
    - Thin Film Deposition
    - Photolithography
    - Etching
    - Sacrificial Release

Micromachining (I)

On the extension of conventional machining

Watch Movement



Miniaturizing

http://www.epson.co.jp/epson/mm/emros/5.htm

Cutting, Slicing, Drilling, Milling, Grinding, Embossing, Blasting,

Electro Discharge Machining (EDM)

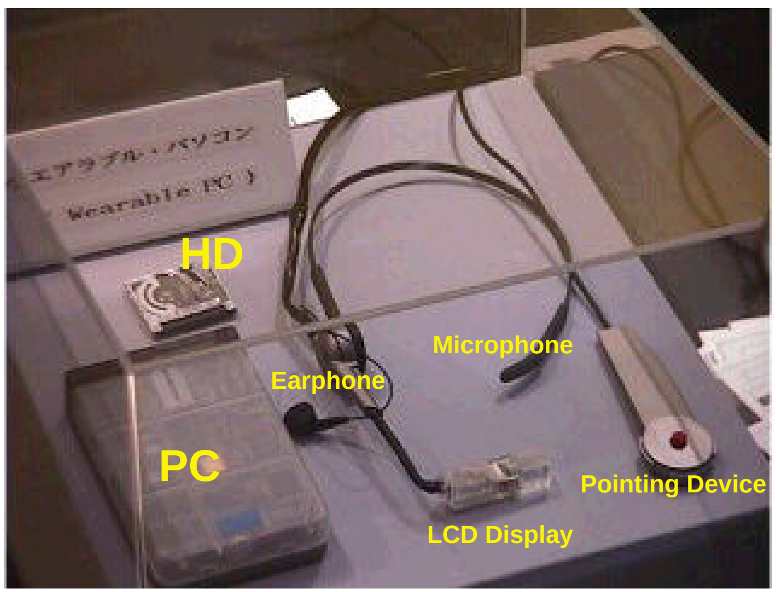
Laser Cutter,

Assembling

Wearable PC and Magnetic Storage

http://www.storage.ibm.com/hardsoft/diskdrdl/micro/

IBM Microdrive
φ 1 inch，42.8x36.4x5mm³
20g， 340MB



Wearable PC
1998.9

http://www.ibm.co.jp/News/leads/980911microdrive/

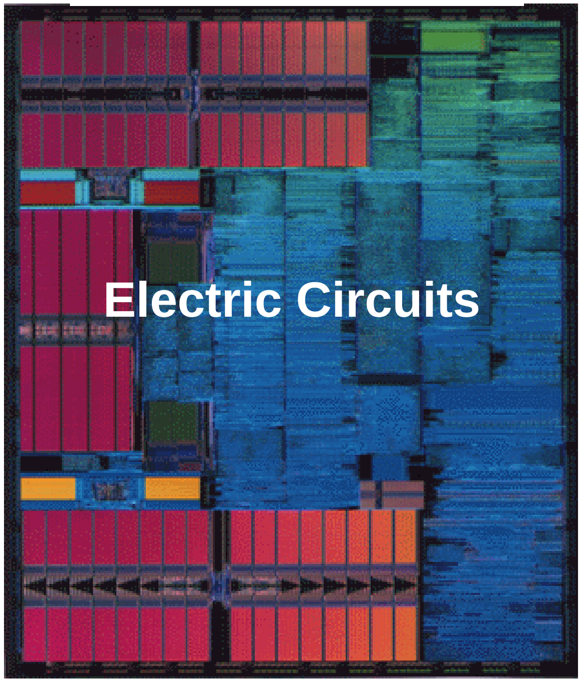
Also for Storage of Digital Camera

Hiroshi Toshiyoshi Hiroshi@ee.ucla.edu

Micromachining (II)

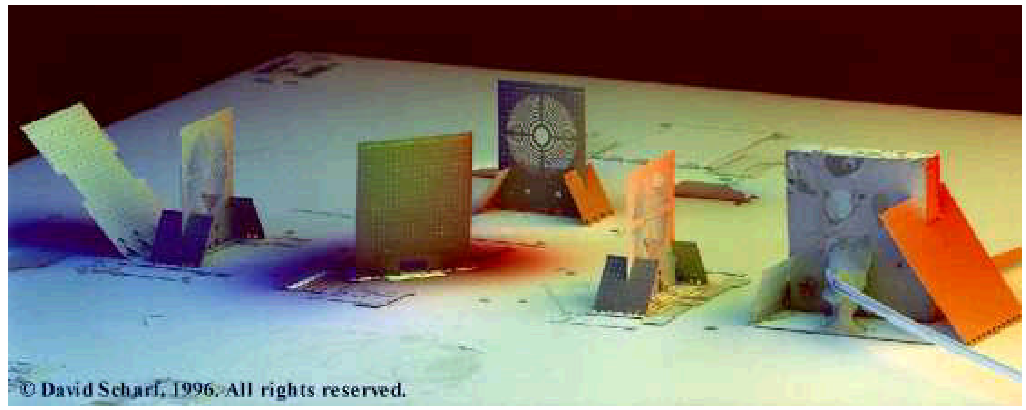
On the extension of IC Fabrication Techniques

Motorola Power PC



http://www.mot.com/

UCLA Micro Optical Bench



http://www.ee.ucla.edu/labs/laser/

Thin Film Deposition

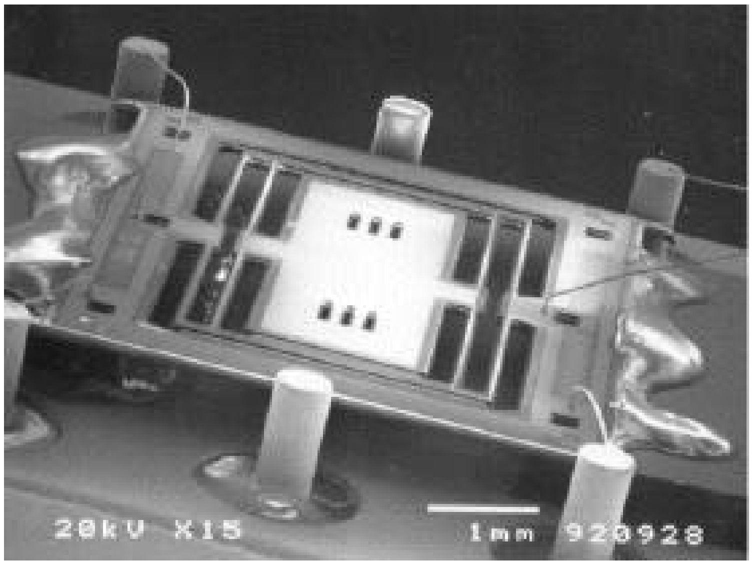
Photolithography

Etching

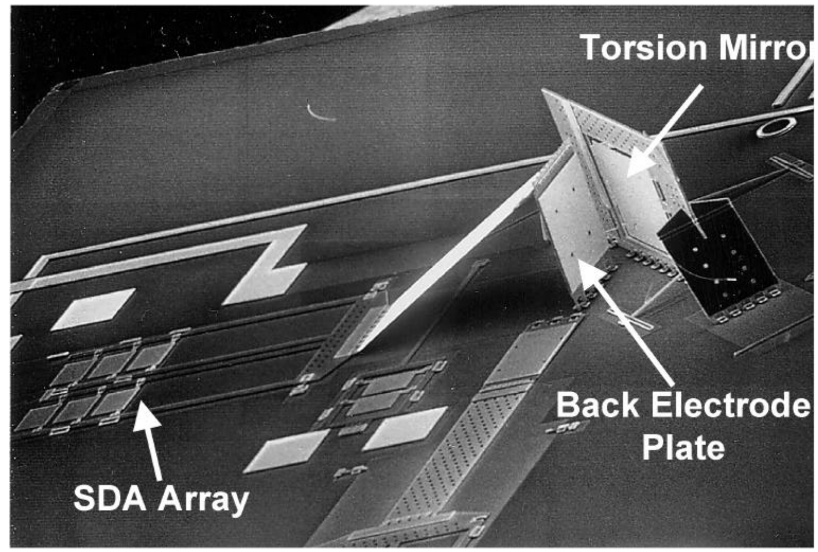
Example of Micromachined Structures

Both of them are micromachined structures.

Can you tell the significant difference ?



