Outline

1 Introduction

2 Basic IC fabrication processes

3 Fabrication techniques for MEMS

4 Applications

5 Mechanics issues on MEMS

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2. Basic IC fabrication processes

2.1 Deposition and growth

2.2 Photolithography

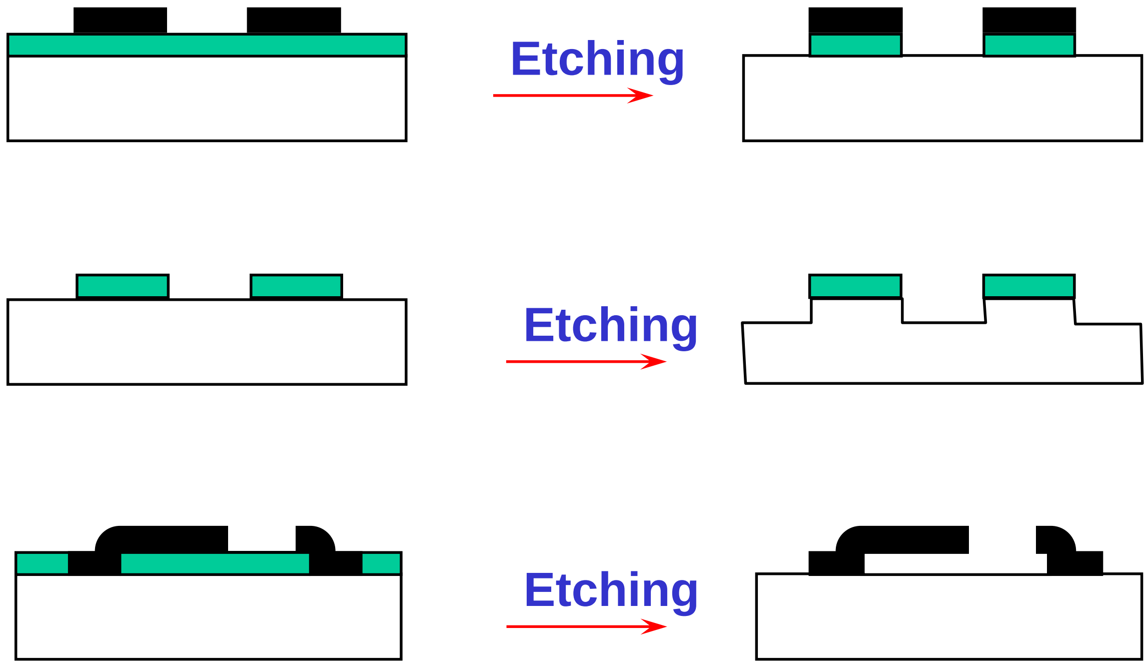
2.3 Etching

2.4 Bonding

2.3 Etching

Runyan Chap. 6, 莊達人 Chap. 8, Wolf and Tauber Chap12~14, or Vossen and Kern Part V.

- Etching: the processes to remove unwanted thin film or substrate



- **Etching techniques can be characterized as**

  + Wet chemical etching

  + Dry etching

  Ion etching - ion milling and sputter etching (physical)

  Plasma etching (chemical)

  Reactive ion etching (RIE) (physical + chemical)

  + Lift off

- Etching mechanisms could be different between the substrate and thin films

- For substrate
  - + Substrate - single crystal material
  - + Etching rate could be crystal plane dependent

- For thin films
  - + Thin film – poly-crystal or amorphous materials
  - + Etching rate is crystal plane independent

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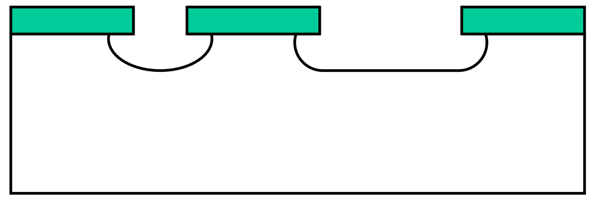
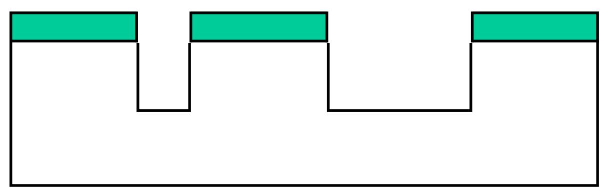
- **Isotropic and anisotropic**

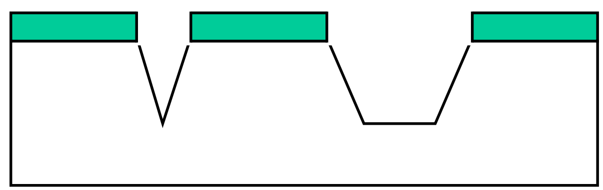
+ Isotropic



+ Anisotropic



Substrate Orientation



Crystal plane Orientation

- **Selectivity**

  + **High selectivity**

  + **Low selectivity**

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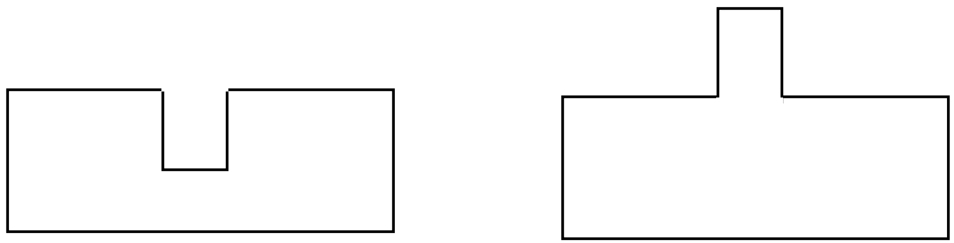
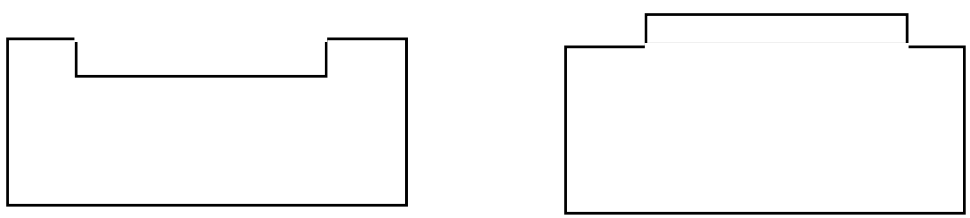
- **Aspect ratio**

+ High aspect ratio



trench **post**

+ Low aspect ratio



recess **mesa**

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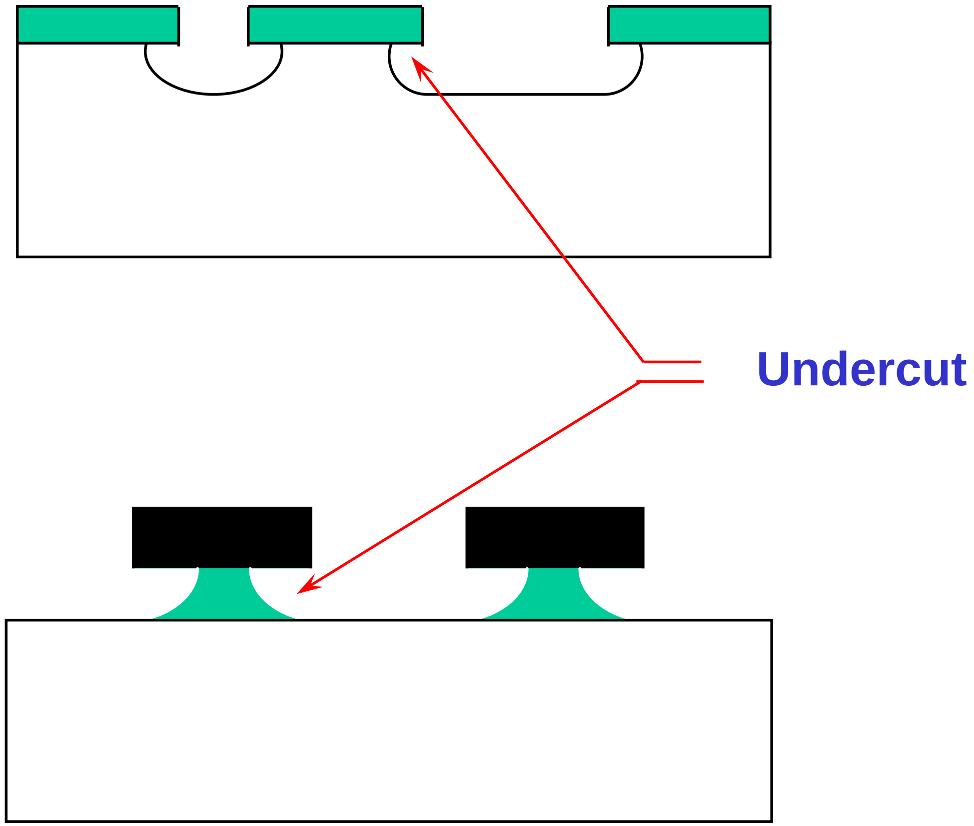
- **Undercut**



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- Etching techniques can be characterized as

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  + Dry etching

    Ion etching - ion milling and sputter etching (physical)

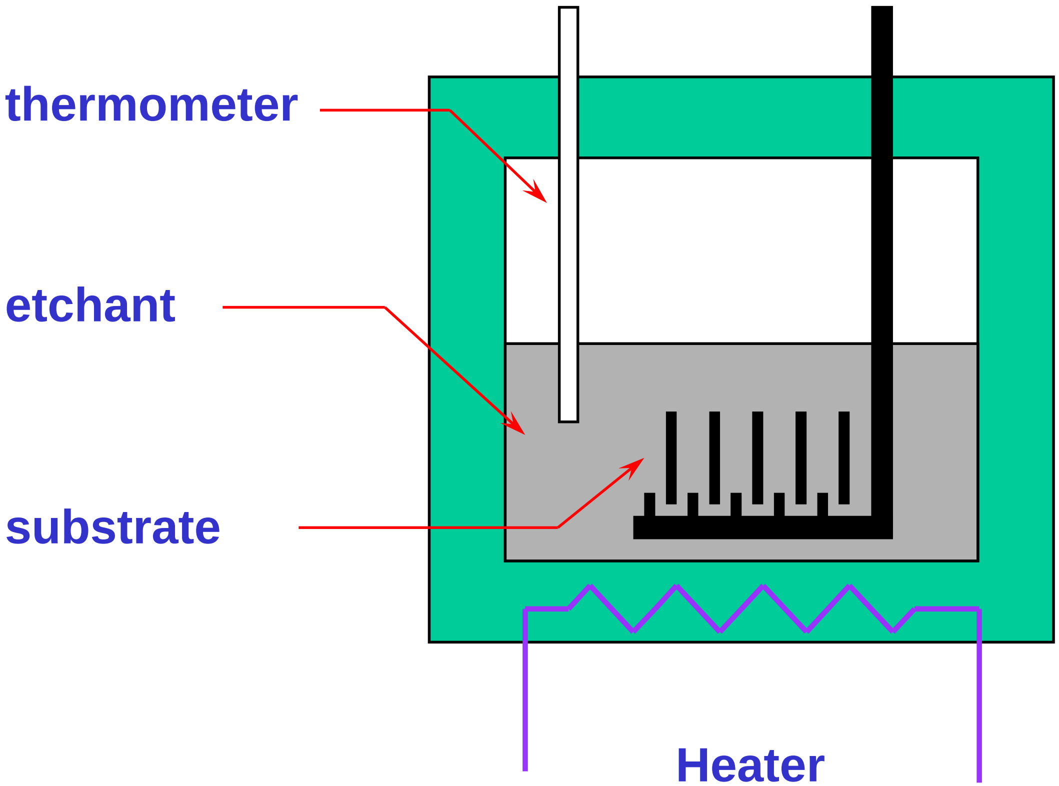
    Plasma etching (chemical)

    Reactive ion etching (RIE) (physical + chemical)

  + Lift off

2.3.1 Wet Chemical Etching

- Wet chemical etching - the wafers are etched inside a aqueous etching solutions



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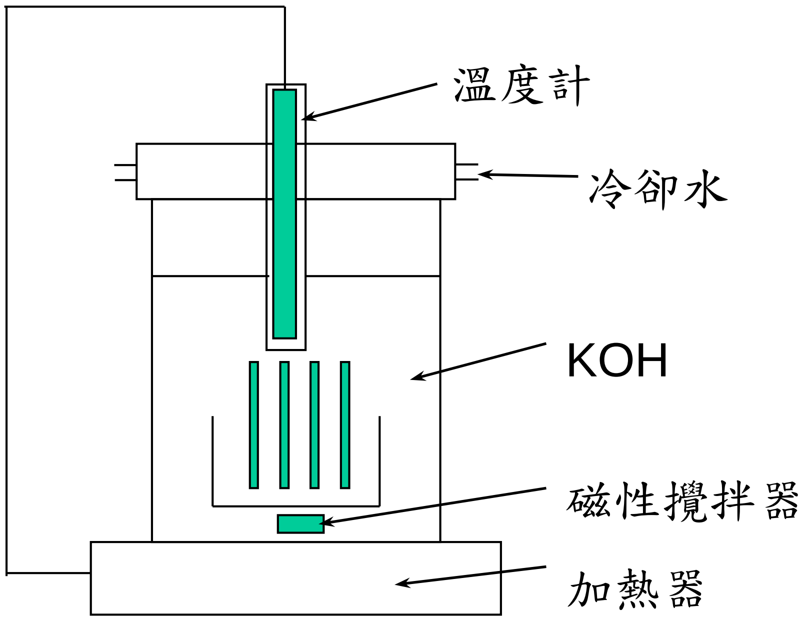

溫度計
冷卻水
KOH
磁性攪拌器
加熱器

Etching Mechanism

- The etching mechanism is similar to CVD, except in CVD the substrate is not involved in the chemical reaction

  + Reactant **transported** from etchant solution to surface

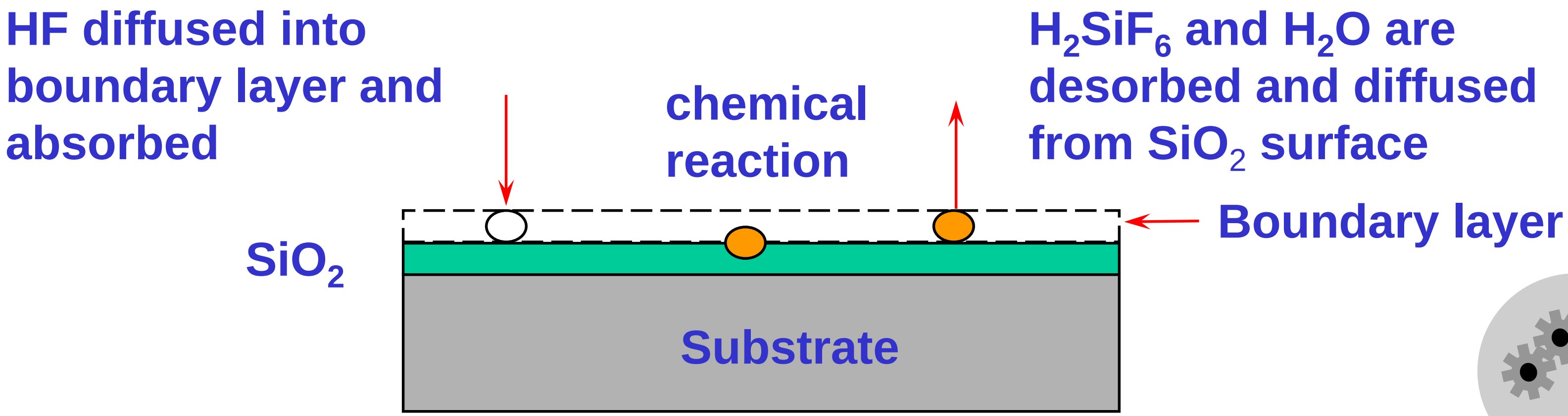
  + Reactant **adsorbed** by the substrate surface

  + **Chemical reaction** on the surface

  + Etch products **desorbed** from the substrate surface

  + **Transport** of etch products from surface into solution

$$SiO_2 + 6HF \rightarrow H_2SiF_6 + 2H_2O$$



Etching Rate

- Since the five-step etching processes are sequential, the one with slowest rate will determine the etching rate

- The etching rate is determined by (1) chemical reaction rate, or (2) mass transportation rate

  + Etching rate can be increased by increasing temperature if it is surface reaction rate limited

  + Etching rate can be increased by agitation if it is mass transportation rate limited

- Ultrasonic excitation is a very common agitation source

- Etching rate is also etchant solution dependent

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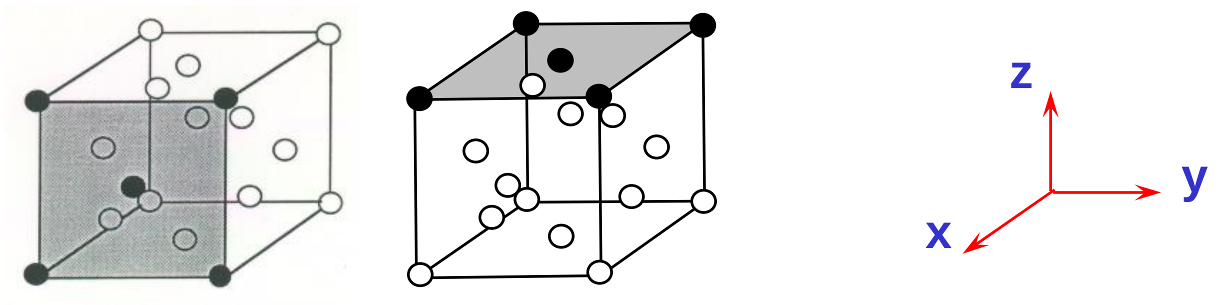
- Single Crystal Silicon

- Thin films

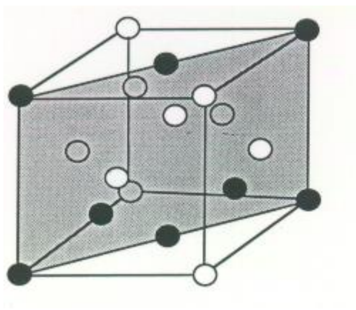
Single Crystal Silicon

- Three important crystal planes in the silicon unit cell

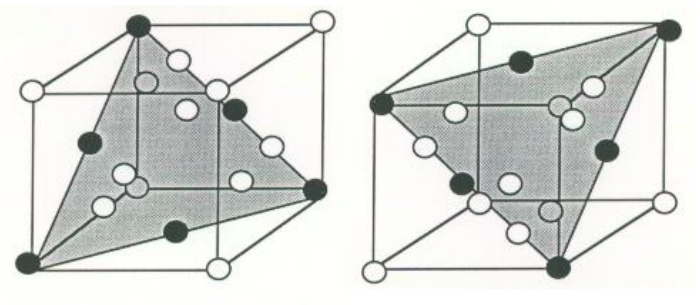
(100)



(110)



(111)



J.A. Wickert, D.N. Lambeth, and W. Fang, STLE/ASME Tribology Conference, 1991.