H. Toshiyoshi, UTIIS



S.-S. Lee, UCLA

Bulk Micromachining		Surface Micromachining
~ 5 mm	Device size	< 1 mm
~ 1 μm	Feature size	~ 1 μm
~ 100 μm	Thickness	1~ 3 μm
Through hole, Trench and grooves in substrate		Thin film patterns on substrate

Fundamental four techniques of micromachining

Reviewing Fabrication Process and Nomenclatures

1. Thin Film Deposition
- Chemical Vapor Deposition (CVD)
- Sputtering
- Vacuum Evaporation
- Electroplating

2. Photolithography
- Photoresist Spin Coating
- Mask Alignment
- Exposure
- Development

3. Selective Etching
- Dry or Wet Chemical Etching
- Isotropic or Anisotropic
- Ion Milling
- Focused Ion Beam

4. Releasing
- Sacrificial Layer Removal
- Anti-sticking Release

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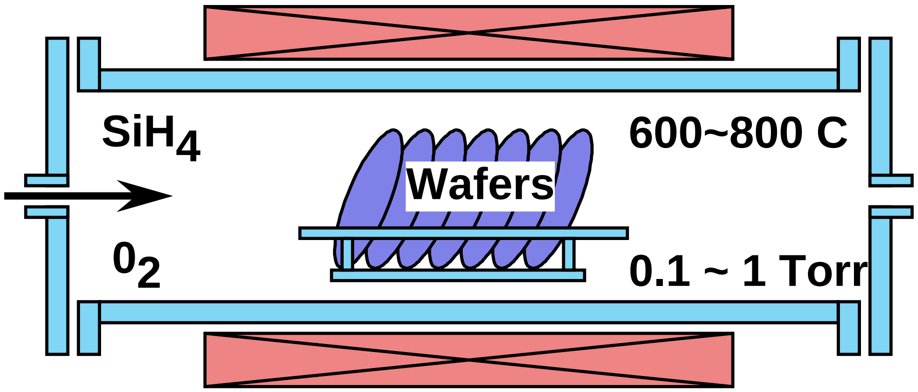
Thin Film Deposition (1)

Chemical Vapor Deposition



$SiH_4 \rightarrow Si + 2H_2$

$SiH_4 + O_2 \rightarrow SiO_2 + 2H_2O$

Polysilicon (~ 2 μm)

SiO2 (~ 2 μm)

PSG (~ 4 μm)

SixNy (~ 0.3 μm)

Mainly Si related materials

+ stress controllable

+ high density

- high temperature

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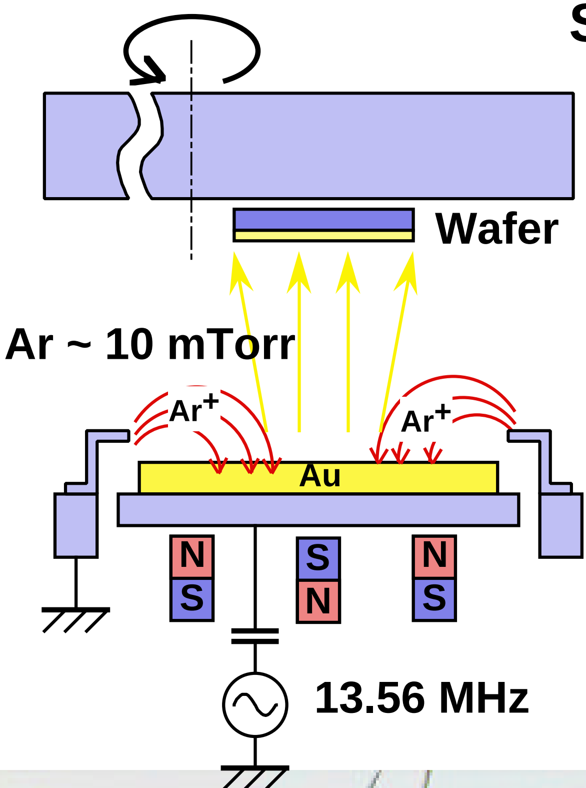
Thin Film Deposition (2)

Sputtering



Metal (Cr, Au, Ni, Fe, Ti, Cu, Pt, ...)

Alloy (FeNi, TiNi, ...)

Oxide (SiO_2, Al_2O_3, ...)

Nitride (AlN, SiN, ...)

All in 0.1 ~ 5 μm range

+ various materials other than oxide or nitride

- residual stress

- less density

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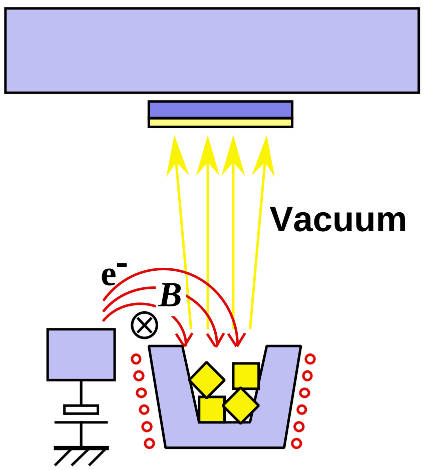
Thin Film Deposition (3)

Evaporation

(Joule Heat or Electron Beam)



Heater or Electron Beam

Metal (Cr, Au, Ni, Fe, Ti, Cu, Pt, ...)

Alloy (FeNi, TiNi, SiW, ...)

Oxide (MgO, ...)

Nitride (AlN, SiN, ...)

All in 0.1 ~ 5μm range

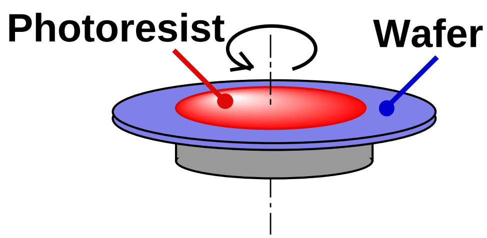
+ high melting temp. materials

+ density higher than sputtering (EB)

- poor adhesion (JH)

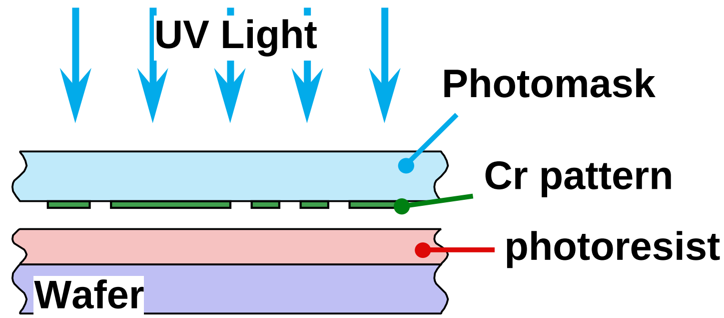
Photolithography

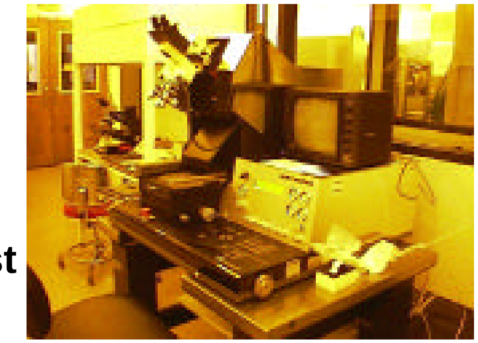
Spin Coating



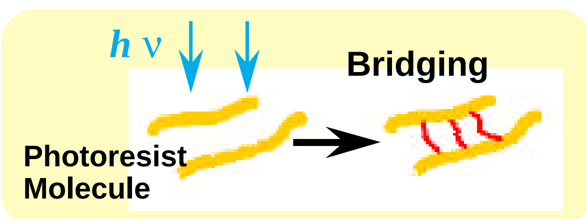
Prebake

Mask Alignment & Exposure

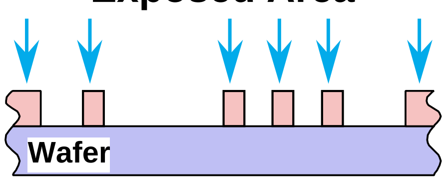




Development



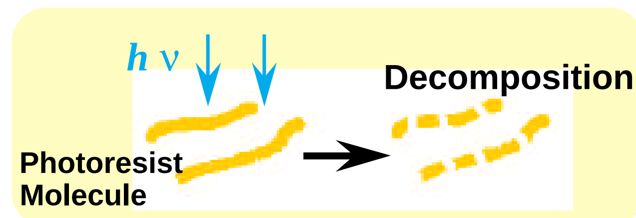
Exposed Area



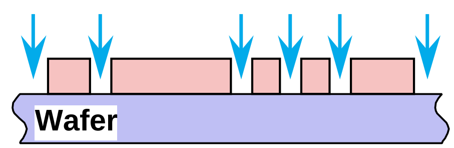
Negative Photoresist
(Dark/Clear Inverted)

Thick Patterns

IBM SU-8 (t > 100 μm)



Exposed Area



Positive Photoresist
(Same patterns as mask)

Fine Patterns ~ 1 μm

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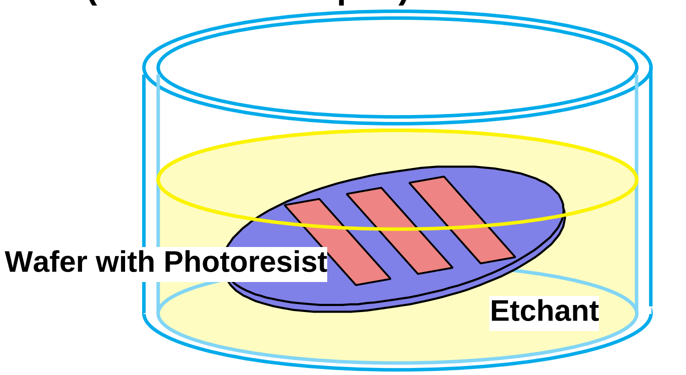
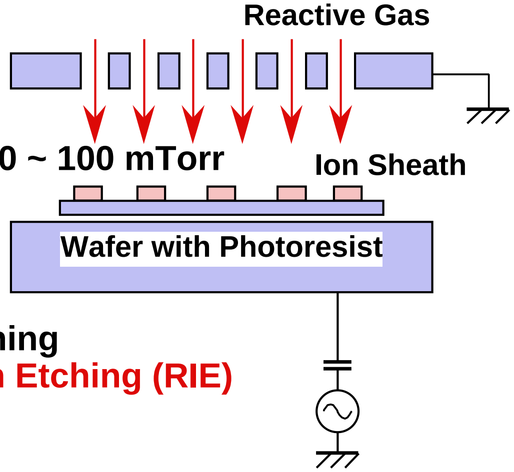
Etching

Wet Etching
(Reaction in Liquid)



Dry Etching
(Reaction in Plasma or Ion Sheath)



Chemical

- Plasma Etching
- Reactive Ion Etching (RIE)
- Sputtering
- Ion Milling

Physical

	Etched Material	Etching Chemical
Wet Etching	Silicon	KOH, TMAH, EDP
	Silicon oxide	HF
	Silicon Nitride	H_3PO_4
	Cr	
	Al	H_3PO_4
Dry Etching	Silicon	SF_6 CF_4
	Silicon oxide	CHF_3
	Al	Cl_2

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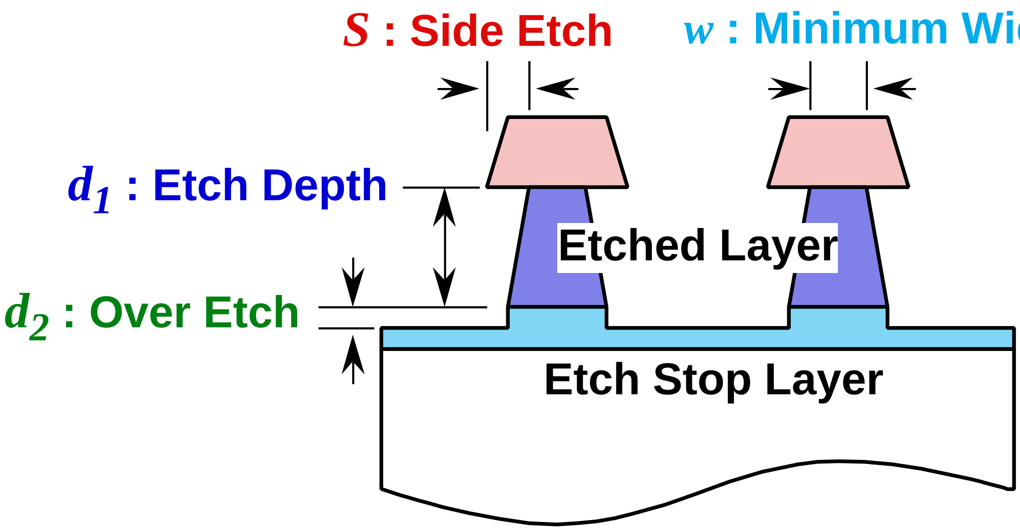
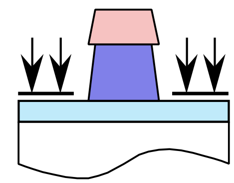
Nomenclature of Selective Etching



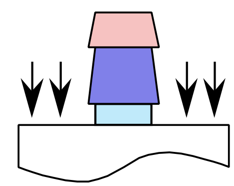
$$\text{Selectivity} = \frac{\text{Etch Depth}}{\text{Over Etch}}$$

$$\text{Aspect Ratio} = \frac{\text{Etch Depth}}{\text{Minimum Width}}$$

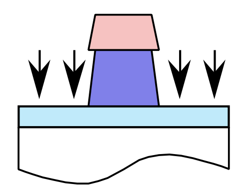
Over Etch << Etch Depth → Selective



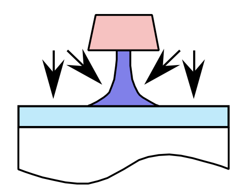
Over Etch ~ Etch Depth → Non-selective



Side Etch << Etch Depth → Anisotropic



Side Etch ~ Etch Depth → Isotropic



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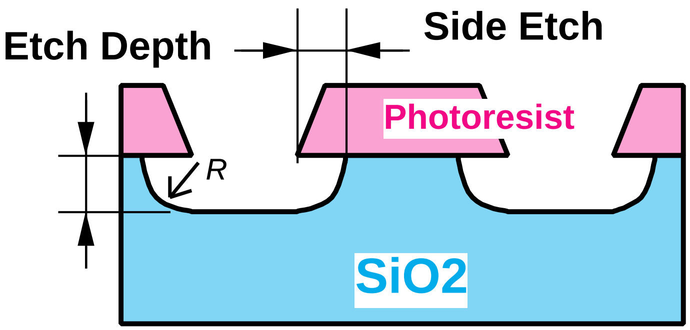
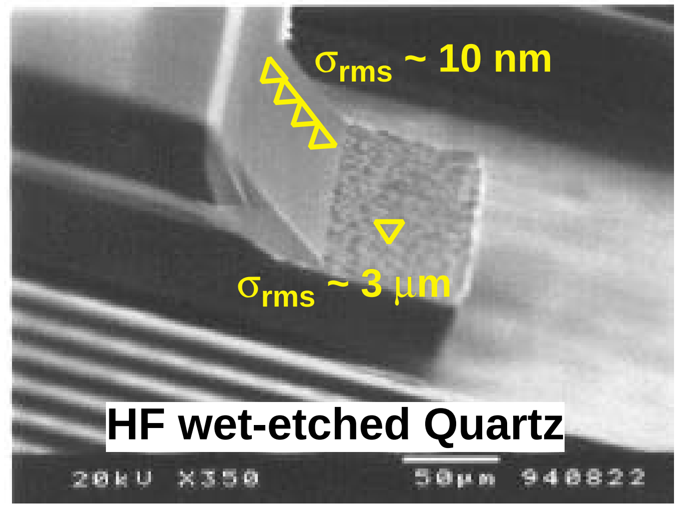
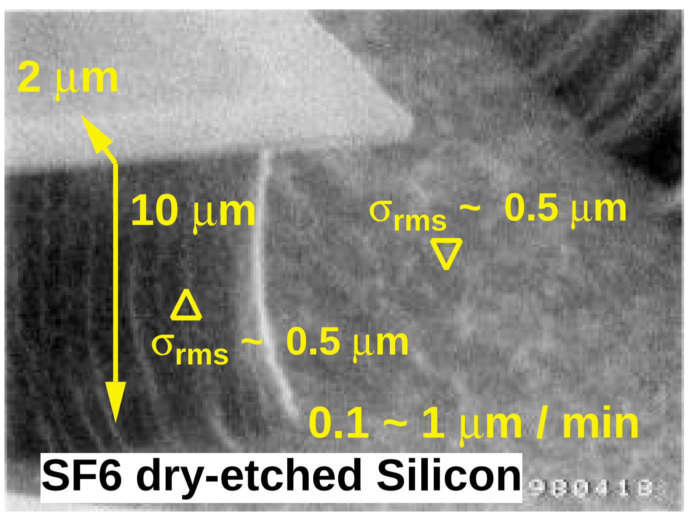
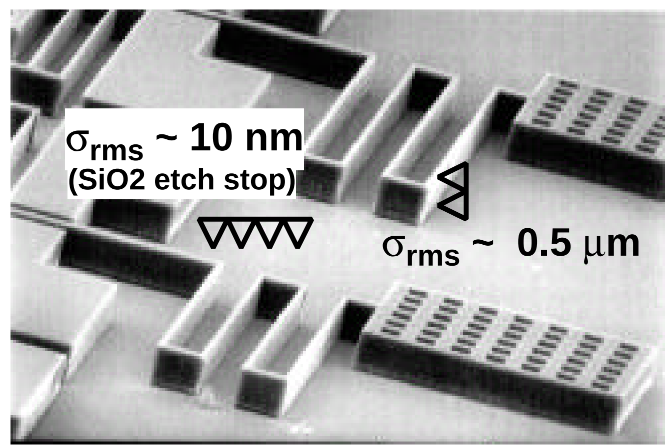
Accuracy of Selective Etching

	Isotropic	Anisotropic
WET	 SiO2 / HF 0.1 ~ 1 μm / min	 HF wet-etched Quartz
DRY	 SF6 dry-etched Silicon	 SF6 + Freon dry-etched Silicon