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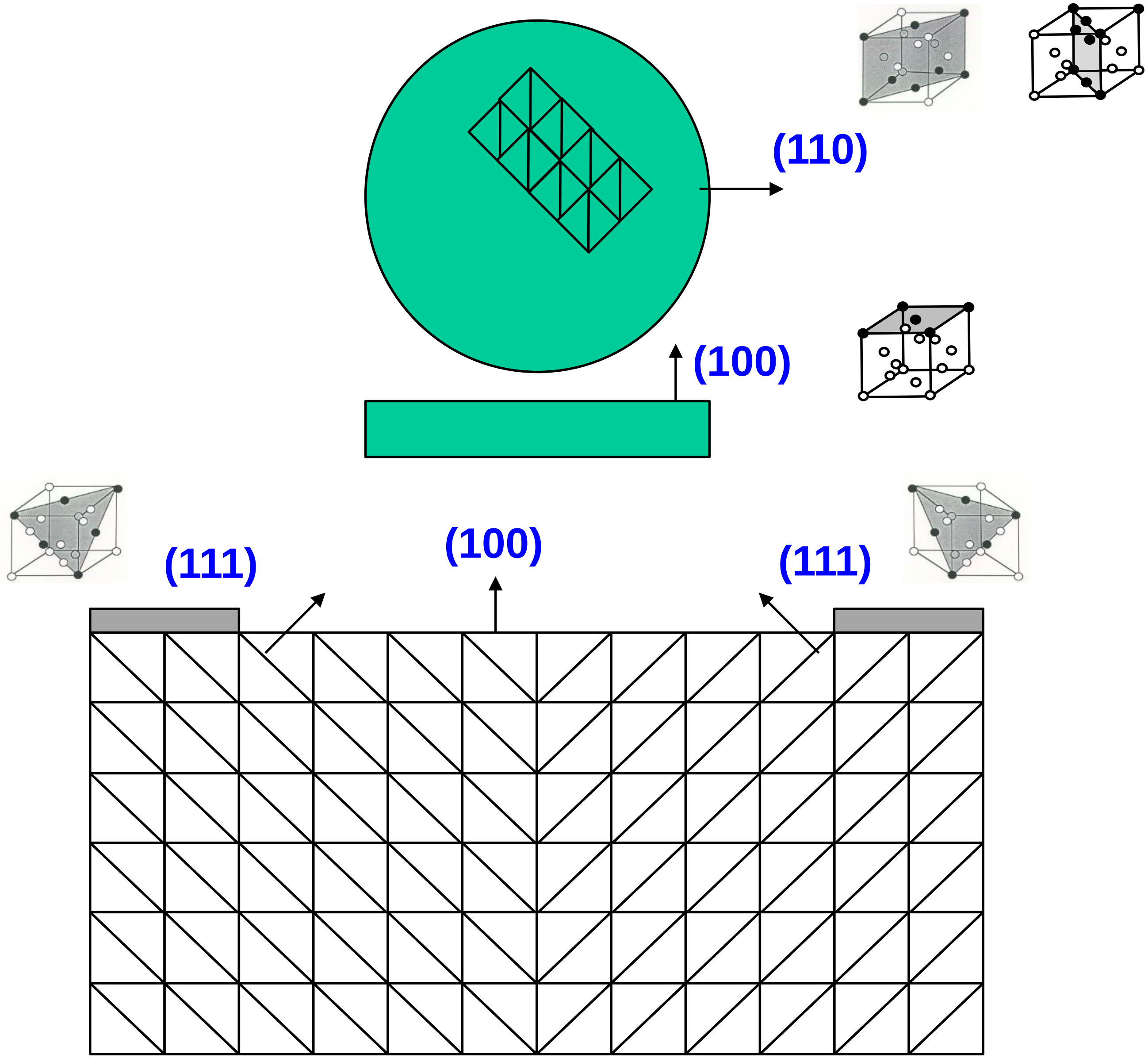

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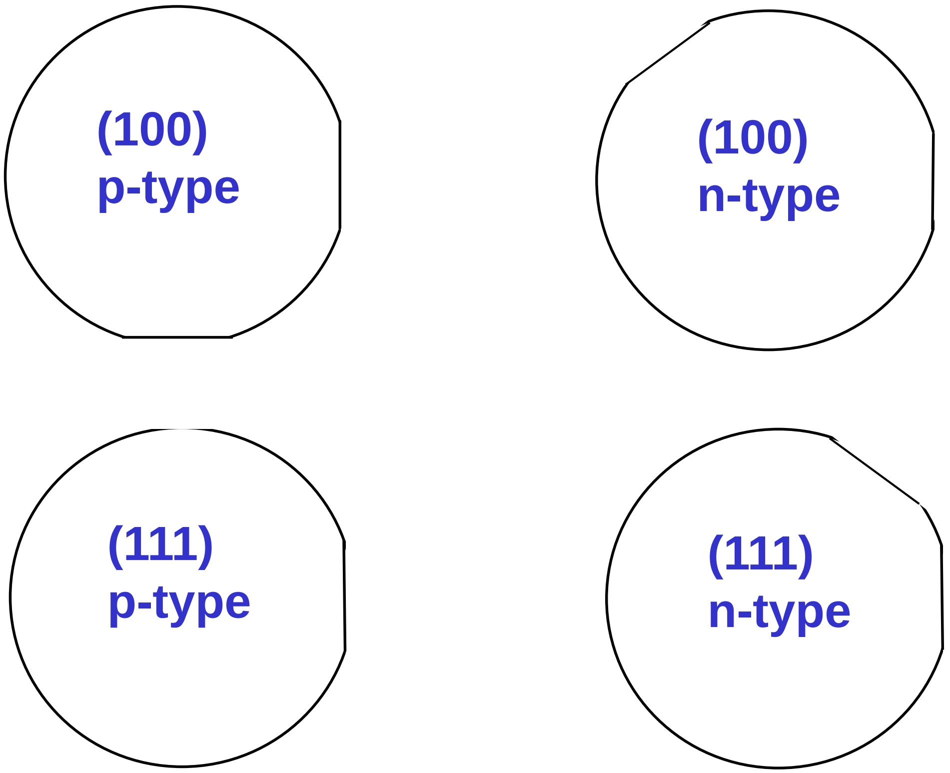
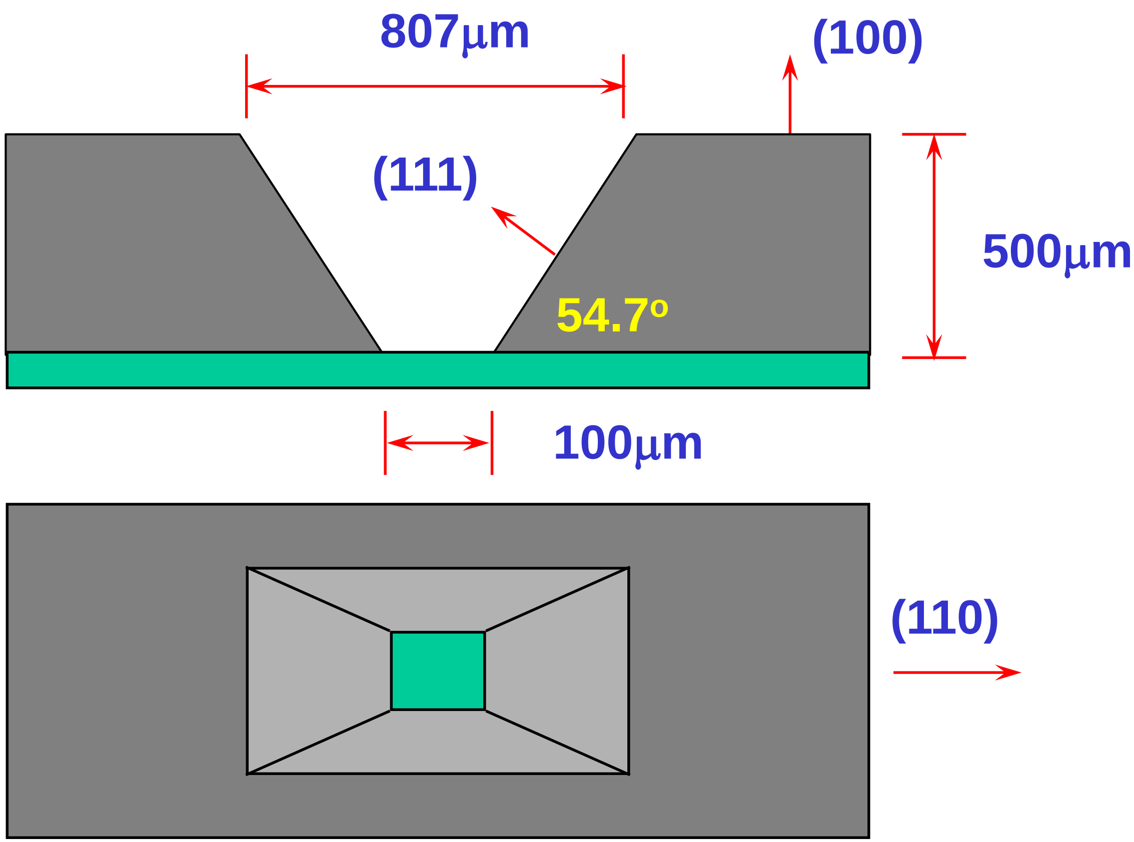
- Flat edge indicate the crystal orientation of the Si substrate



Anisotropic Etch

- Shape of (100) Si substrate after anisotropic etch



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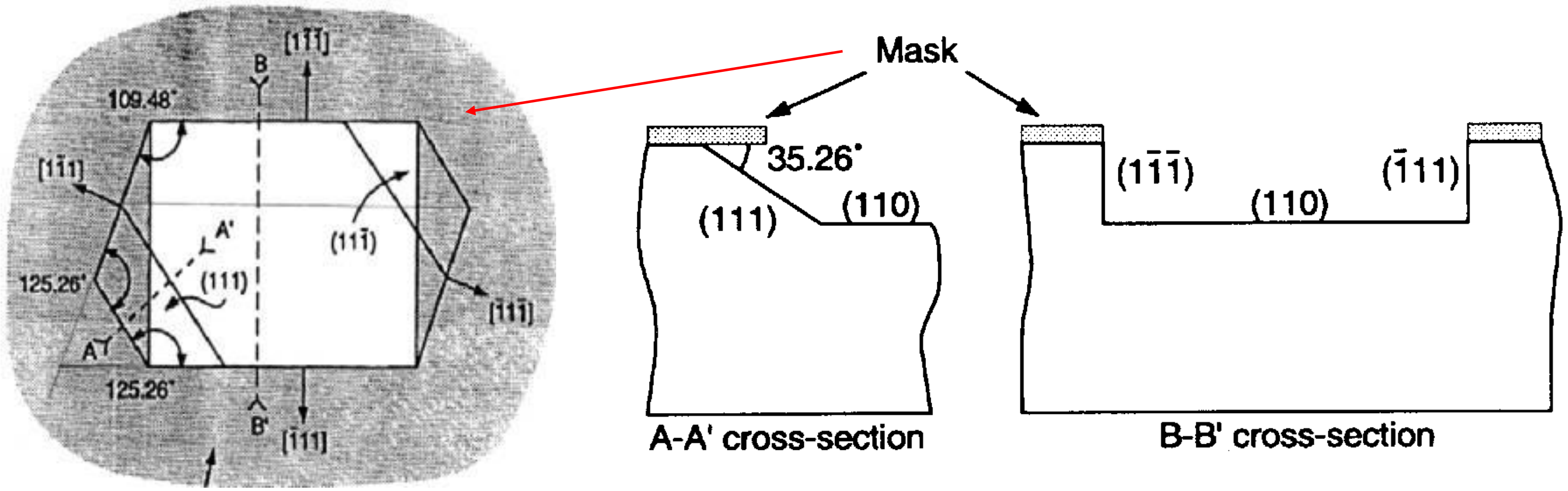
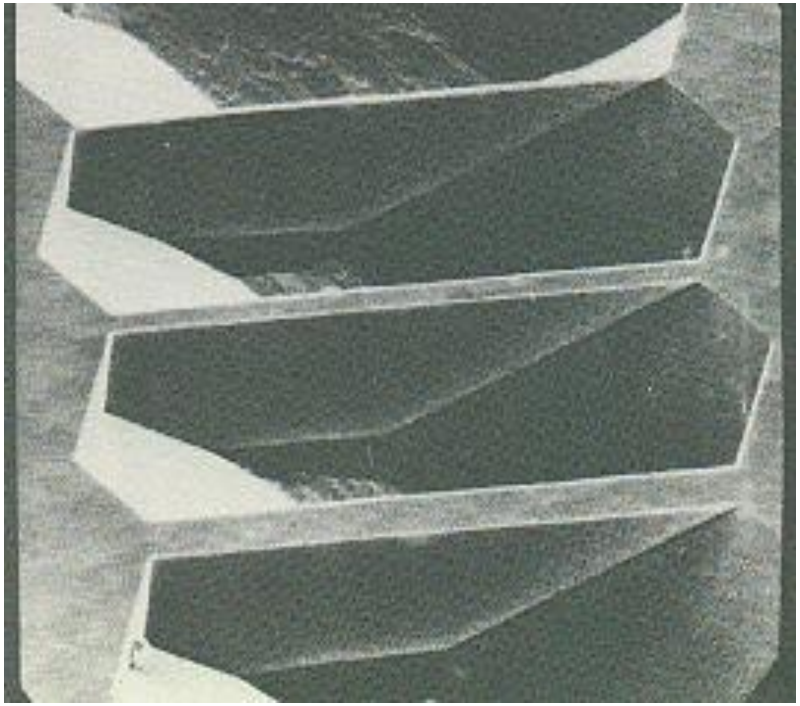
- **Shape of (110) substrate after anisotropic etch**



Semiconductor sensors, edited by S.M. Sze, 1994



B. Hok, Integrated micro-motion systems, edited by F. Harashima, 1990.

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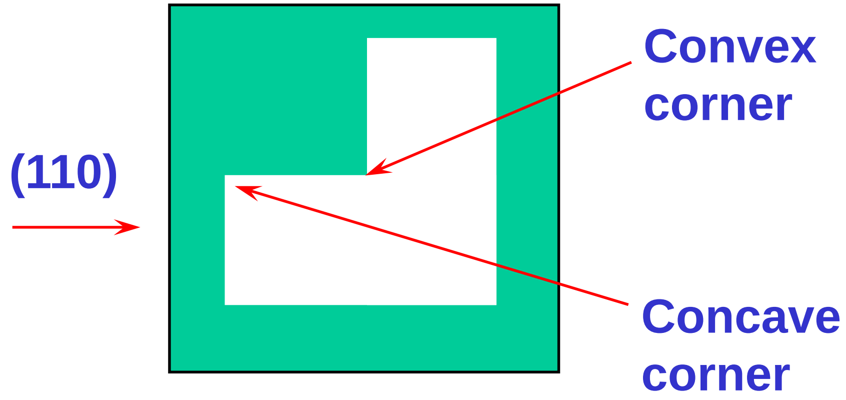
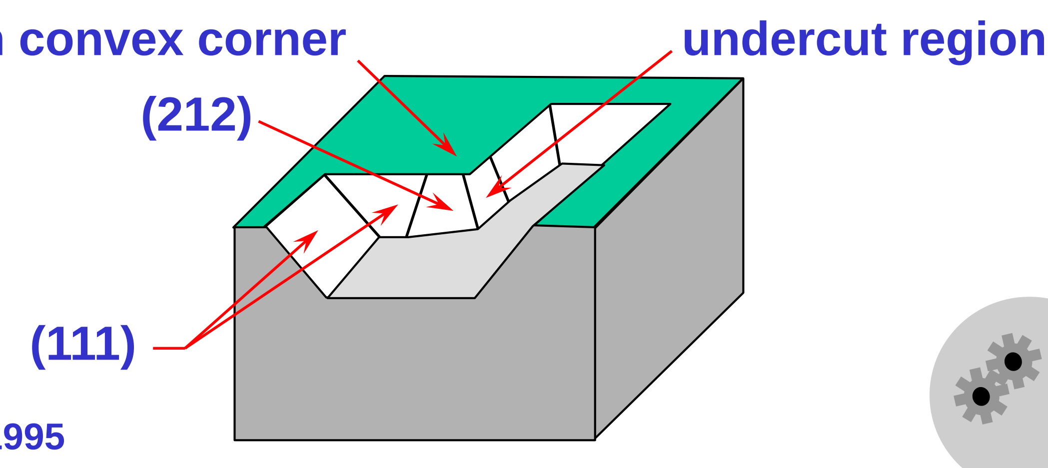
Convex Corner Undercut

- Convex corner



- If the mask pattern exist convex corners, Si will be undercut along (212) planes when the etchant is KOH plus 2-proponal