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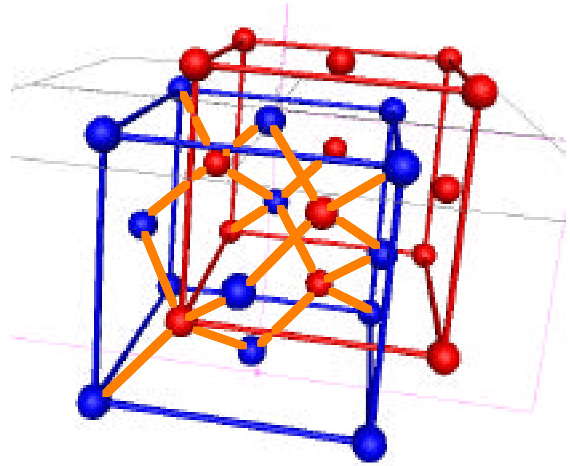
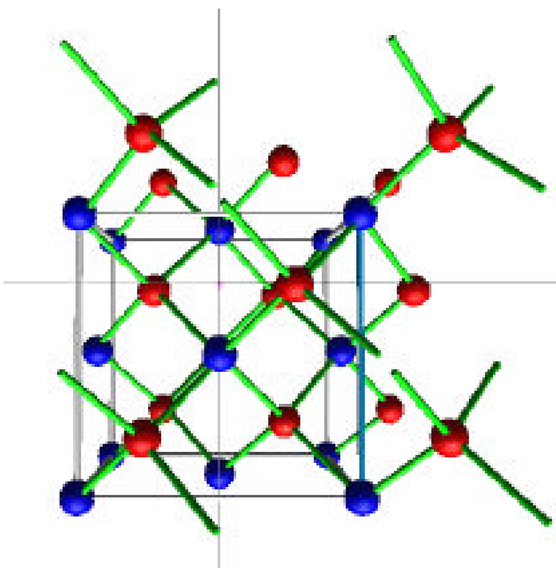
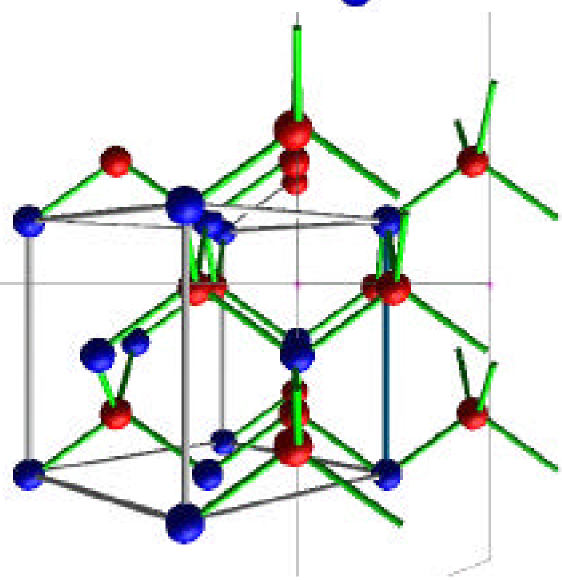
Anisotropic Etching of Single Crystalline Silicon

fcc@(0,0,0) + fcc@(1/4,1/4,1/4) = diamond / silicon

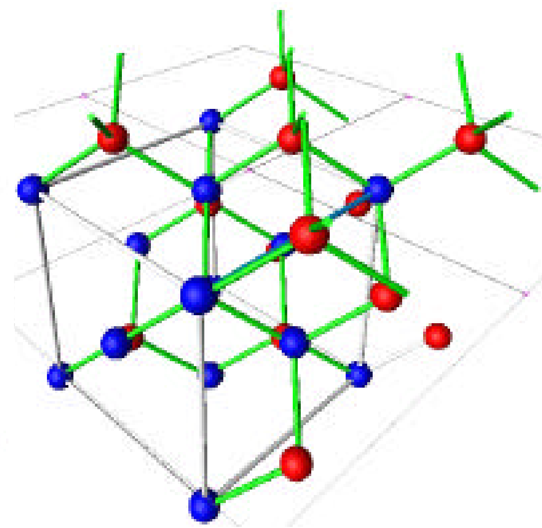




<100>



<110>



<111>

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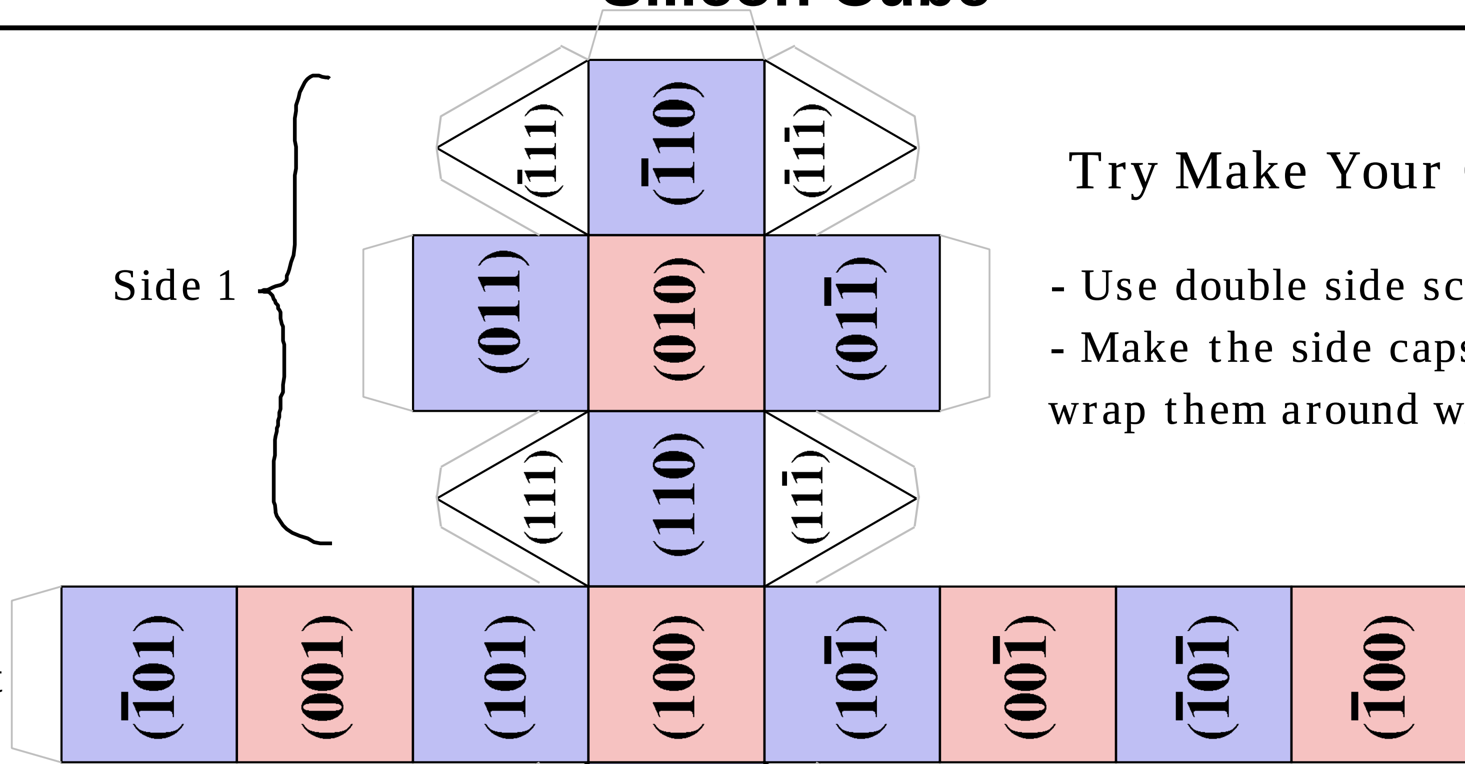
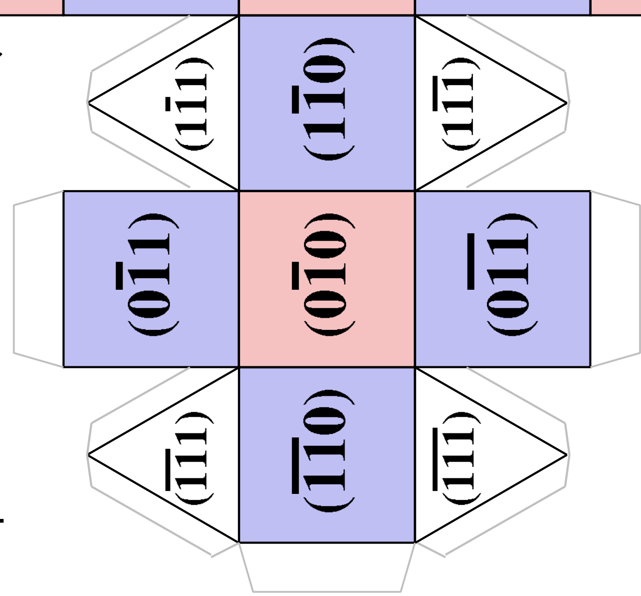
Silicon Cube

Try Make Your Own Cube

- Use double side scotch tape
- Make the side caps first and wrap them around with the belt

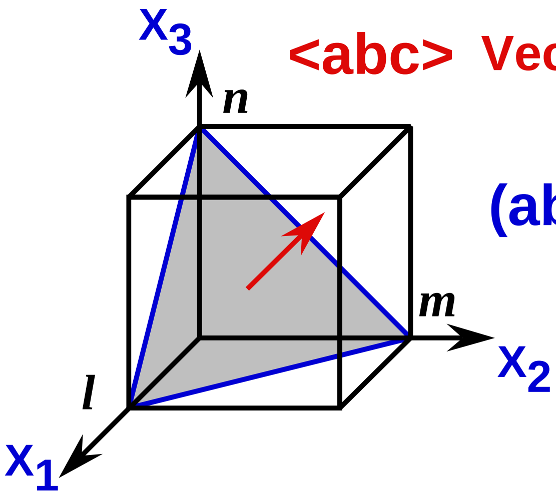
By H. Toshiyoshi 1999

Best results when printed on a transparency foil.