W. Fang, Ph.D. Thesis, 1995

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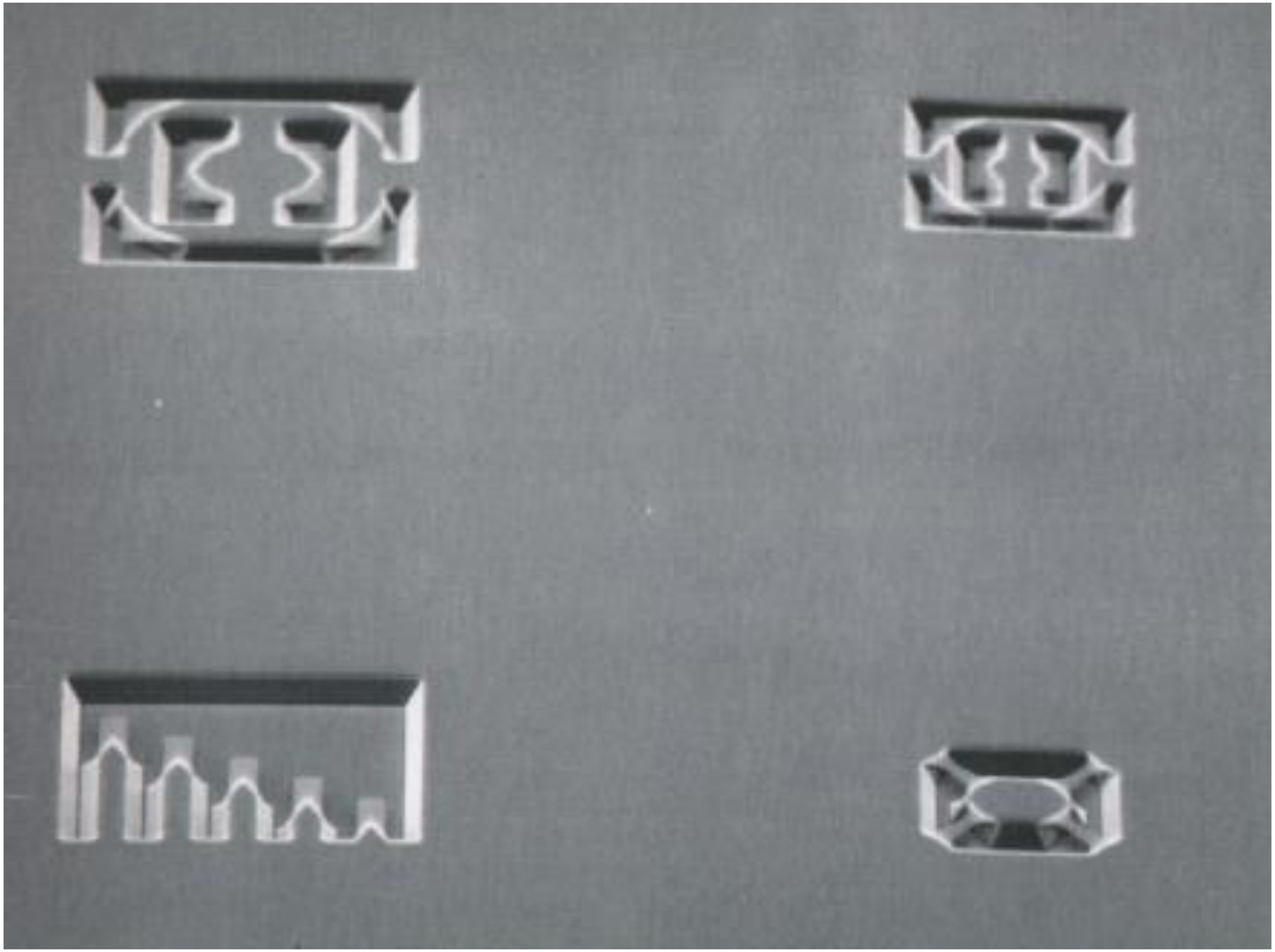

W. Fang and J.A. Wickert, DSSC annual report, 1993

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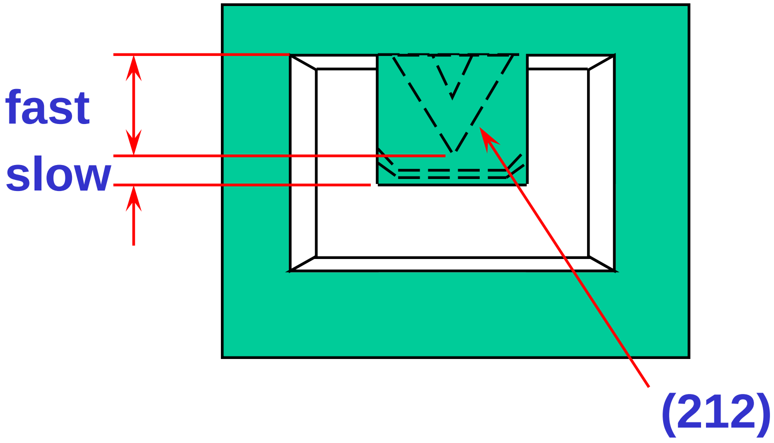
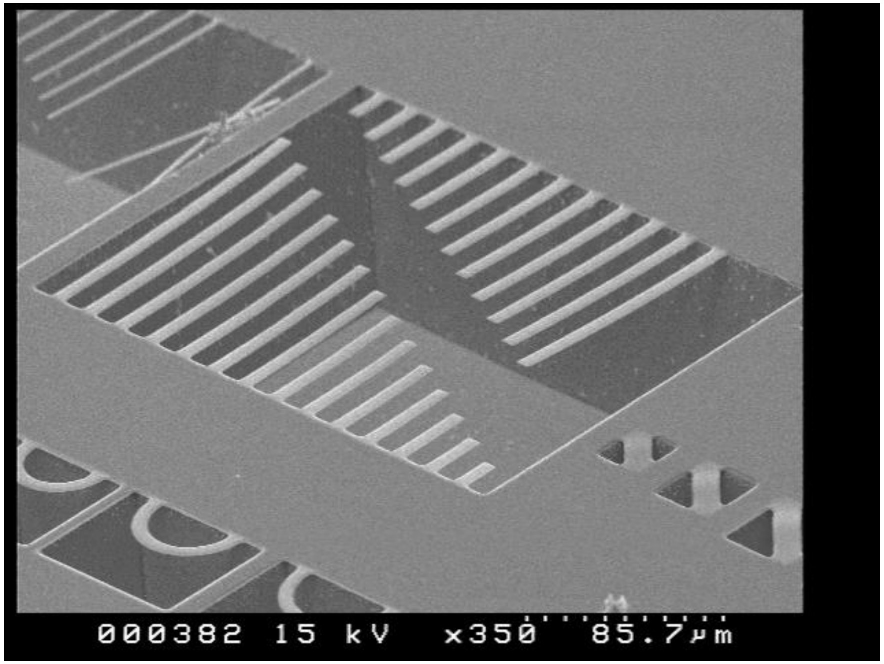
- **Undercut effect** is exploited to make micromachined structures such as beams, suspensions, etc.





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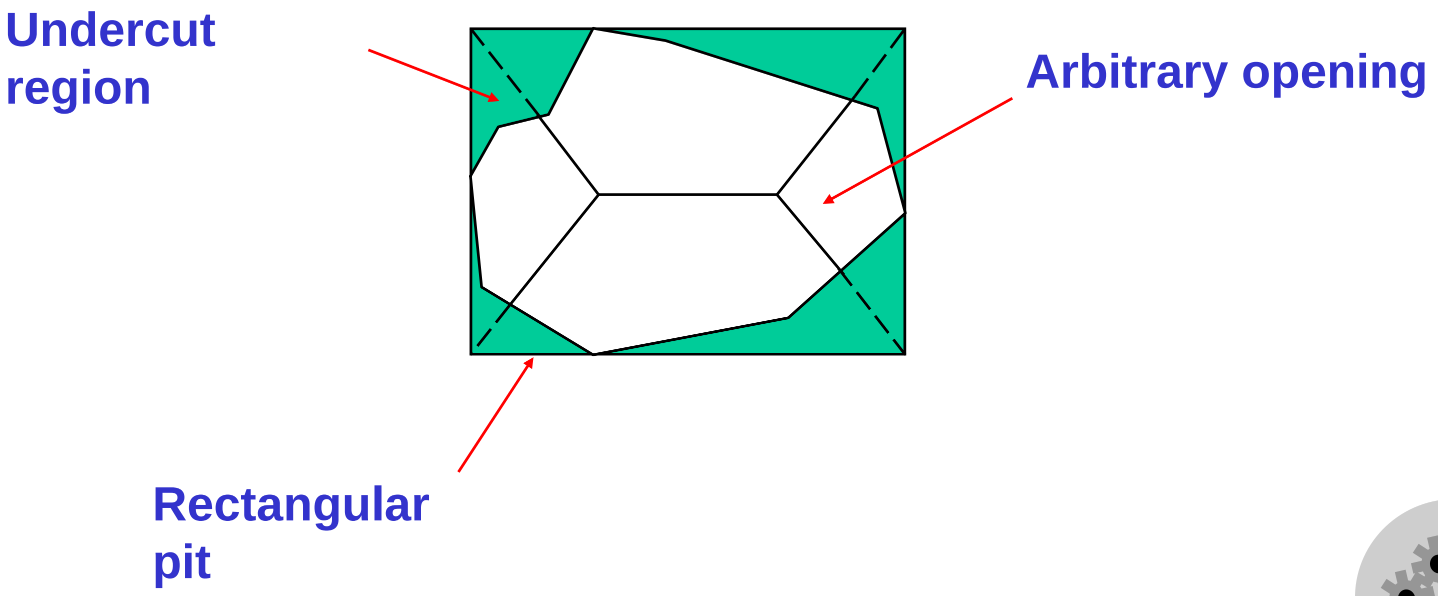
- If Si wafer is etched long enough, any arbitrary opening on the mask will result in a rectangular pit in the wafer
- The arbitrary opening is perfectly inscribed in the rectangle



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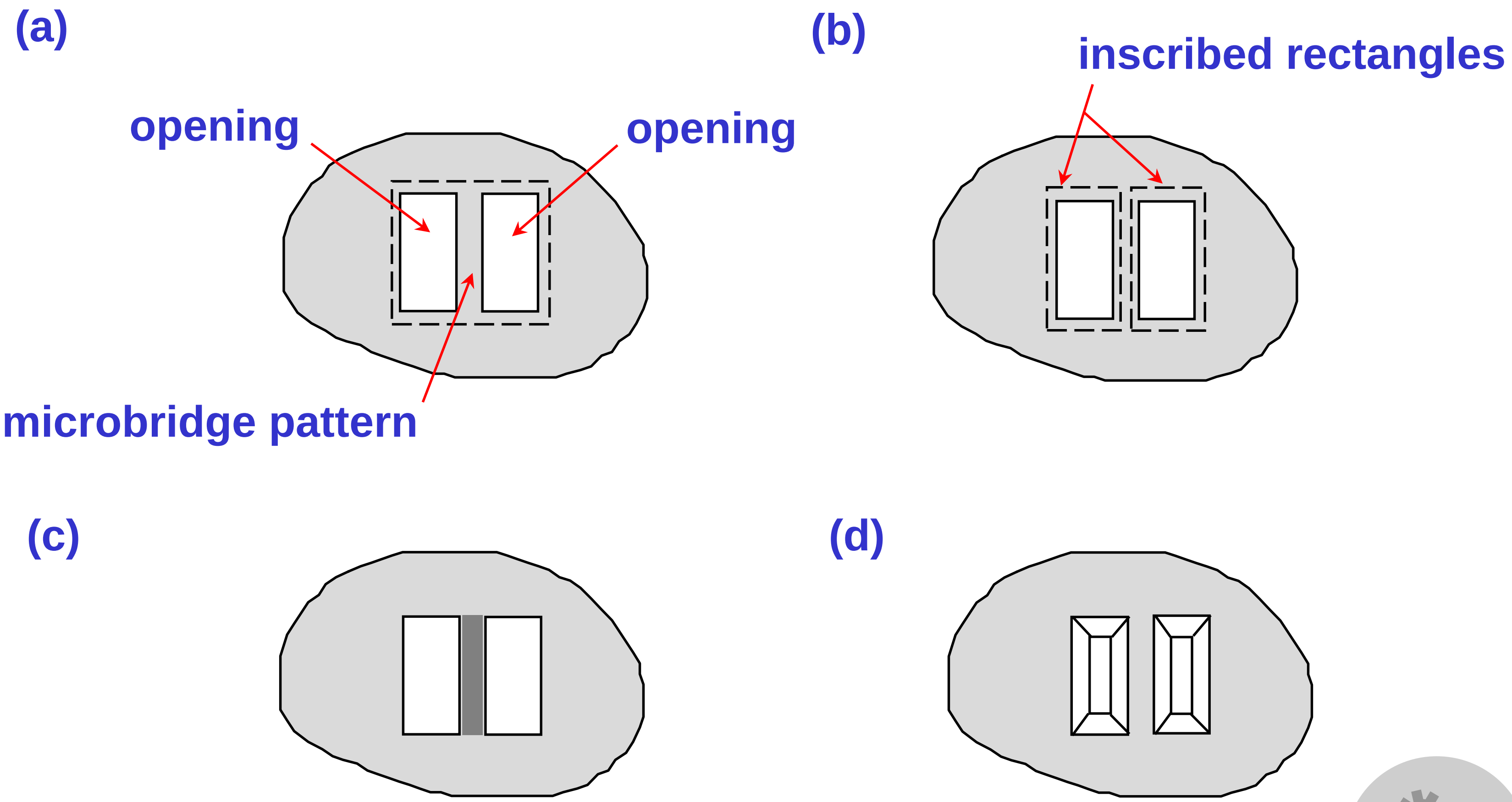
- Similar effect to design the clamped-clamped beam (2 openings)



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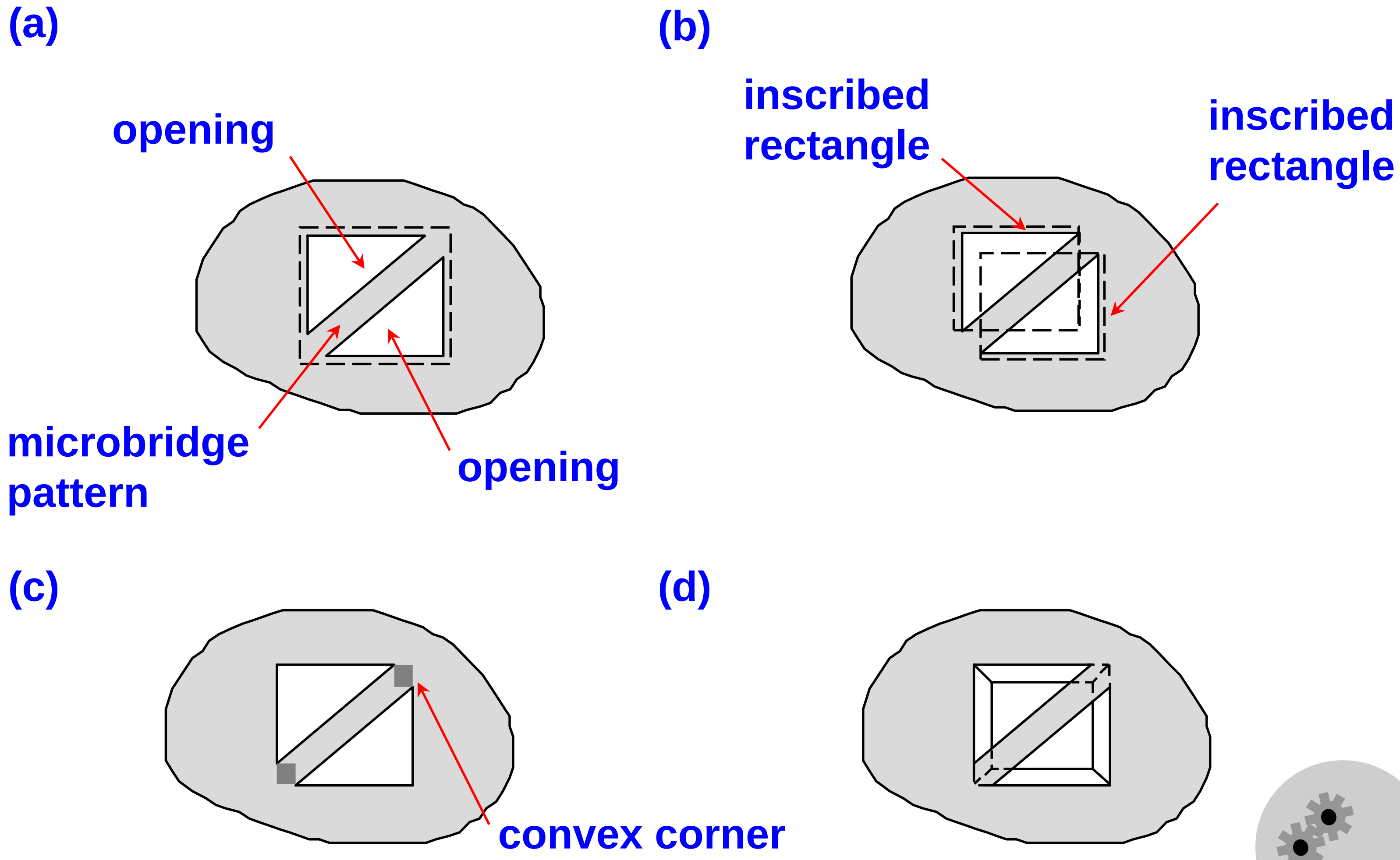
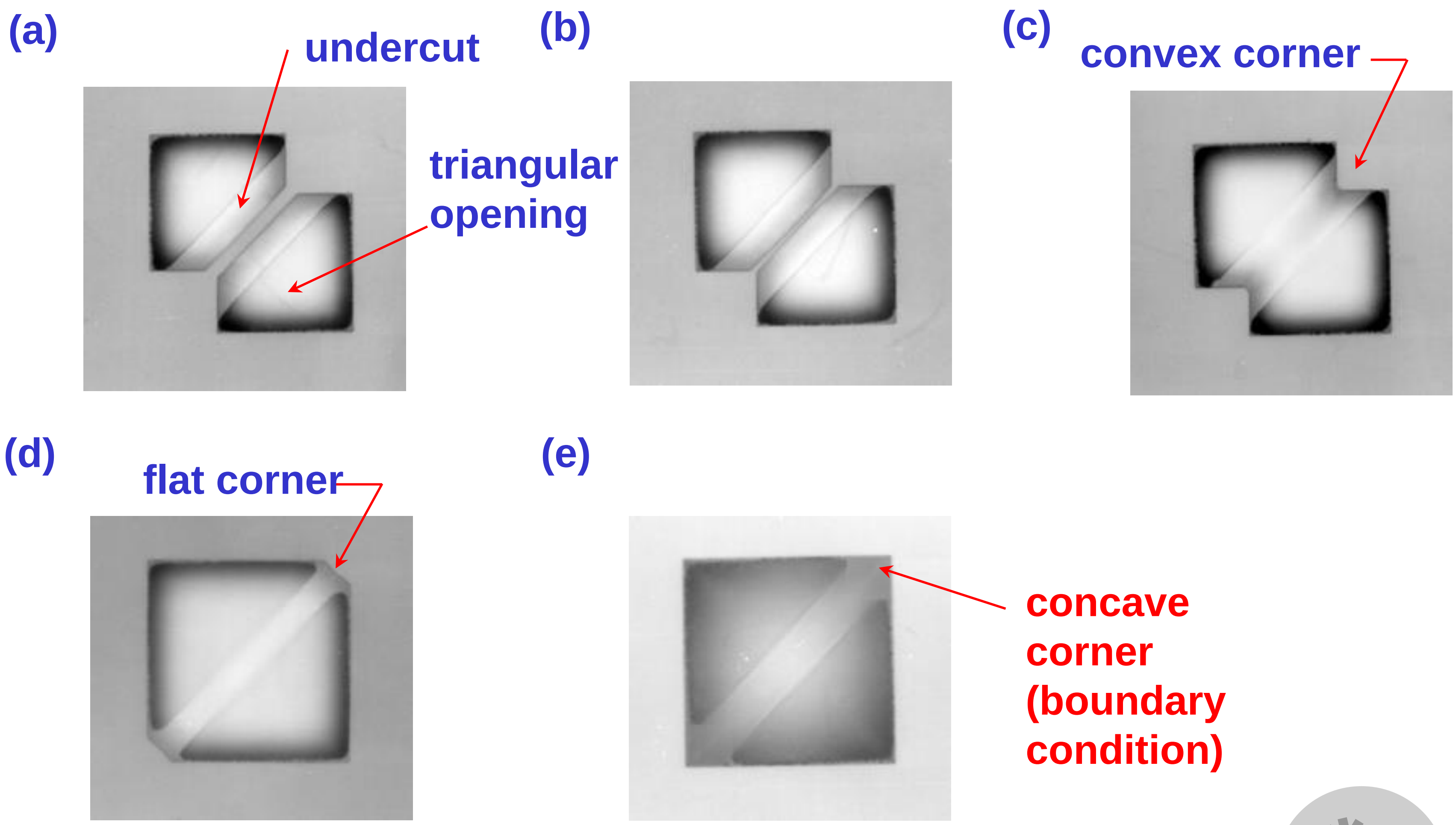
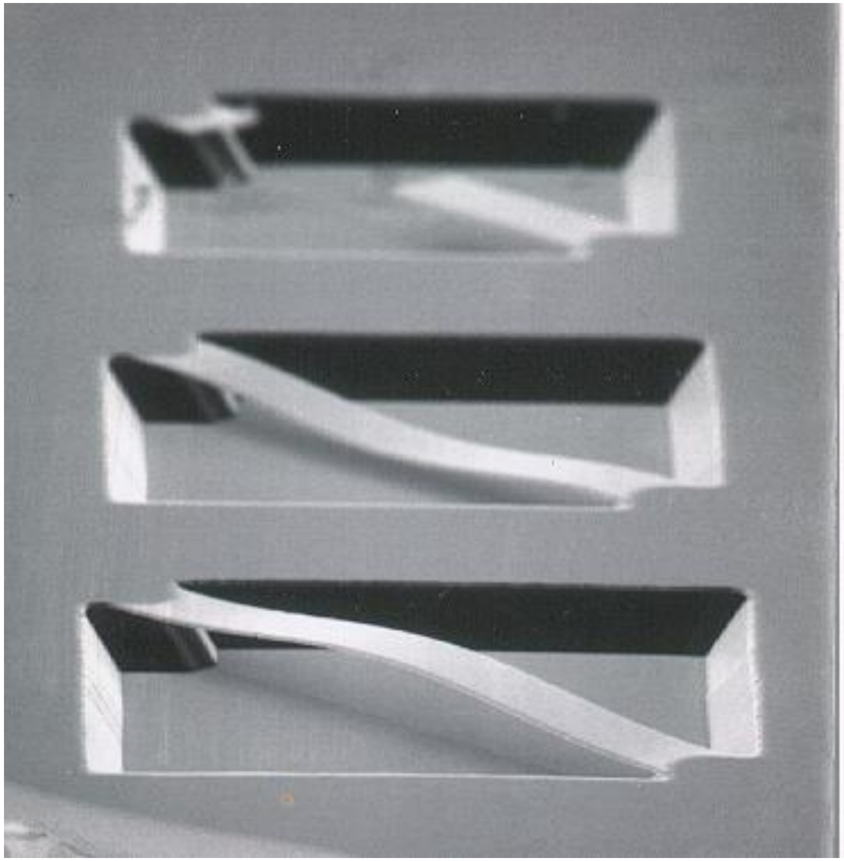
- **Similar effect to design the clamped-clamped beam (2 openings)**



- The sequence of undercut



C. Li, H.-H. Hu, and W. Fang, J. of Micromechanics and Microeng., 1999



W. Fang and J.A. Wickert, DSSC annual report, 1993

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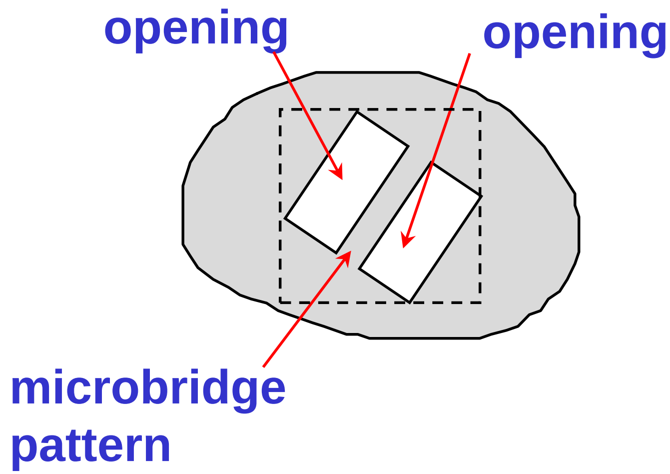
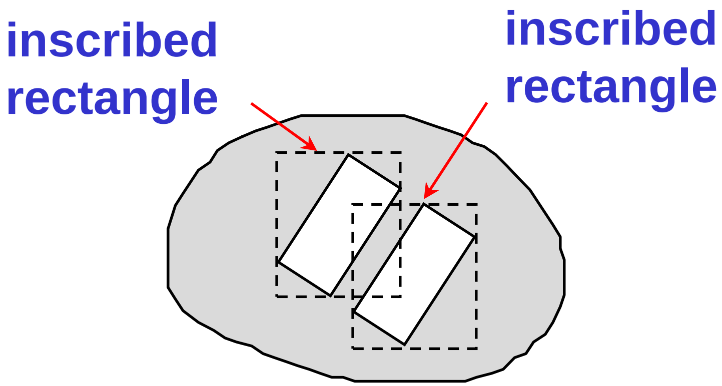
- **Another design of the clamped-clamped beam (2 openings)**

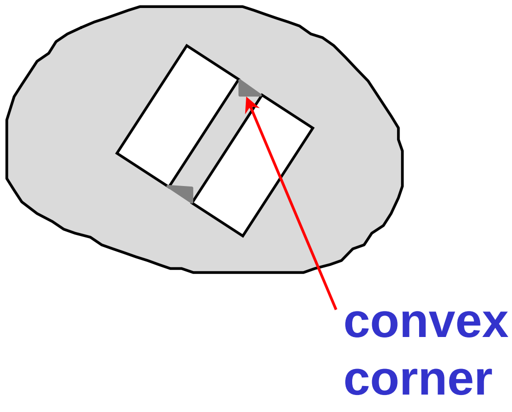
(a)



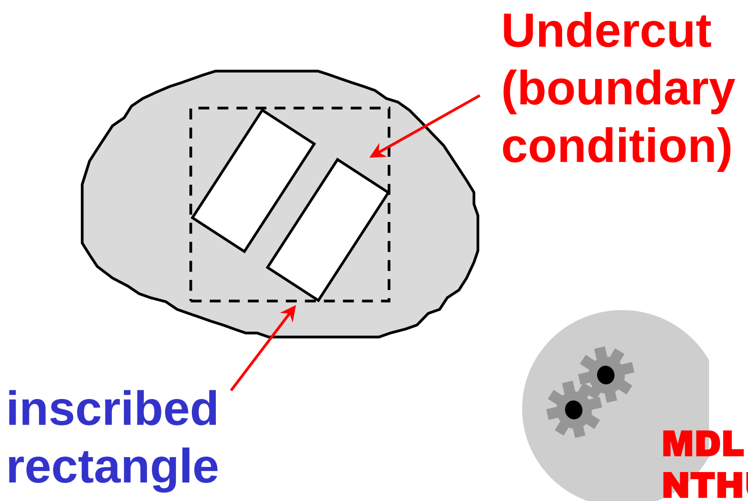
(b)



(c)



(d)



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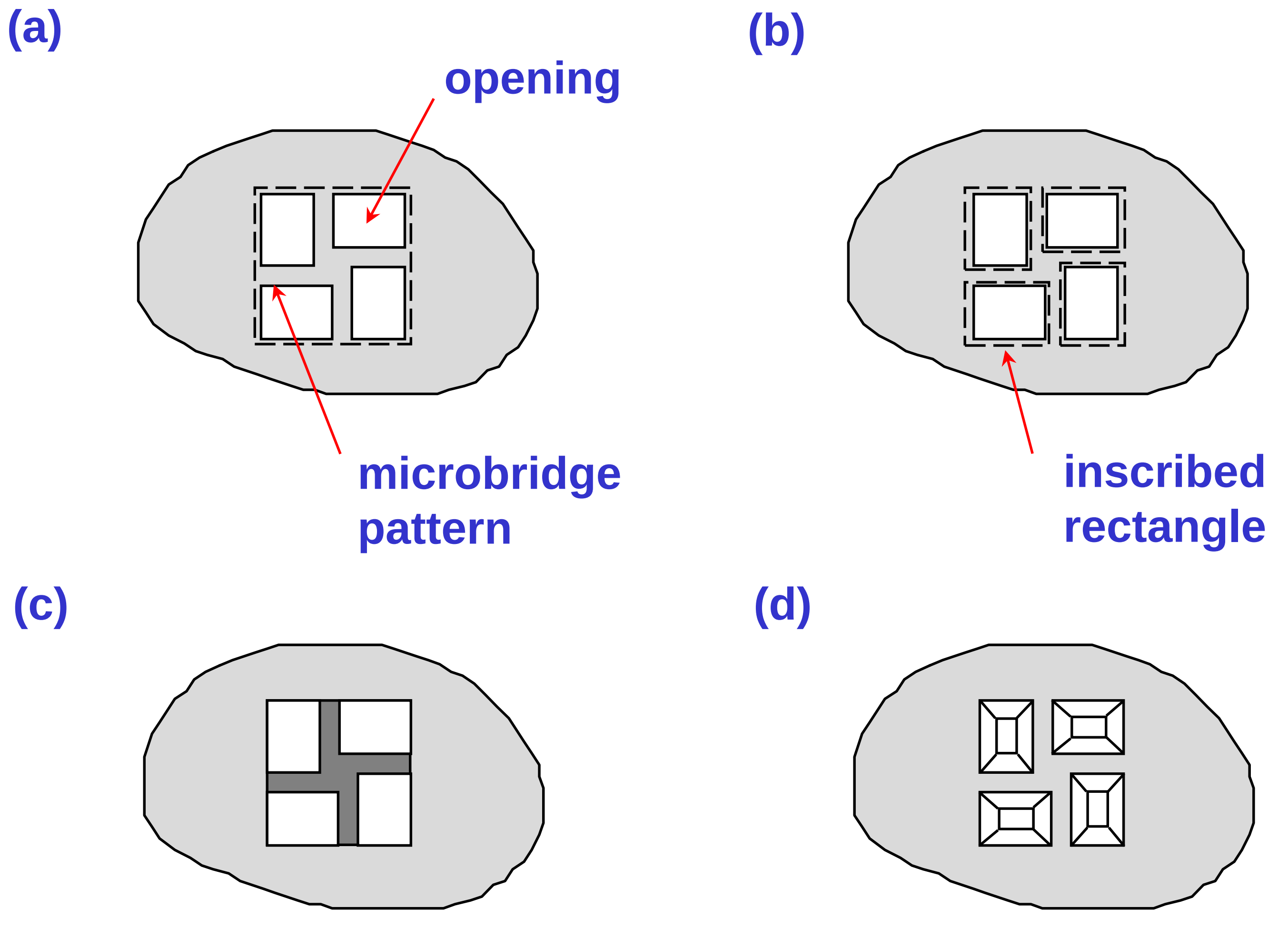
- **Similar effect to design the micro suspensions (4 openings)**



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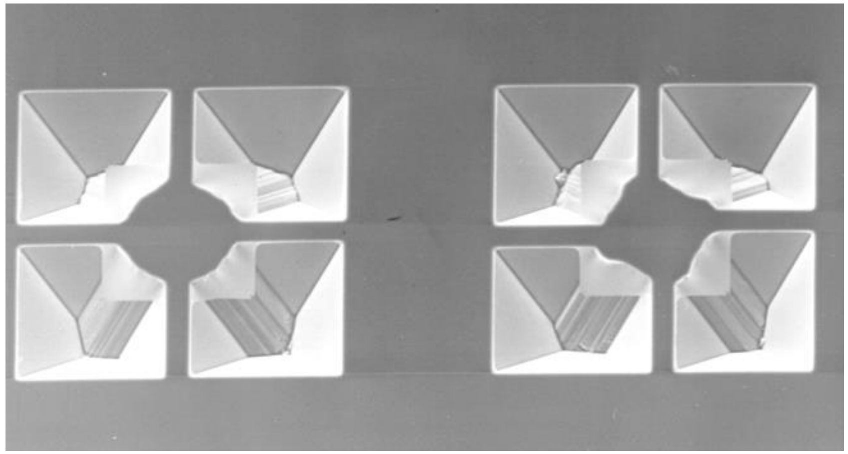
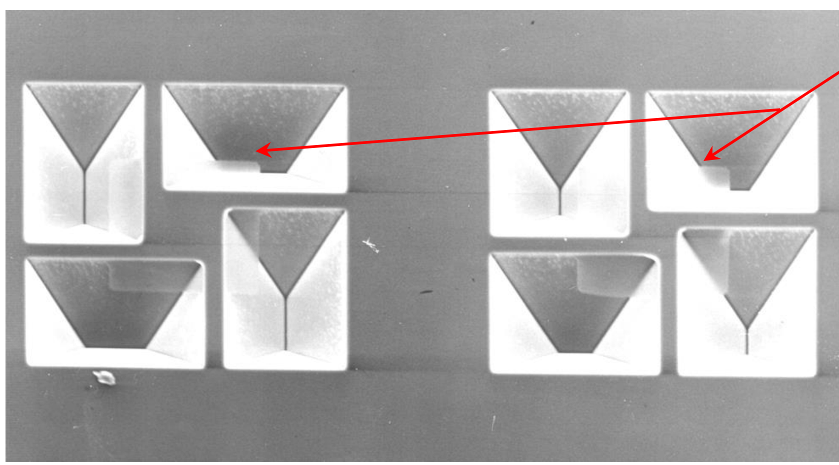
- **Mask pattern which can not be fully undercut**





W. Fang, SPIE conference, 1997

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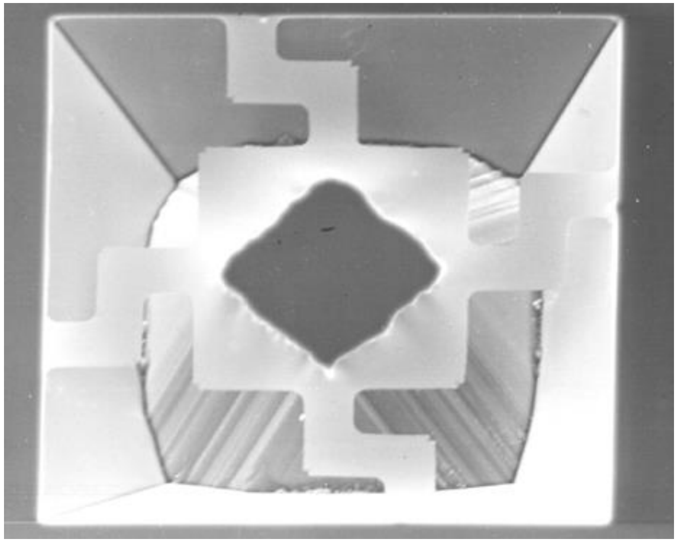
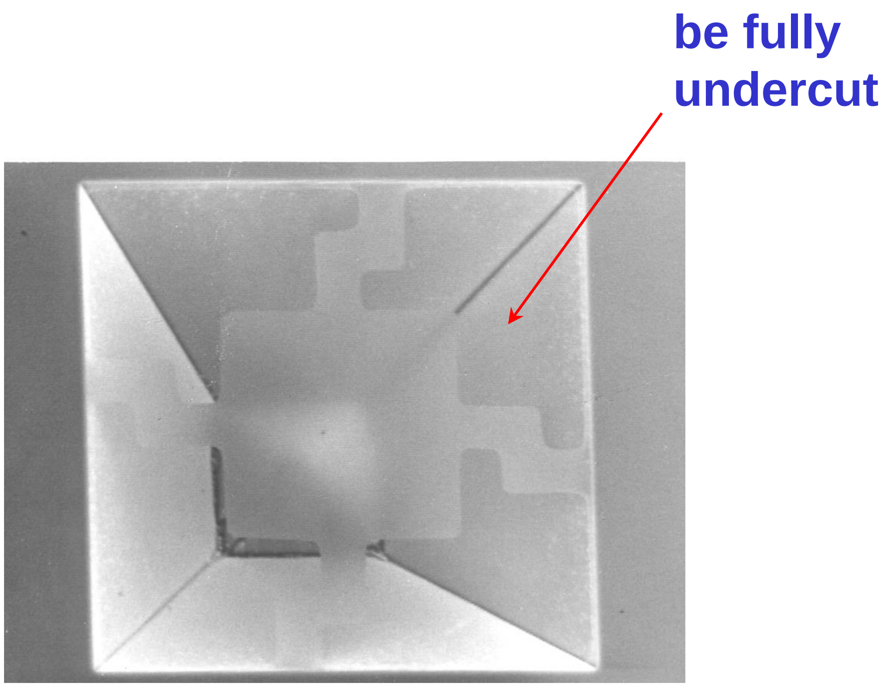
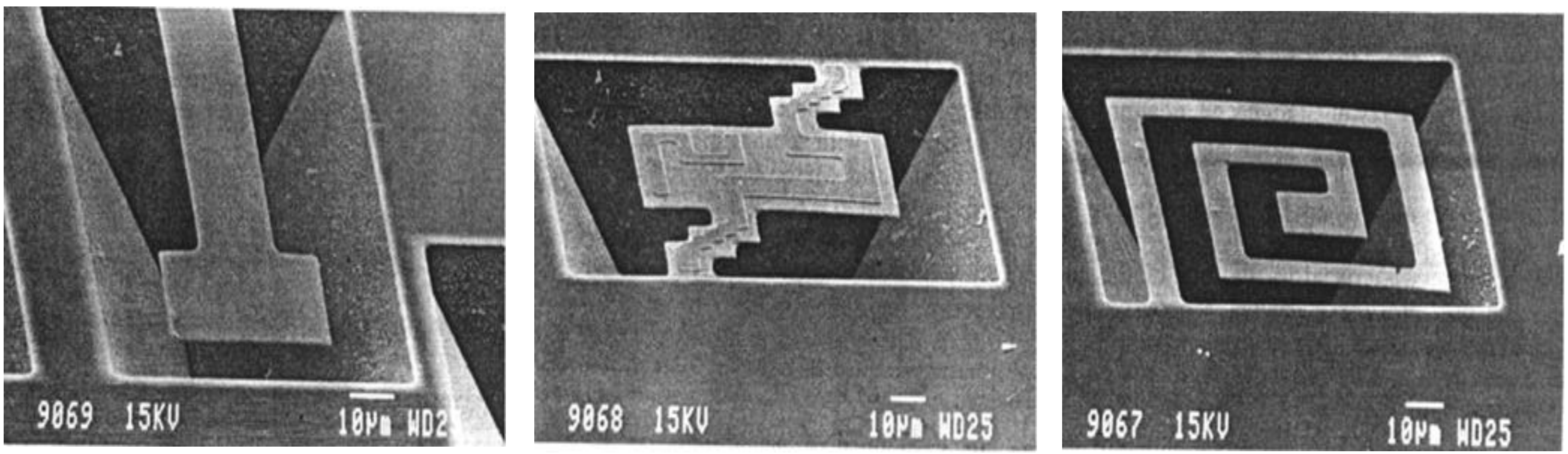
- **Mask pattern which can be fully undercut**