Crystallographic Facets of Silicon

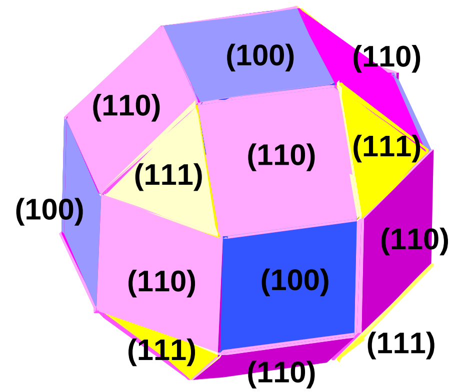
$$N = (1 / l,\ 1 / m,\ 1 / n) = (a,b,c)$$

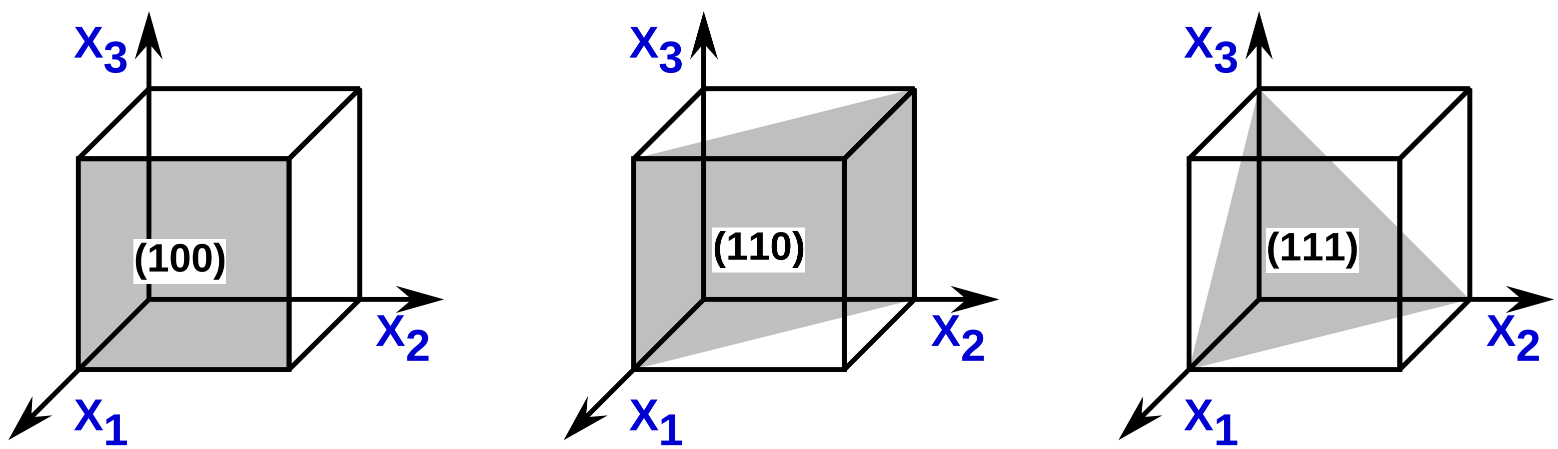
LCM



<abc> Vector

(abc) Surface





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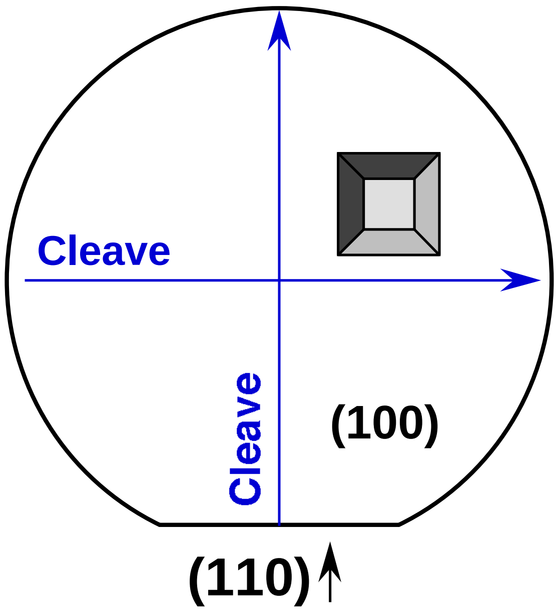
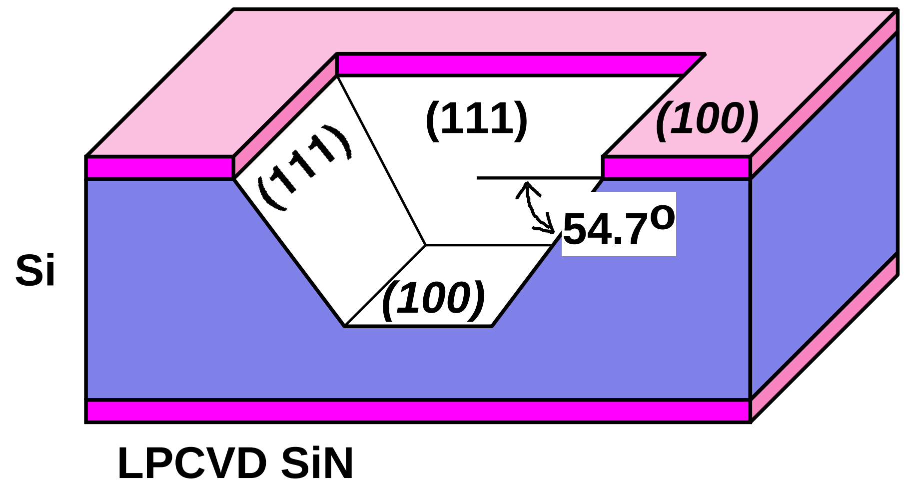
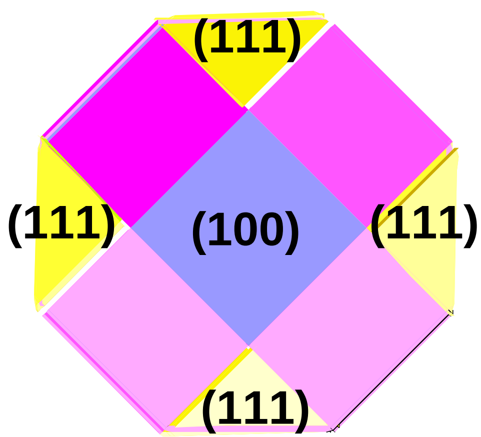
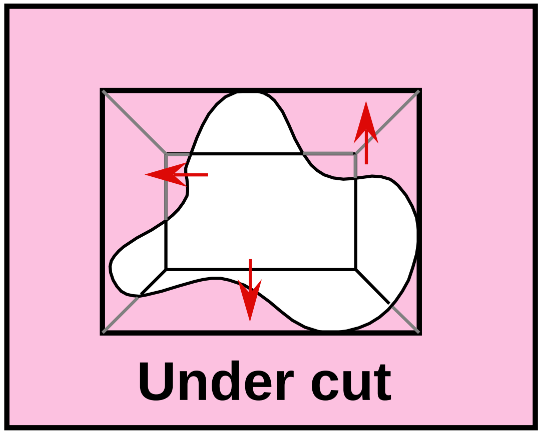
Anisotropic Wet Etching of (100) Silicon