W. Fang, SPIE conference, 1997

- **Other examples**



10 µm

D. Moser, M. Parameswaran, and H. Baltes, Sensors and Actuators, 1990

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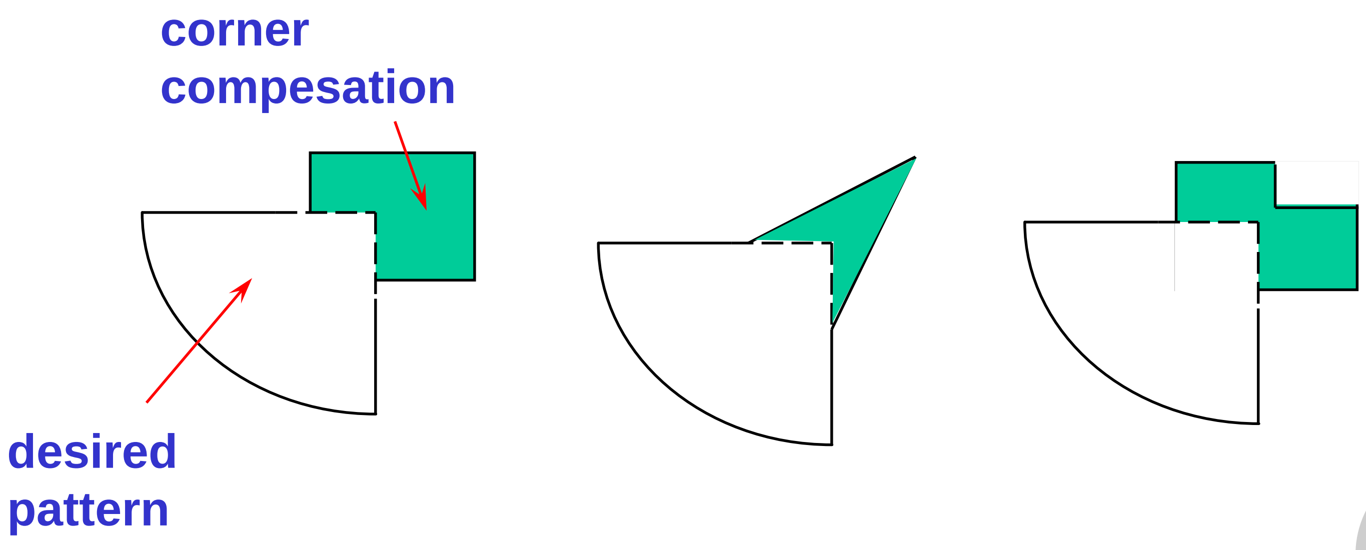
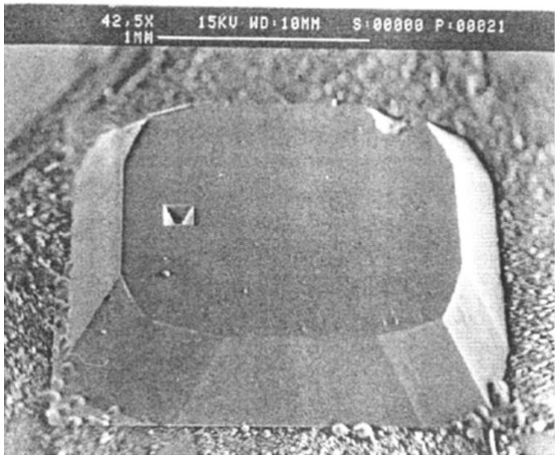
Convex Corner Compensation

- As square block (mesa) structure is required for device, an extra pattern can be added to the convex corner to prevent undercut
- The shape of the corner compensation is determined by (1) shape of the corner, and (2) depth of the mesa



- Mesa

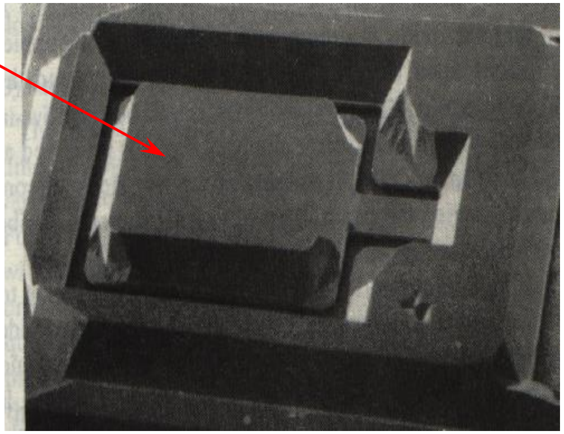


1 mm

B. Puers, and W. Sansen, Sensors and Actuators, 1990

- Application of the mesa - inertia of the accelerometer

mesa



L.M. Roylance and J.B. Angell, IEEE Transaction on ED, 1979.

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Common Etchant for Single Crystal Si

- KOH (anisotropic etchant)

  + etch rate ~ 1 μm/min on (100) substrate at 85ºC

  + selectivity is ~ 400:1 for (100):(111)

  + selectivity is ~ 600:1 for (110):(111)

  + selectivity is ~ 500:1 for Si (100) : SiO_2

  + add isopropyl alcohol (IPA) for better selectivity to crystal planes

  + etch rate decreases ~ 20x on boron doped silicon

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- **EDP (anisotropic etchant)**
  - + etch rate ~ 1 μm/min on (100) substrate at 115ºC
  - + selectivity is ~ 35:1 for (100):(111)
  - + selectivity is ~ 5000:1 for Si (100) : SiO_2
  - + may get rougher Si surface than KOH
  - + etch rate decreases ~ 50x on boron doped Si
  - + toxic
- **TMAH (anisotropic etchant)**
  - + selectivity is >4000:1 for Si (100) : SiO_2 (or Si_3N_4)
  - + higher surface roughness than KOH or EDP
  - + etch rate decreases ~ 50x on boron doped Si

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- **N_2H_4 (anisotropic etchant)**

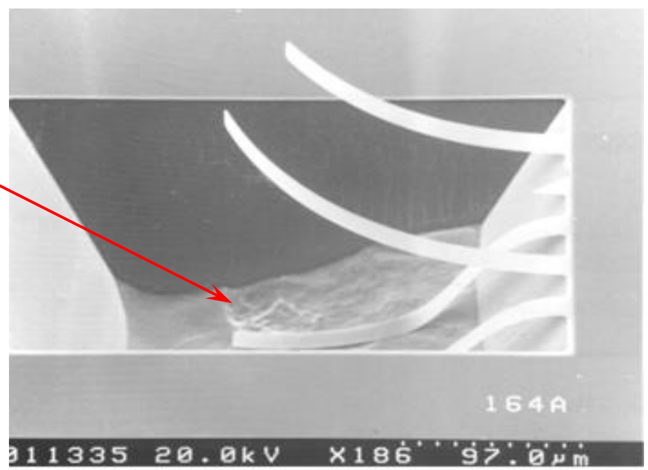
  + High selectivity for Si : SiO_2

  + Low selectivity for (100) : (111) - undercut at boundary

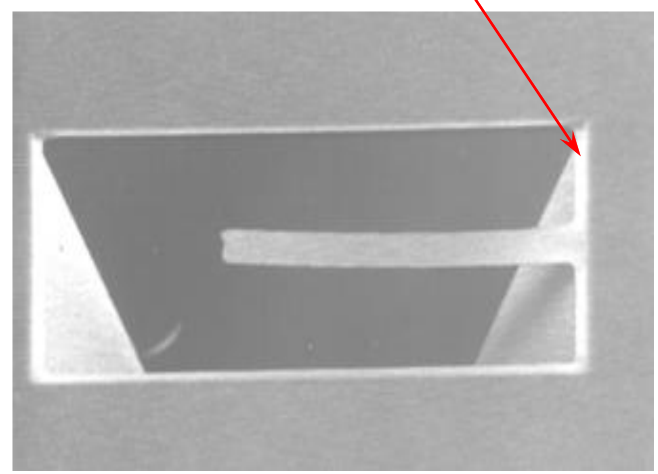
  + May get rougher Si surface than KOH

  + Toxic

Flatness and roughness



Undercut



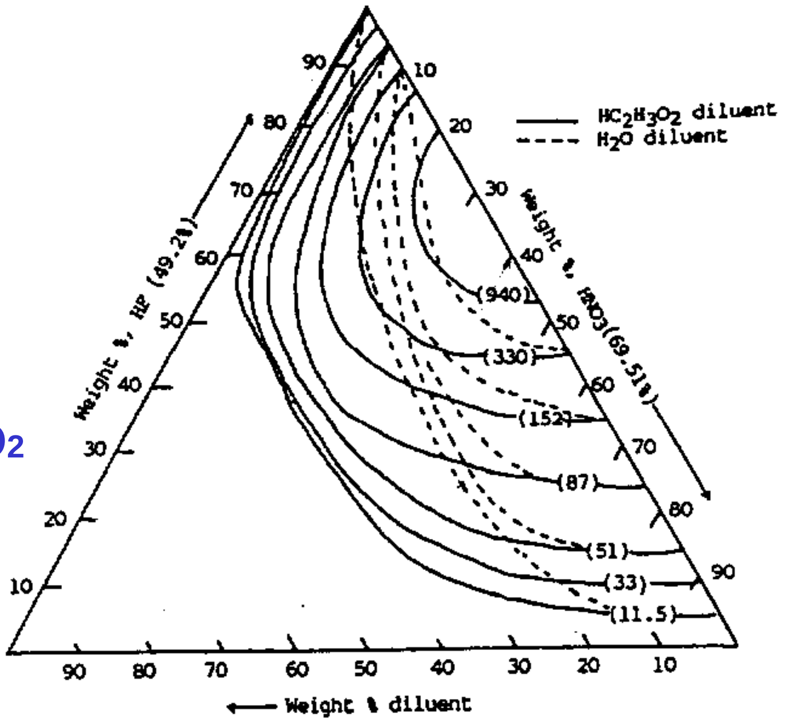
Y.-L. Chen, J.-H. Hsieh, and W. Fang, 1997

- **HNA (isotropic etchant) : Hydrofluoric acid (HF) + Nitric acid (HNO_3) + Acetic acid (CH_3COOH)**

+ Etch rate ~ 0.7 - 3.0 μm/min for HF : HNO_3 : CH_3COOH is 10 : 30 : 80 at 22°C

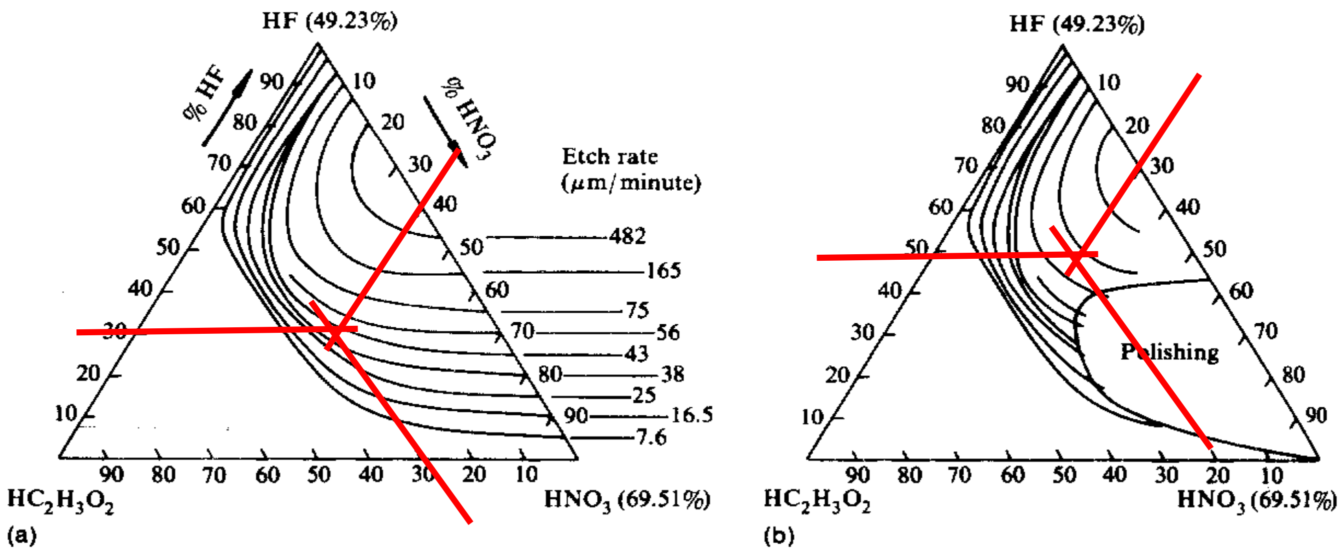
+ SiO_2 etch rate is 300 Å/min

+ Selectivity is ~ 100 : 1 for Si : SiO_2



M.J. Theunissen, et al, J. Electrochem. Soc., 1970

- Two-step etching process including : (1) the **silicon is oxidized** by HNO_3 first, and (2) the **oxide is then dissolved** by HF
- At **high HF low HNO_3** concentration, etching rate is dominated by process (1)
- At **high HNO_3 low HF** concentration, etching rate is dominated by process (2), this region is used as **polishing etch**