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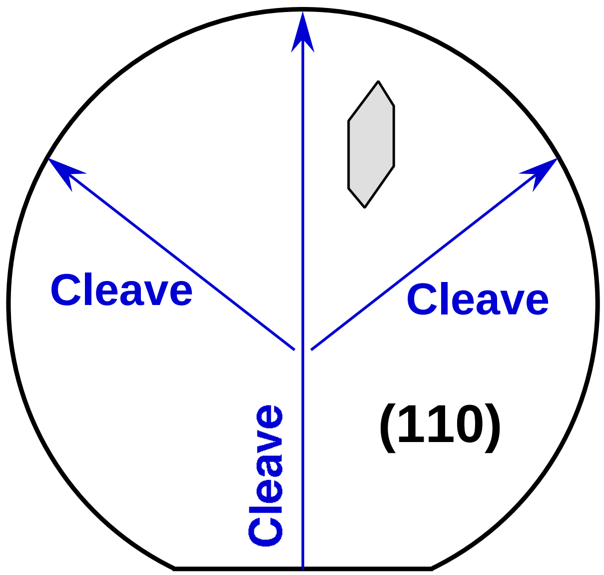
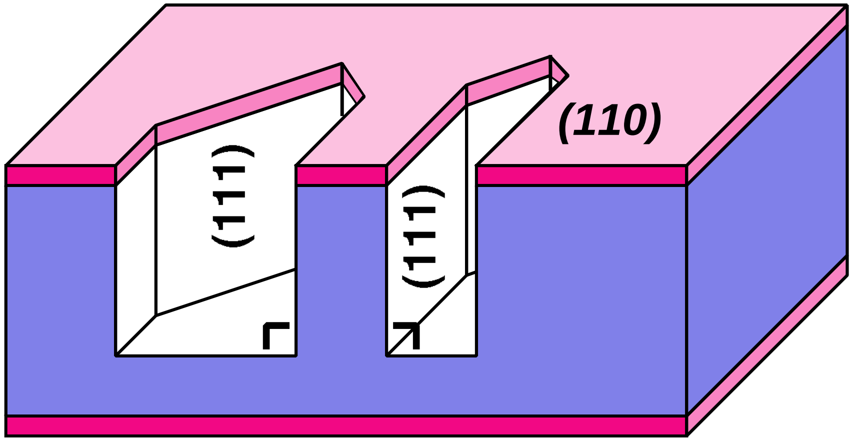
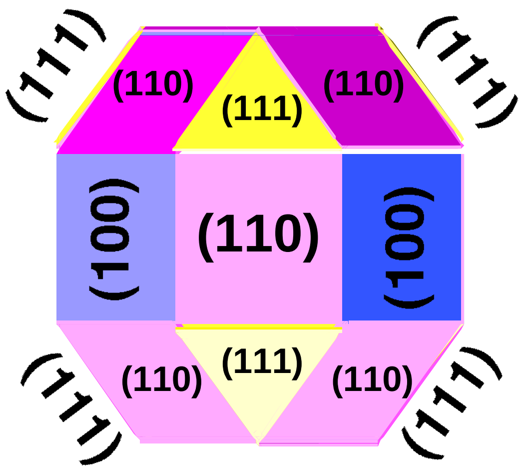
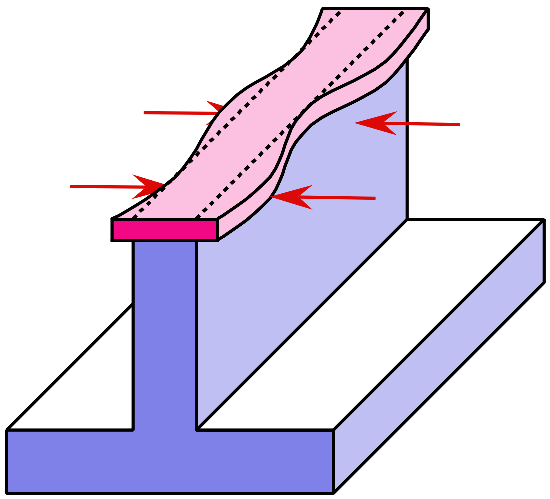
Anisotropic Wet Etching of (110) Silicon









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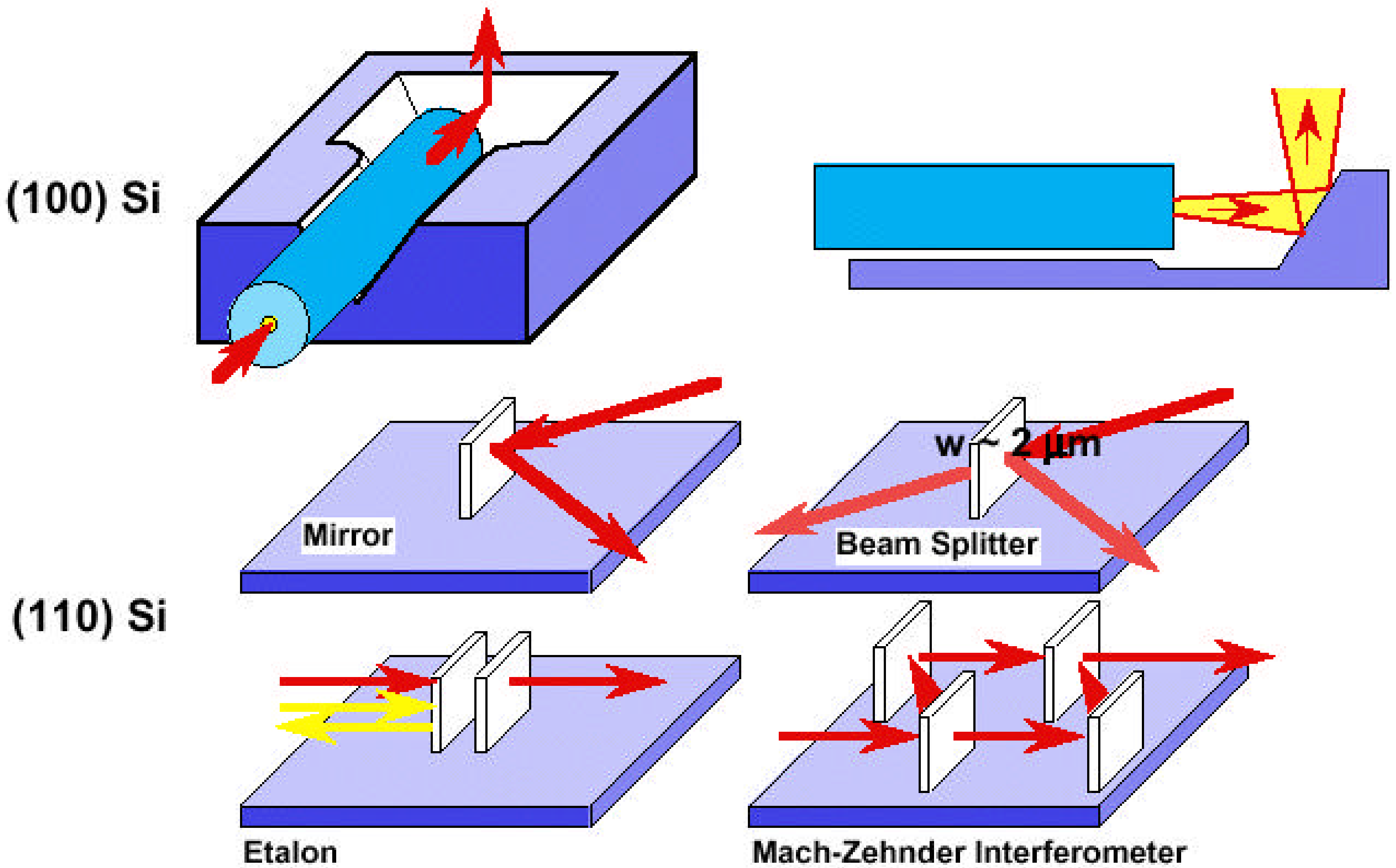
Examples of Silicon Bulk Micromachining



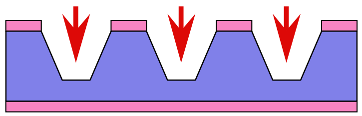
- Y. Uenishi, M. Tsugai, M. Mehregany, "Micro-Opto-Mechanical Devices Fabricated by Anisotropic Etching of (110) Silicon," J. MEMS vol. 5, 305 (1995).
- Y. Uenishi, "Low-damage and smooth etching of GaAs by using a neon ion beam," Jap. J. Appl. Phys. Part 1, vol. 34 2037 (1995).

Fiber-optic Switch by Silicon Micro Joinary

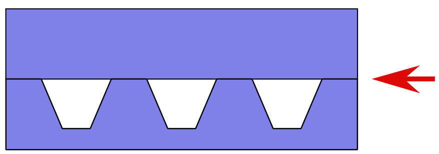
C. Gonzalez, S.D. Collins, "Micromachined 1xn fiber-optic switch,"

IEEE Photon.Tech.Lett. vol.9, (no.5), IEEE, May 1997. p.616-18.

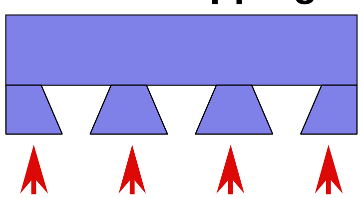
Anisotropic Etching of (100) Silicon



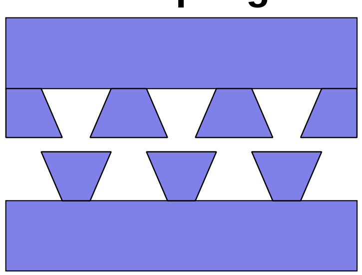
Wafer Bonding

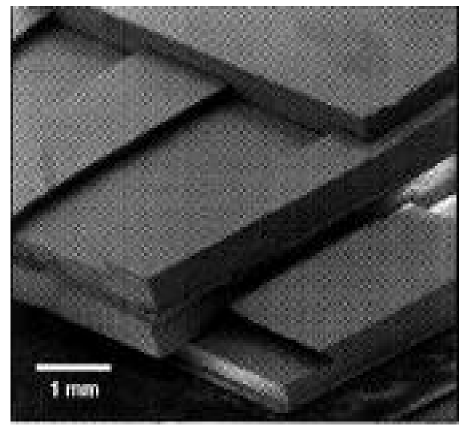


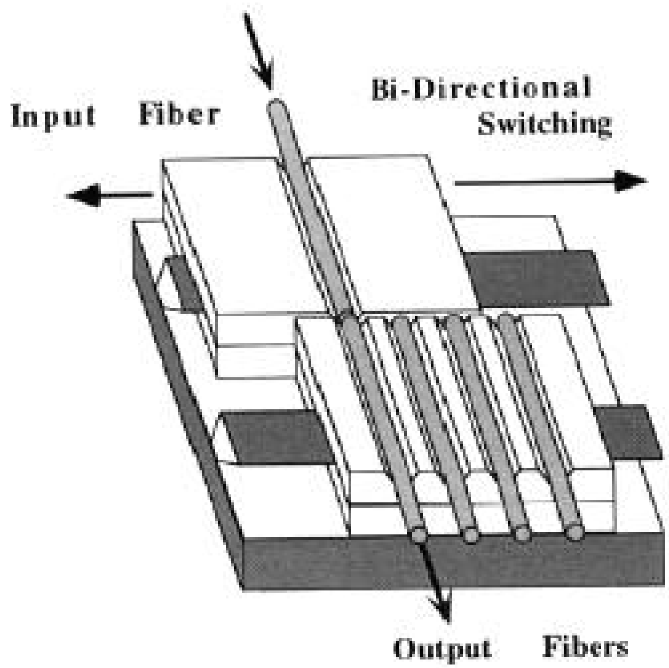
Wafer Lapping



Coupling







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What happens on Silicon Sphere after KOH Etching ?

Prof. K. Sato's Group at Nagoya University, Japan
http://www.kaz.mech.nagoya-u.ac.jp/research/projects.html

Fig.1 Silicon test piece before and after etching

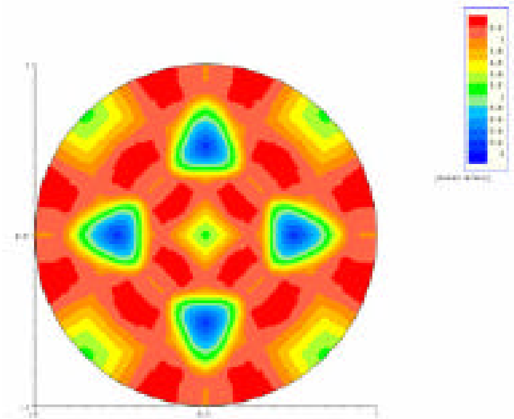
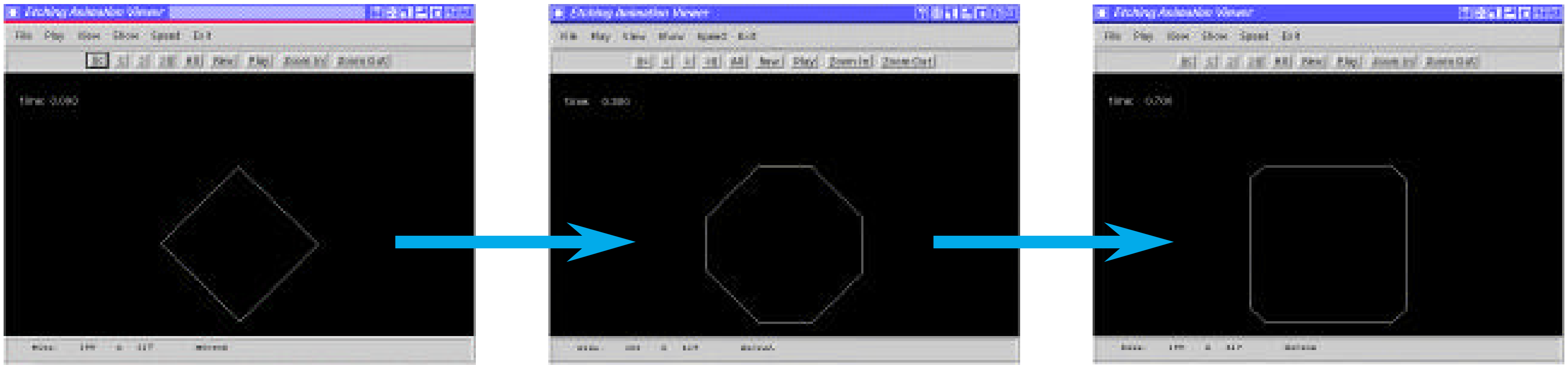


Fig. 2 Etching rate contour lines for all directions

Silicon Etching Simulator

SEGS: On-line Etch Simulator, DalTech / Caltech

http://mira.me.tuns.ca/segs/Welcome.html



Other simulation soft wares

- Prof. J. Judy, UCLA
  http://www.ee.ucla.edu/~jjudy/classes/ee151a/cad/animations/
- Anisotropic Silicon Etching Program from the University of Illinois at Urbana-Champagne
  http://galaxy.ccsm.uiuc.edu/aces/

Etching rates of MEMS materials

K. R. Williams, R. S. Muller, "Etch Rates for Micromachining Processing," IEEE J. Microelectromech. Sys. vol. 5, no. 4 (1996), p.256-.

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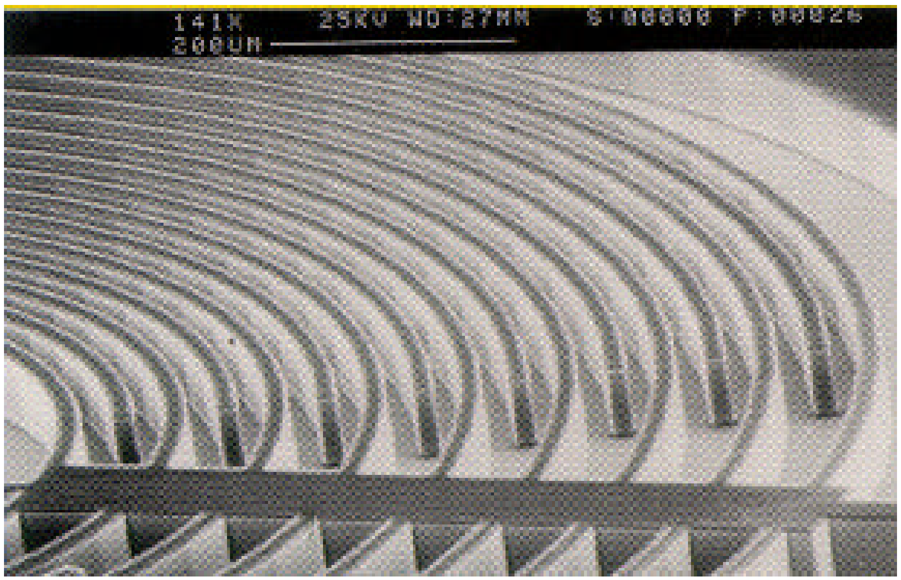
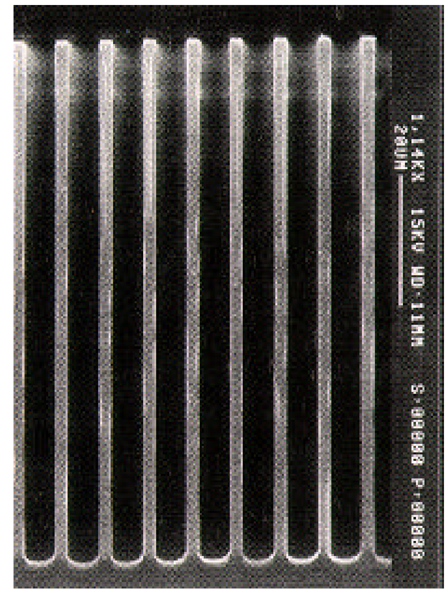
Silicon Bulk Micromachining by Deep RIE

Inductively-Coupled-Plasma Reactive Ion Etching



Lucas NovaSensor

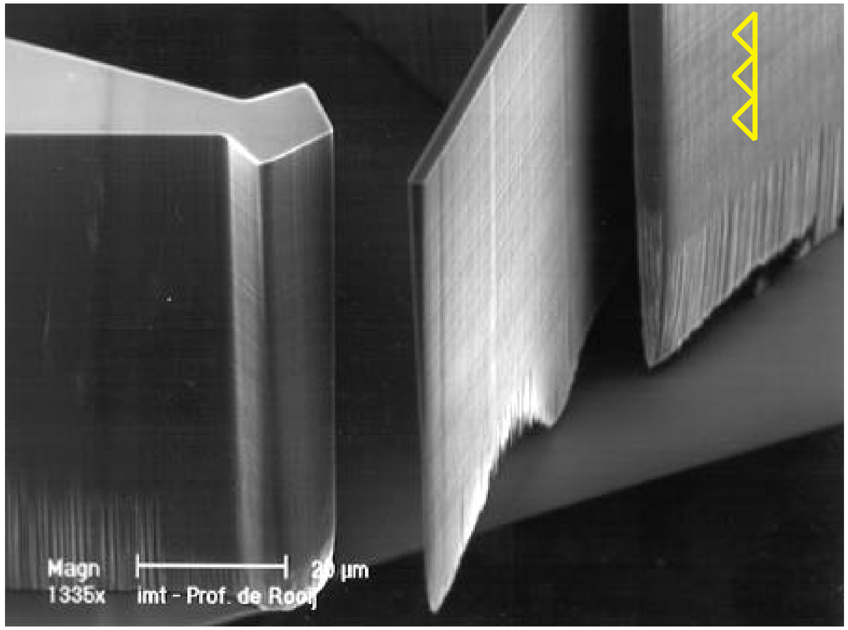


STS

- Aspect ratio > 200
- Etch depth > 200 μm (through wafer)
- Etch speed 1~2 μm / min
- Independent of crystallographic axis
- DRIE machine available from STS and Plasmatherm

Robert Bosch GmbH,
Patent 5501893,
March 26, 1996

Mirror Surface (Vertical Side Wall) by Deep RIE



σ_{rms} ~ 36 nm

Scattering Loss

$$\beta = 1 - \exp\left\{ -\left(\frac{4\pi\sigma\cos\theta}{\lambda} \right)^2 \right\}$$

σ_{rms} ~ 36 nm ⟶ **Loss < 0.27 dB**

C. Marxer, C. Thio, M. Gretillat, N.F. de Rooij, R. Batig, O. Anthematten, B. Valk, P. Vogel, " Vertical mirror fabricated by deep reactive ion etching for fiber-optic switching applications," J. MEMS vol. 6, 277 (1997).