B. Schwartz and H. Robbins, J. Electrochem. Soc., 1976

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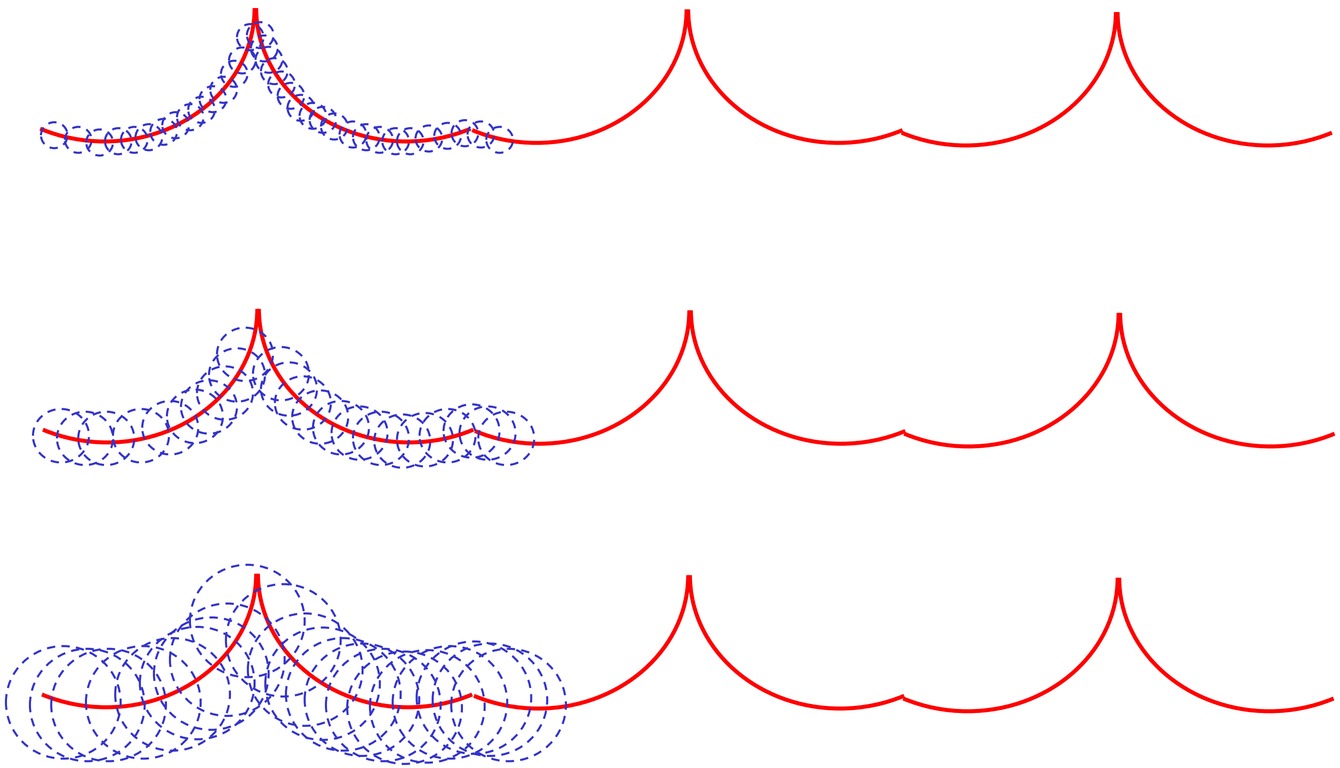
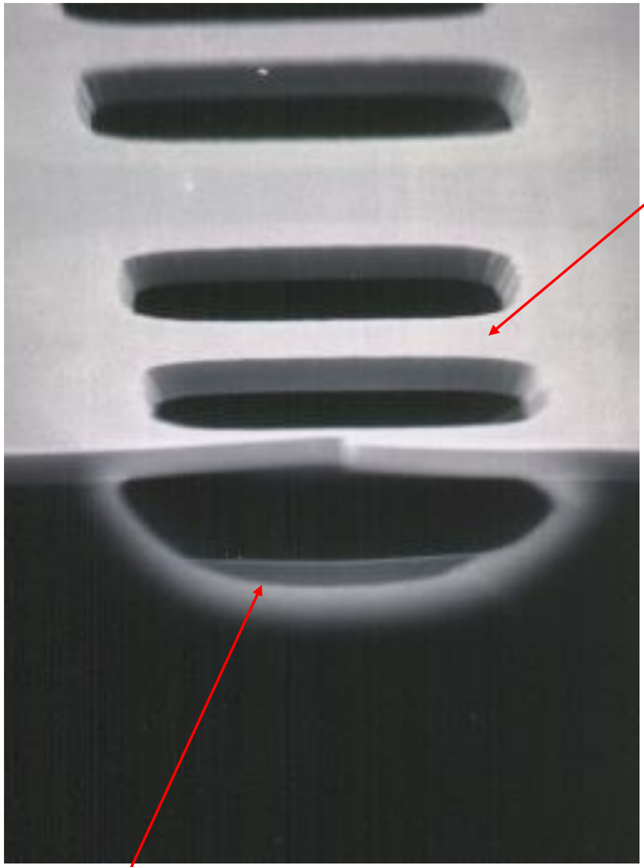
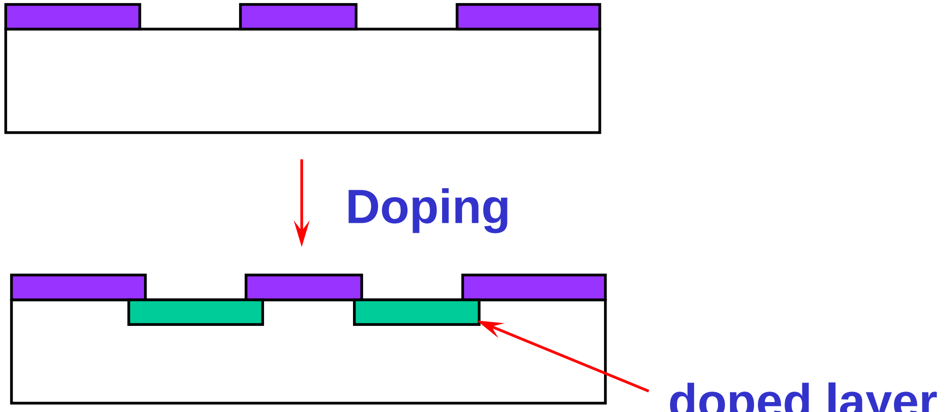



Clamped-clamped beam
isotropic etching

Dopant Dependent Etch Stop

- Doping - the process to add dopant into a silicon substrate by (1) diffusion, or (2) ion implantation



- Etch stop - if Si substrate is heavily doped, etching rate for anisotropic etchants (e.g. KOH, EDP) will be reduced drastically
- The most common dopant for etch stop is boron

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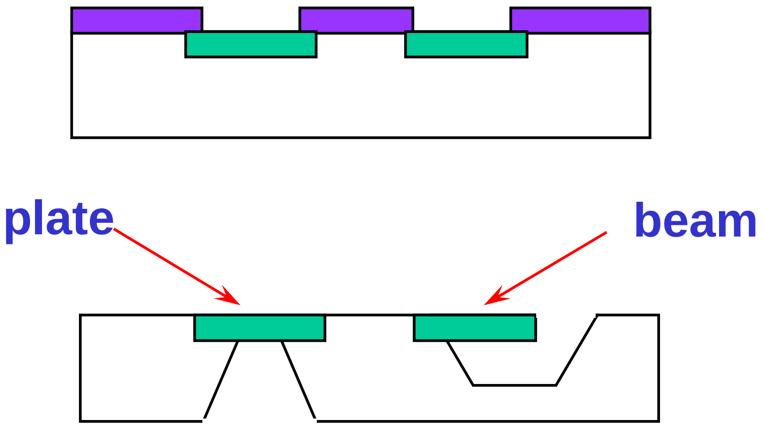
- **Doped etch stop layer could precisely define the thickness of a beam, membrane, or plate**



- **If Si substrate doped with boron to about 10^{20} atoms/cm^3, the etch rate will be reduced**

  + **For KOH - the etch rate become 1/20 if the doped boron $\geq 1\times10^{20}$ atoms/cm^3**

  + **For EDP - the etch rate become 1/50 if the doped boron $\geq 7\times10^{19}$ atoms/cm^3**

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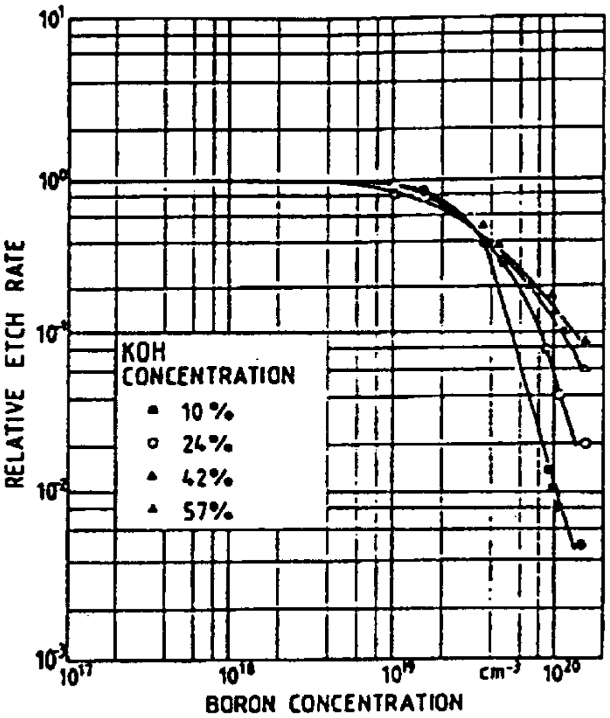
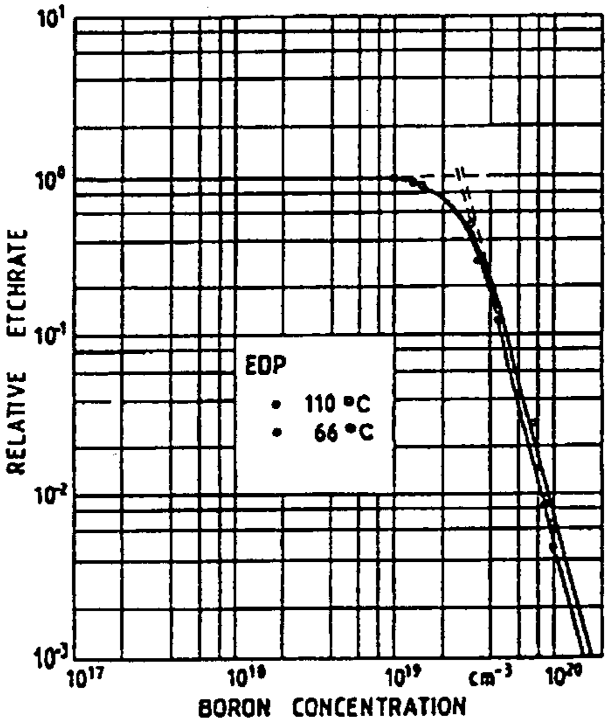
- **Boron concentration vs etch rate for KOH and EDP**

For KOH



For EDP



H. Seidel, 4th Int. Conf. on Solid State Sensors and Actuators, 1987

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- **The doping process can be completed by two approaches**
  - + **Diffusion**
  - + **Ion implantation - a technique by which impurity atoms, traveling at high energy, are made to impinge on the substrate**

- **Comparison of diffusion and ion implantation method**
  - + **In general, the thickness of doped layer is approximate 10~20 μm by diffusion method, but only several microns by ion implantation**
  - + **The equipment for ion implantation is very expensive**
  - + **Although diffusion method is less accuracy in controlling dopant concentration and thickness of doped layer, it still satisfied the requirement for MEMS**

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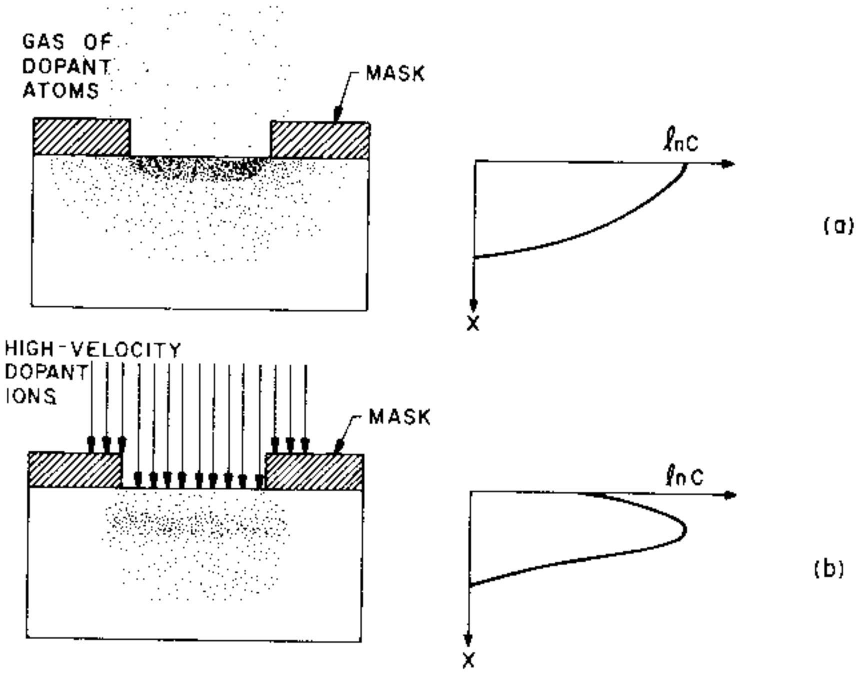
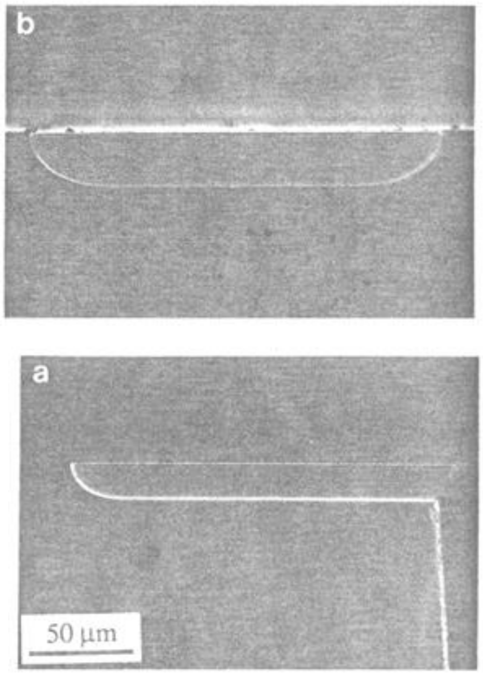
- **Distribution of the doped atoms**





S.M. Sze, Semiconductor Devices Physics and Technology, 1985

F. Ericson and J-A. Schweitz, J. of Appl. Physics, 1990

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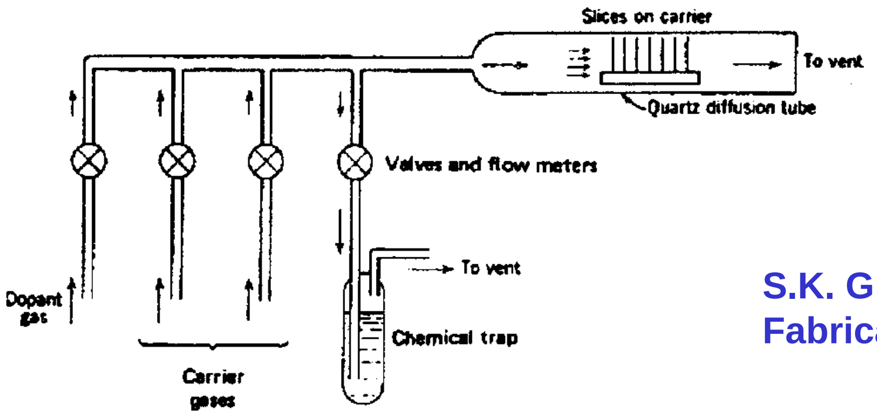
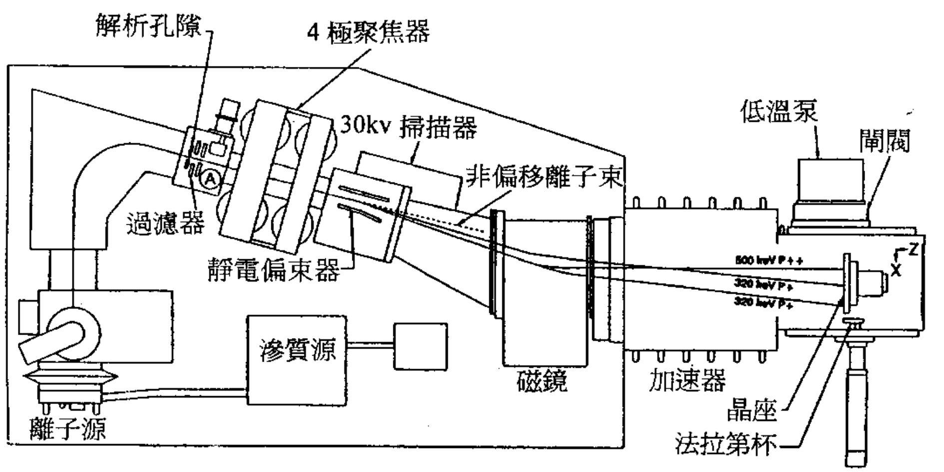
- Devices for diffusion



S.K. Ghandhi, VLSI Fabrication Principles, 1983

- Devices for ion implantation



莊達人, VLSI 製造技術, 1995

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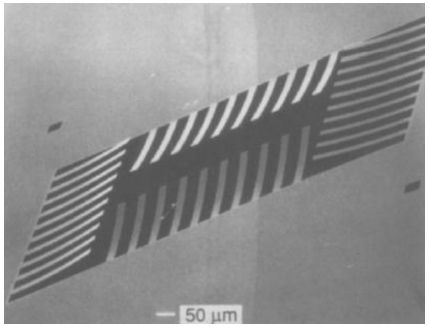
- The doped boron is replaced silicon in the crystal structure to form B-Si

- Since the boron atom is smaller than silicon, the doped layer is in tensile residual stress



Ding, Ko, Mansour, Sensors and Actuators, 1990

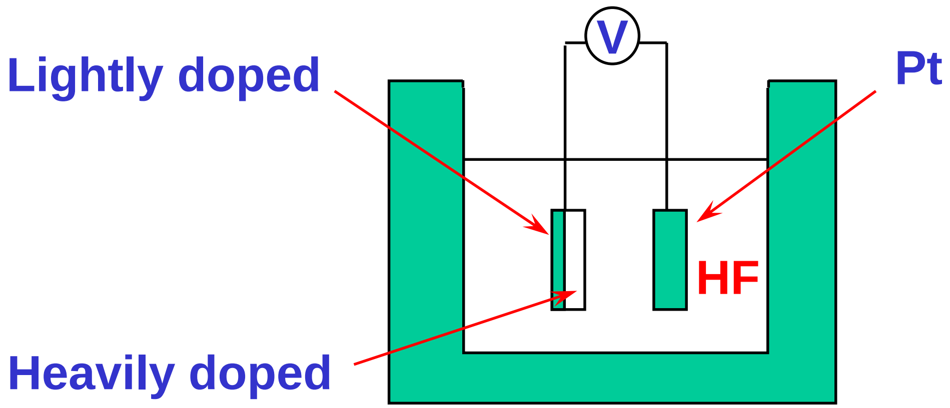
- For more details about the doping processes please read

Diffusion - S.M. Sze Chap7, 莊達人 Chap 9, W.R. Runyan and K.E. Bean, Chap. 8

Ion implantation - S.M. Sze Chap8, 莊達人 Chap 9, W.R. Runyan and K.E. Bean, Chap. 9

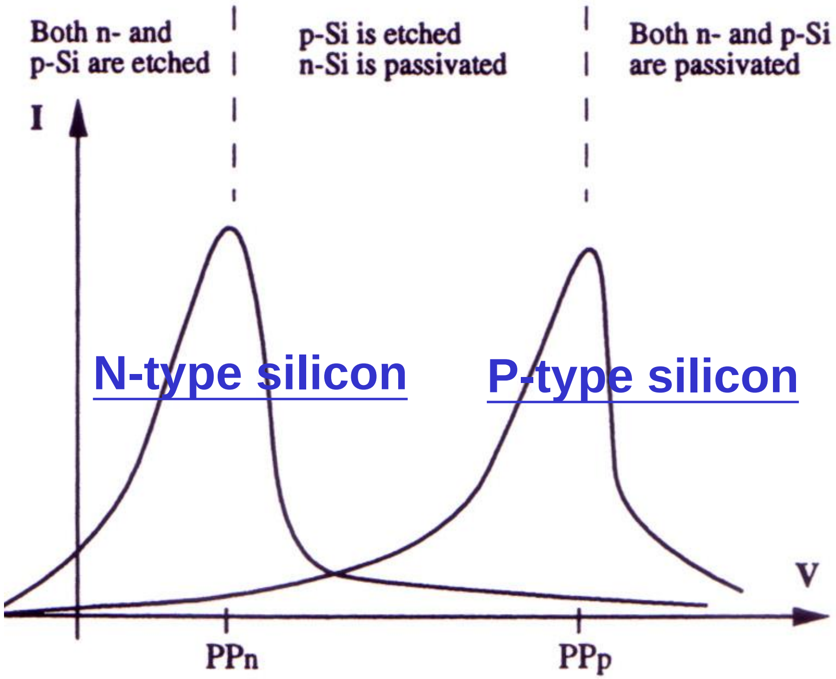
Electrochemical etch stop I (isotropic)

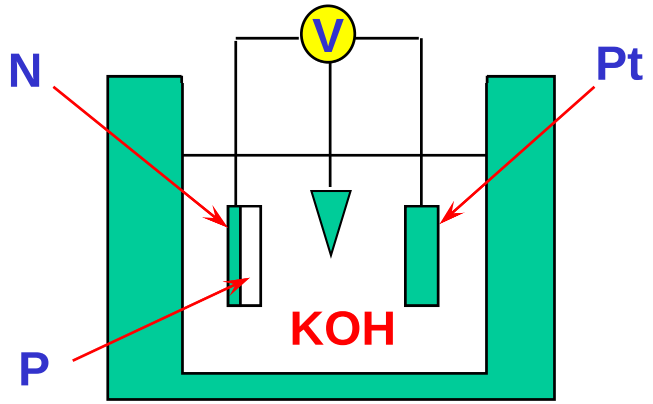
- The etching process includes two steps
  - + oxidation of the substrate by voltage
  - + etching of the silicon oxide by HF

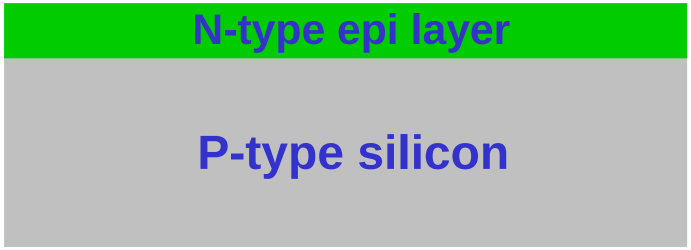


- Substrate contains two parts with different doped concentration
- Heavily doped part has higher conductivity and will be oxidized more quickly - the heavily doped Si will be etched faster than the lightly doped Si

Electrochemical etching stop II (anisotropic)







Epitaxial silicon wafer

Typical I-V plot for p/n Si in alkaline solution

Ref: L. Smith, J. Electrochem. Soc., 1993

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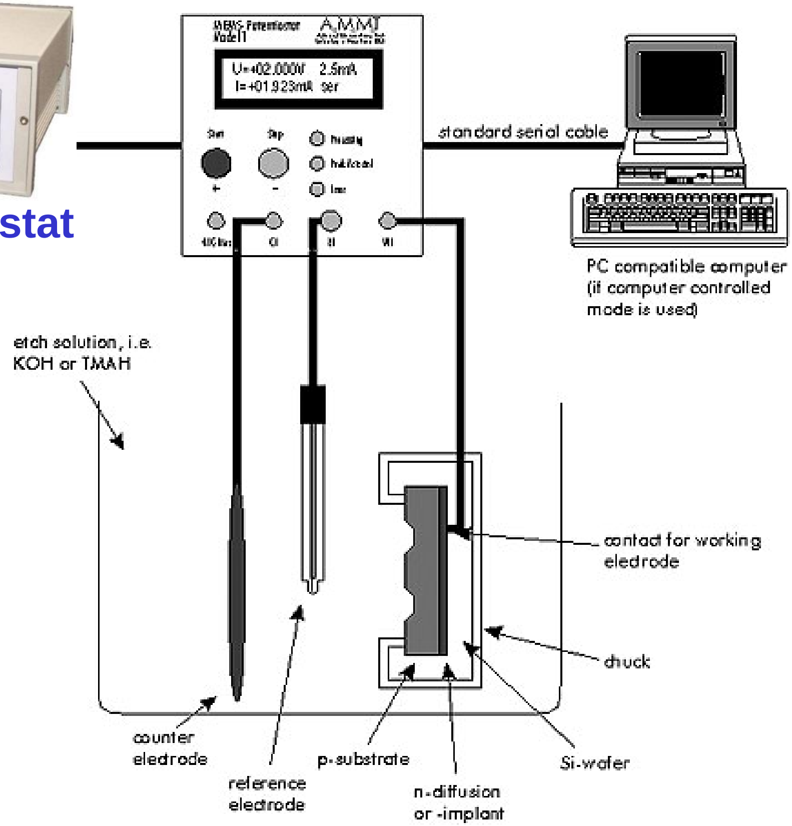
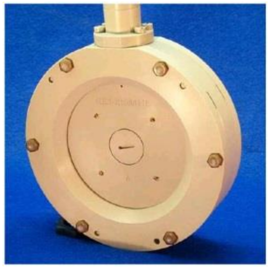
Equipment setup

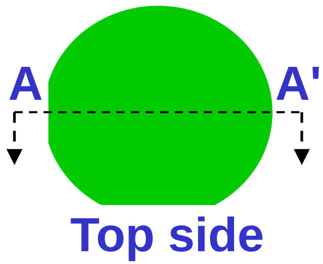
MEMS potentiostat

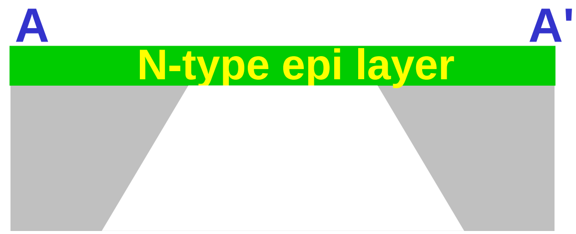


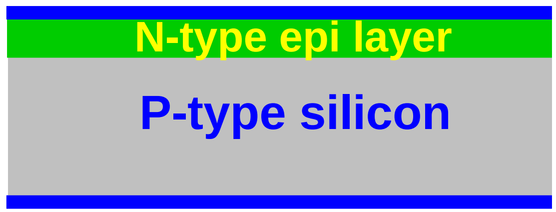


Wafer holder

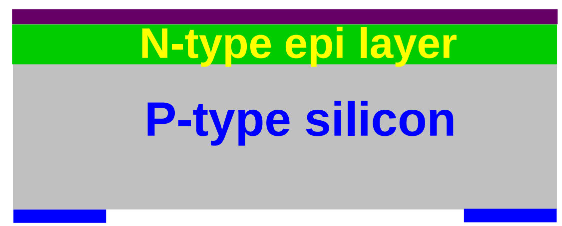
Source: http://www.ammt.com/



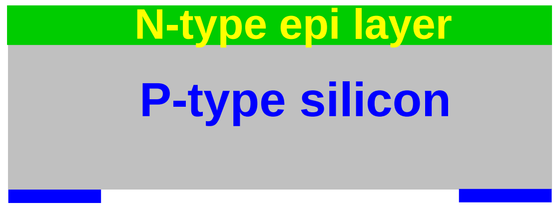




(1) LPCVD Si_3N_4 1500 Å



(3) E-gun Al 5000 Å



(2) Pattern Si_3N_4

(4) ECE Stop

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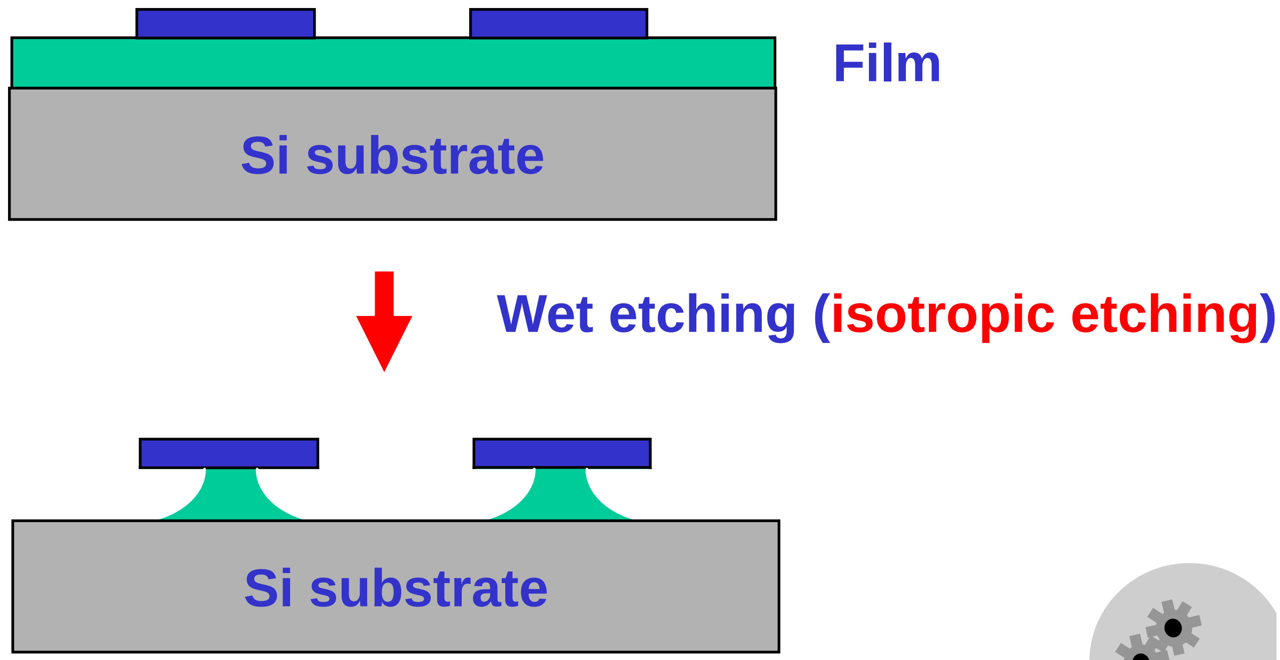
- **Single Crystal Silicon**

- **Thin films**

- In general, thin films are poly-crystal or amorphous materials
- No crystal-plane oriented anisotropic etching (wet etching)



Common Etchant for SiO_2

- HF
  - + Buffer HF - add NH_4F to HF to control pH yield
  - + etching rate depends on density, residual stress, and microstructures of SiO_2
  - + toxic
  - + can not store in glass bottle

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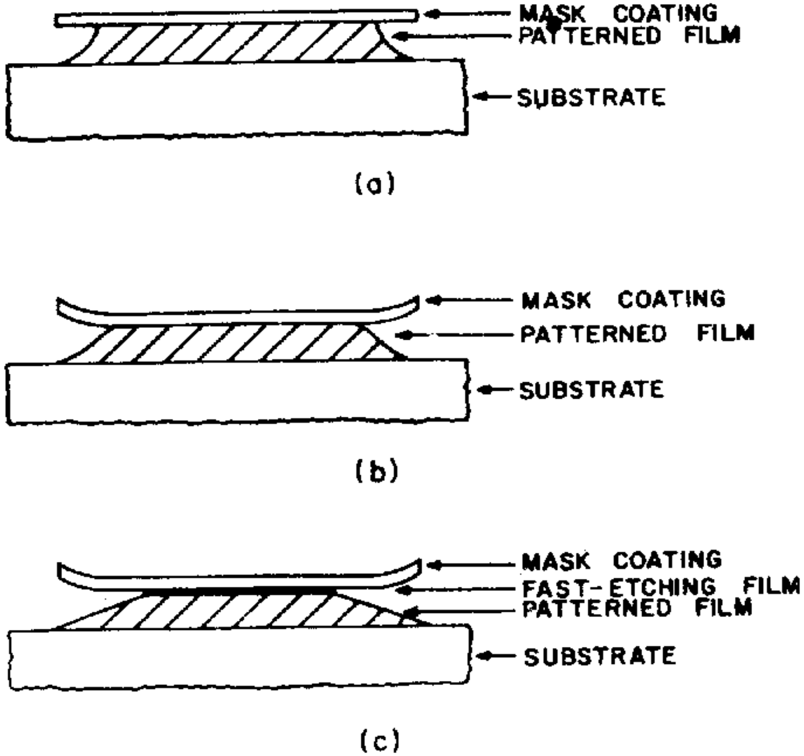
- **Undercut of the thin film structure**



Thin Film Processes edited by J.L. Vossen and W. Kern, 1985.

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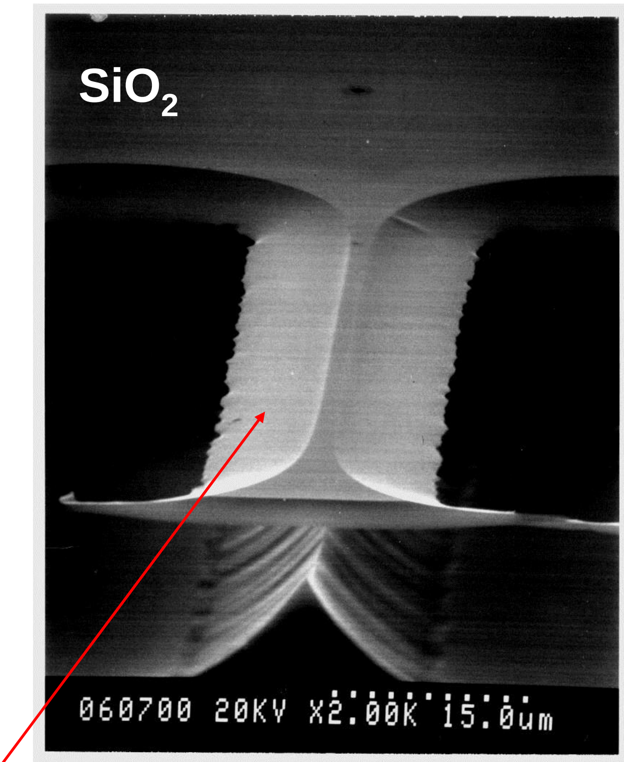
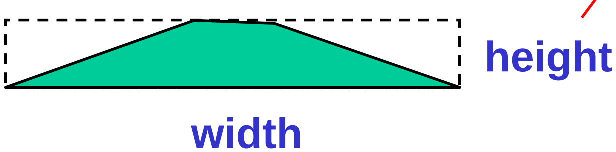
- It takes longer time to pattern very thick film
  Undercut effect significantly influence structure dimensions





Cross-section of the beam

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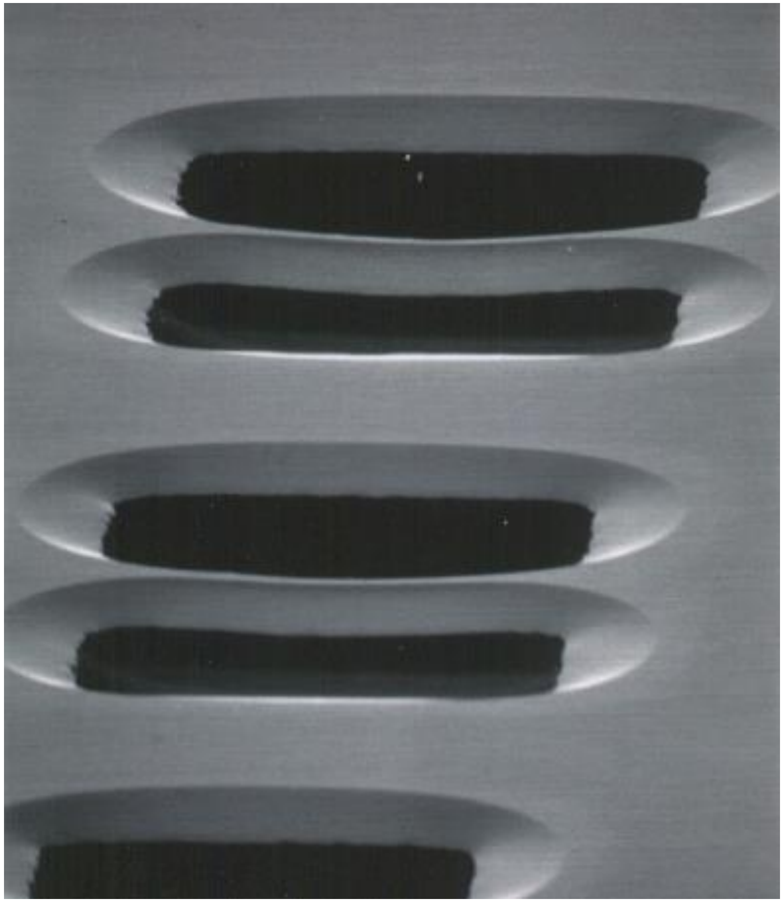

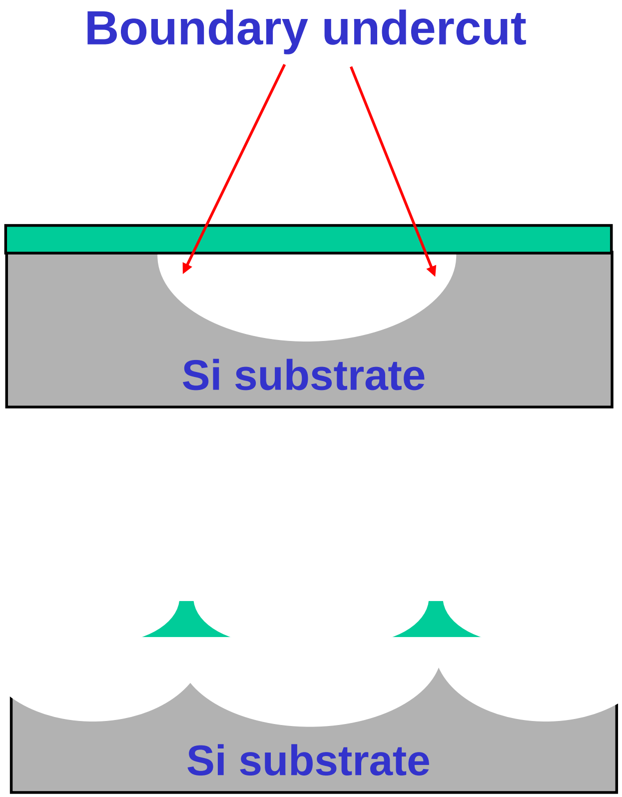

Boundary undercut
Si substrate
Si substrate

- The undercut effect can be exploited to **prevent step coverage**, if additional layers are to be deposited subsequently
- The undercut effect can also be applied to **smooth the edge of the structure**

W. Fang, Ph.D. thesis, 1995

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Common Etchant for Metal

- **Au etchant (type TFA)：at 25℃ etching rate 28 Å /sec**
- **Al etchant (type A)：at 50℃etching rate 100 Å /sec**
- **Ni etchant (type TFB)：at 25℃ etching rate 30 Å /sec**
- **Cr etchant： Cr-7**

- Etching techniques can be characterized as

  + Wet chemical etching

  + Dry etching

    Ion etching - ion milling and sputter etching (physical)

    Plasma etching (chemical)

    Reactive ion etching (RIE) (physical + chemical)

  + Lift off

2.3.2 Ion Etching (Physical)

Reading : J.L. Vossen and W. Kern, 1985.