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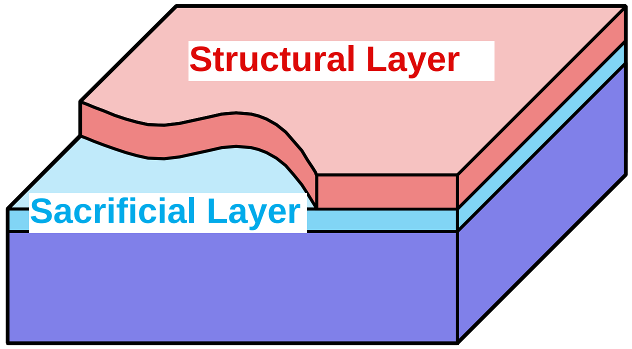
Simplified Total Process of Micromachining

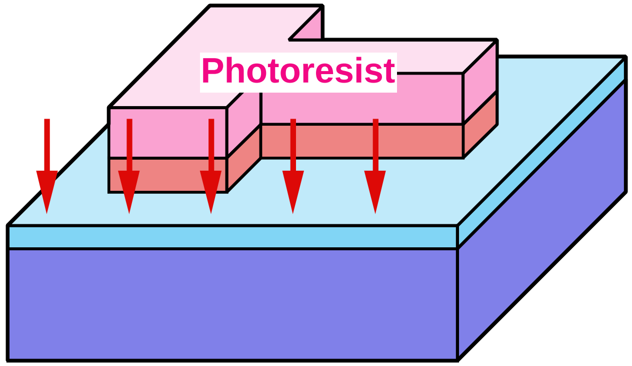
Sacrificial Layer Release by Selective Etching

1. Thin Film Deposition

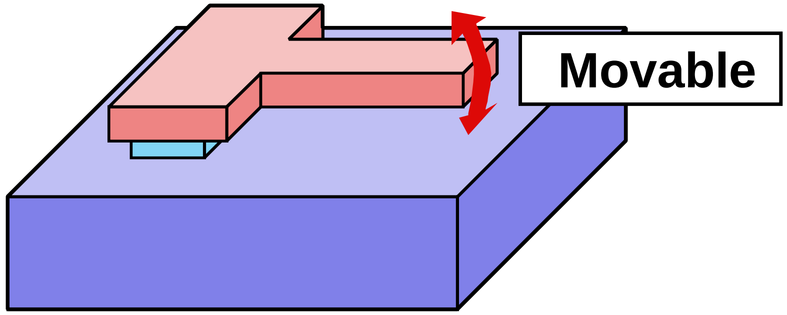


2. Photolithography

3. Selective Etching



4. Releasing



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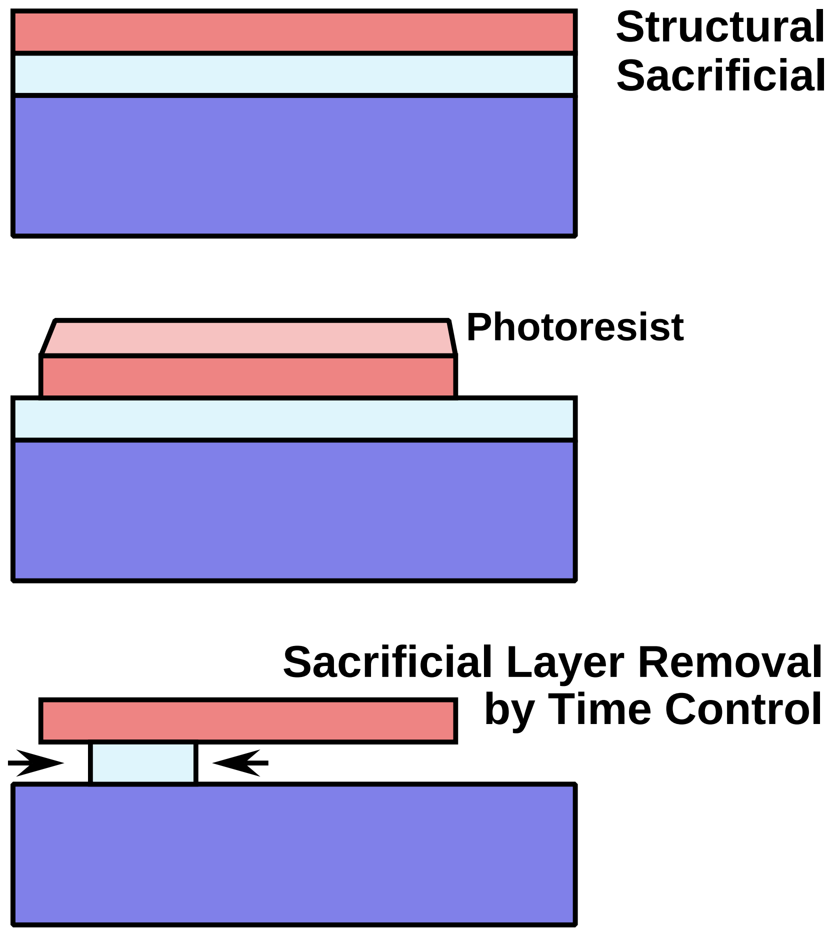
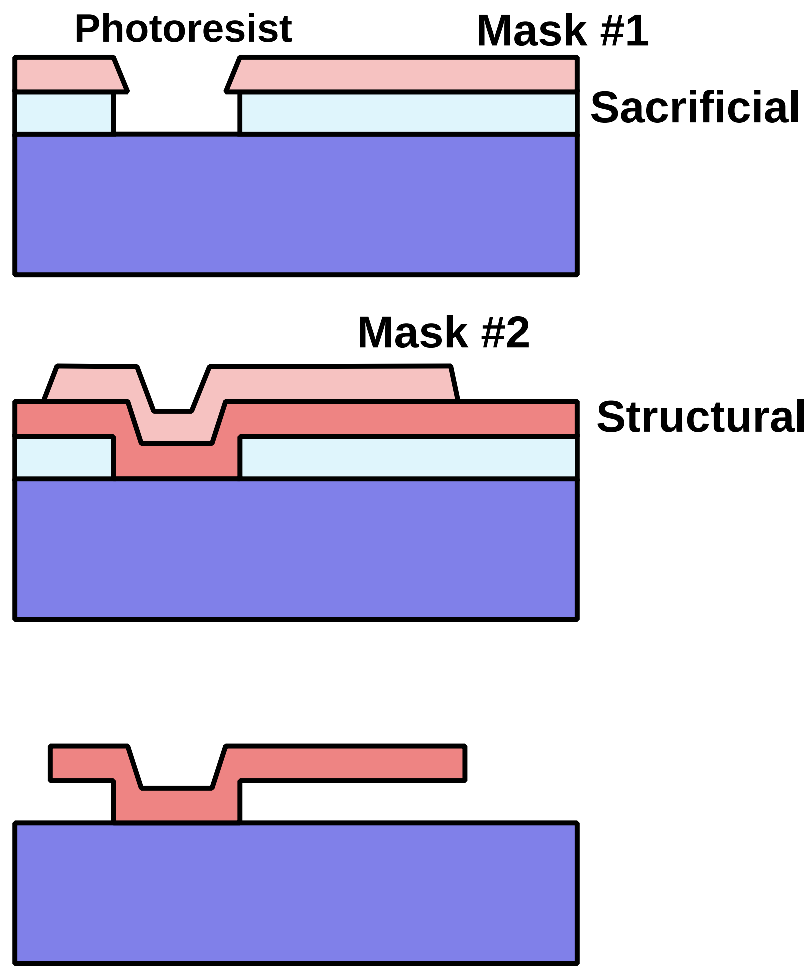
Surface Micromachining

One-mask Process



Two-mask Process



+ Simple Process (self alignment)
- Time control

- Needs Mask alignment
+ No time control

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