- Ion etching - to remove atoms from substrate surface by bombardment with energetic ions (i.e. physical process)
- Ion etching contains two different approaches: (1) ion milling (or ion beam etching), and (2) sputter etching
- Ion milling - ions are generated in a plasma remote from substrates and subsequently accelerated towards them
- Sputter etching - the substrates are an integral part of the cathode of a parallel plate discharge
- Anisotropic etch (substrate orientation) and low selectivity

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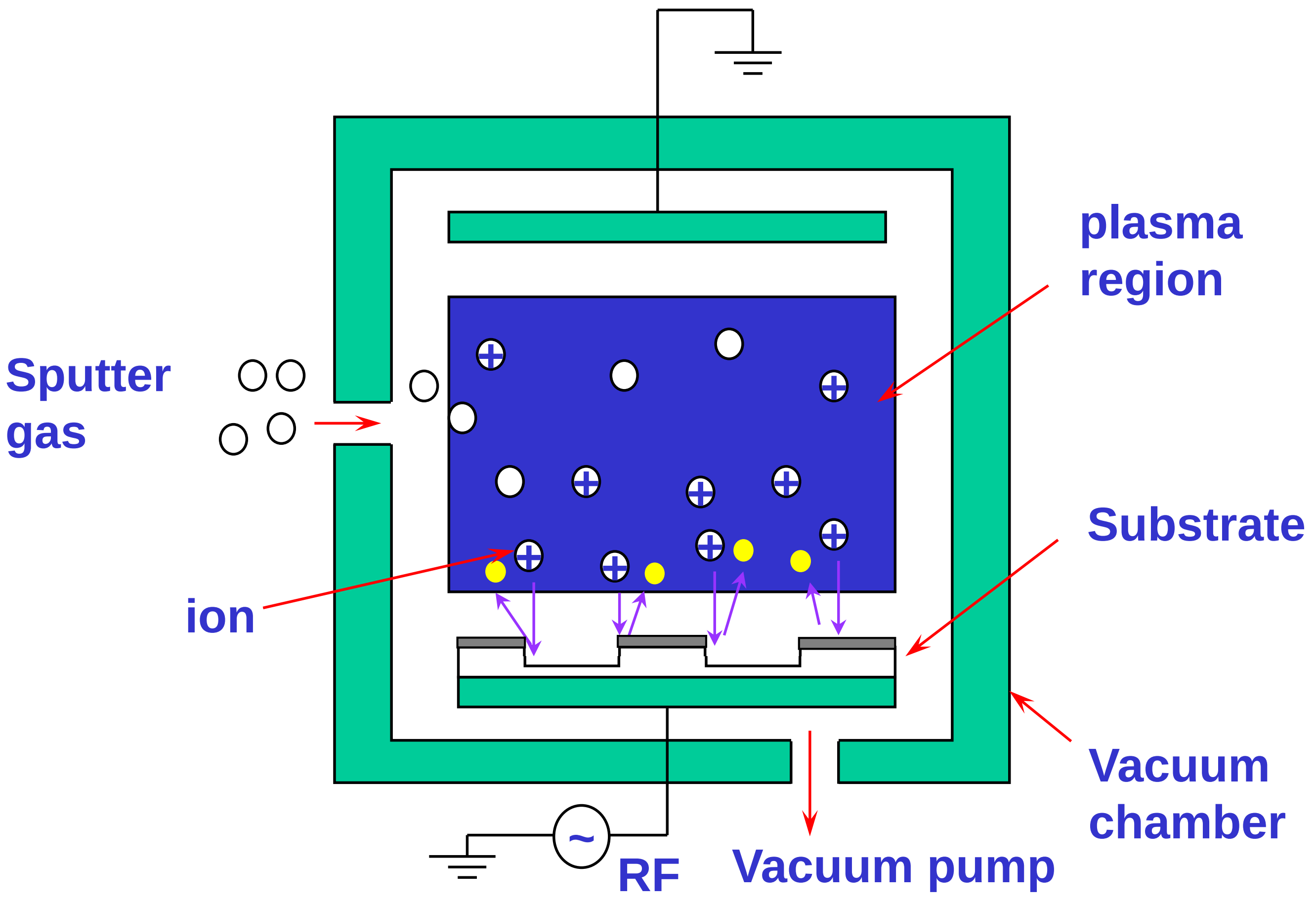
Sputter Etching

- Sputter etching - to etch the substrate by the bombarding of high energy ions generated by plasma



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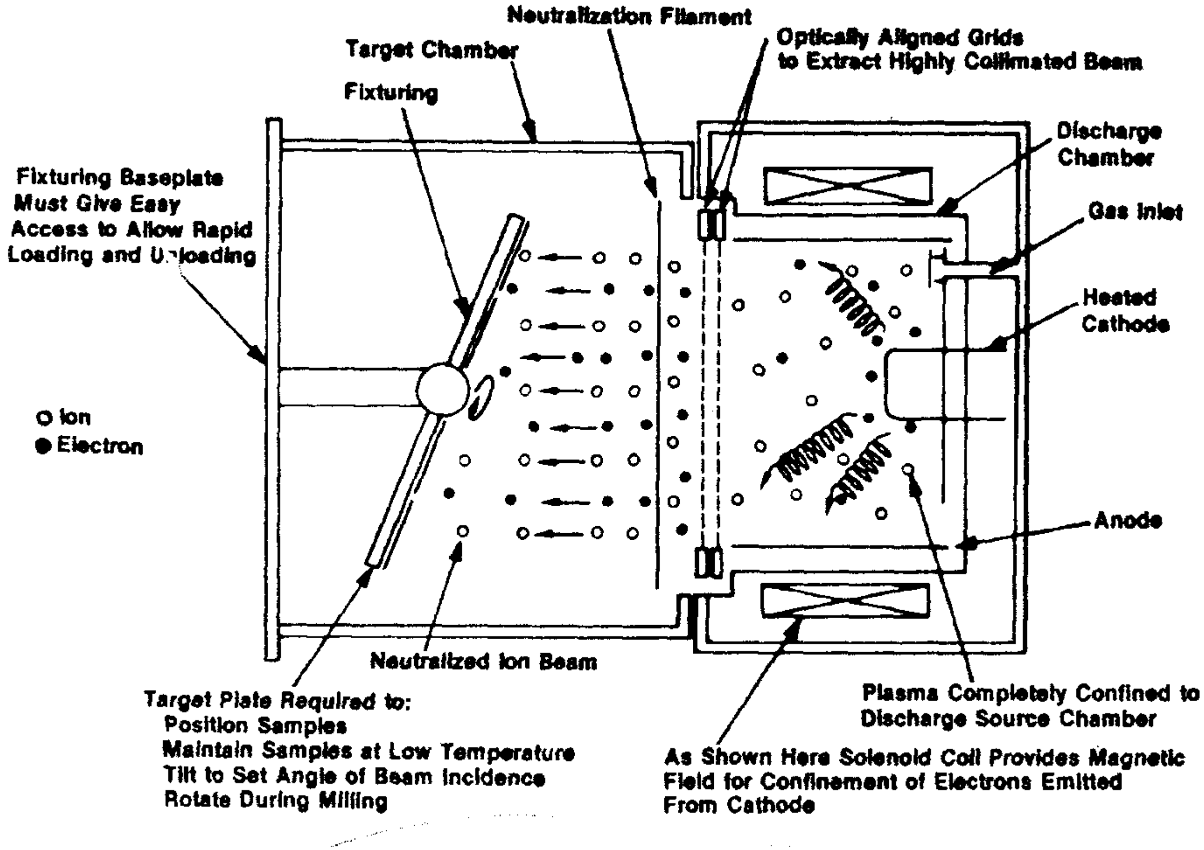
Ion Milling

- **Ion milling - ions are generated in a plasma remote from substrates and subsequently accelerated towards them**



L.D. Bollinger, Solid state technology, 1983.

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Basic Steps in Ion Milling

- Electrons are emitted from the cathode filament
- Emitted electrons are accelerated toward the anode and their path length is increased by the magnetic field
- Neutral gas atoms in discharge chamber will then be impacted and ionized by accelerated electrons
- Ions created in the discharge chamber are extracted and formed into an ion beam by a set of grids
- Electric potential corresponding to the ion beam energy required for ion milling is applied across a parallel set of grids
- Accelerated ions are neutralized by a neutralization filament to prevent space charge effect

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Etching Rate

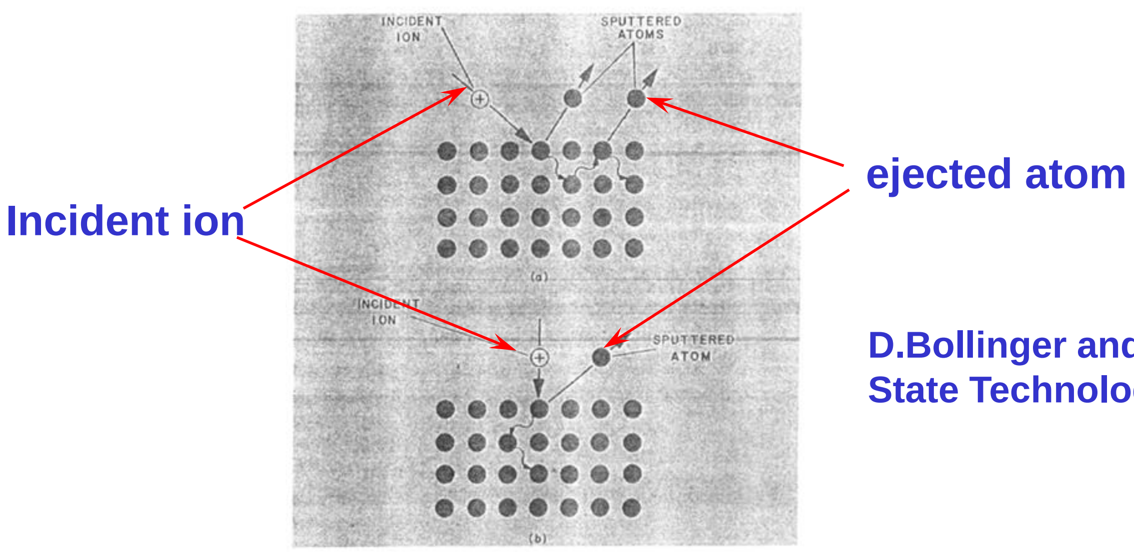
- **The factors determining sputtering yields, and consequently ion milling rates are**

  + Target material - binding energy

  + Beam energy - momentum of the bombarding ions

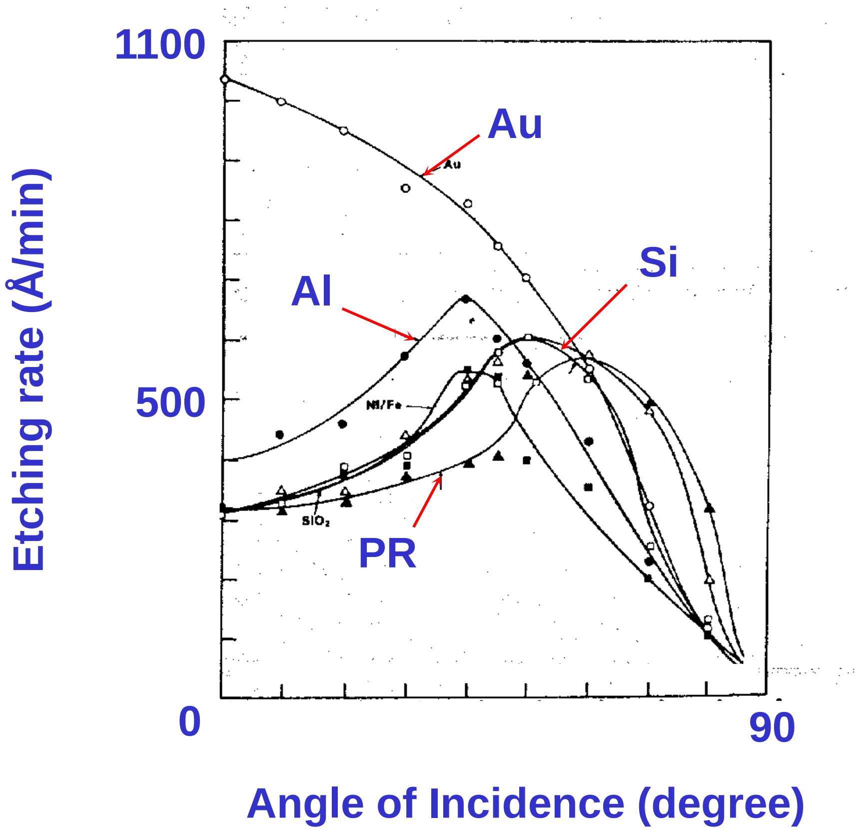
  + Impact angles

  + Gas type - mass (momentum) of the ion



D.Bollinger and R. Fink, Solid State Technology, 1980.

- **Etching rate vs Impact angle for different materials**



D.Bollinger and R. Fink, Solid State Technology, 1980.

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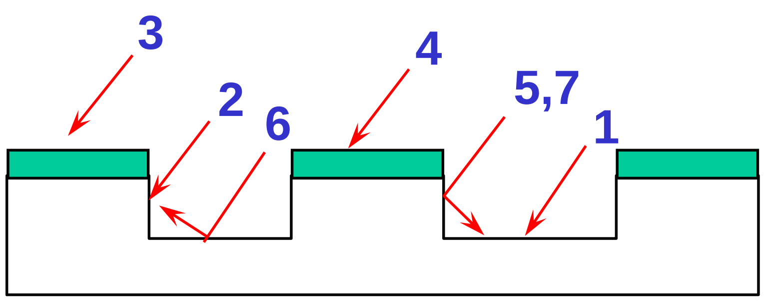
Basic Physical Effects during Impact

1. The **base** of the groove is etched by **direct impingement** of ions
2. The **wall** of the groove is etched by **direct impingement** of ions
3. The **etching mask** is etched by **direct impingement** of ions
4. The area near the base of wall is **shadowed** by etching mask and step
5. Etching rate of the base near wall is increased by the **ions reflecting from the wall**
6. **Redeposition** of the material from the base of the groove onto the wall
7. **Redeposition** of the material from the wall onto the base of the groove



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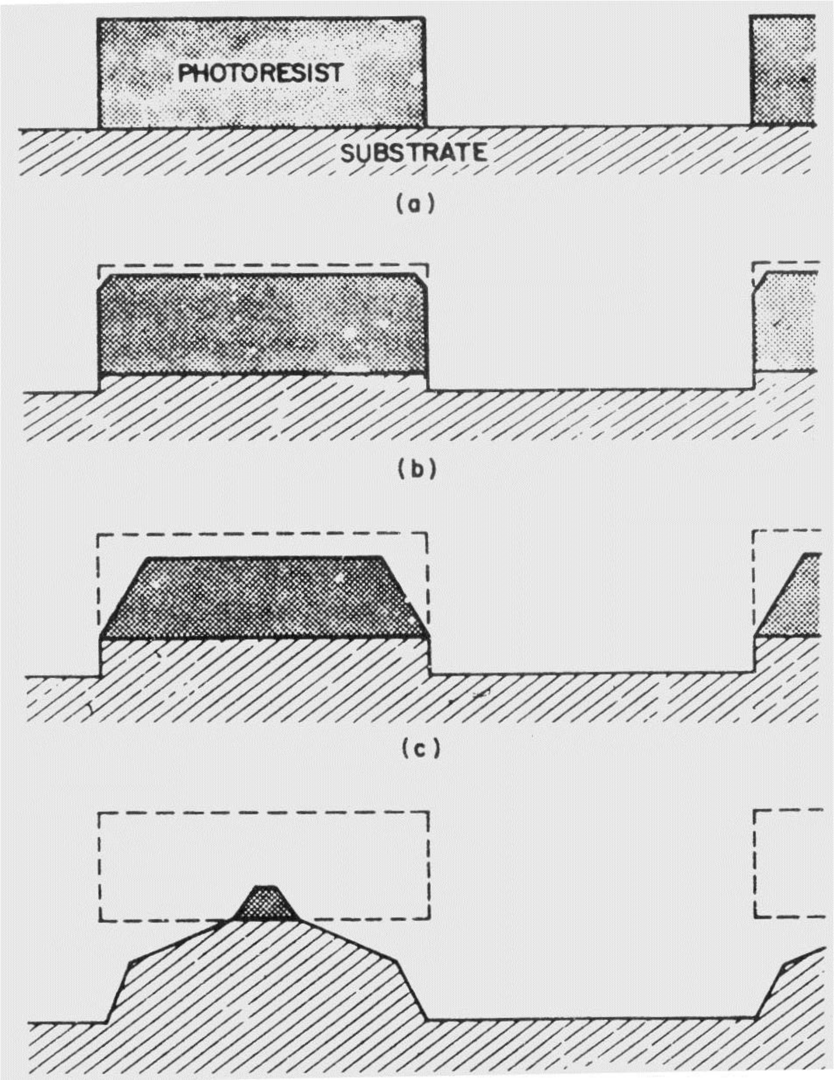
Facets



Thin Film Processes edited by J.L. Vossen and W. Kern, 1985.

- Facets is due to the effect No. 3
- The angle formed on the photoresist is the angle of maximum etching rate with respect to the beam
- The thin film can be etched even when much of the resist remains
- The angle formed on the thin film is also the angle of maximum etching rate with respect to the beam
- Increase the thickness of photoresist can protect thin film

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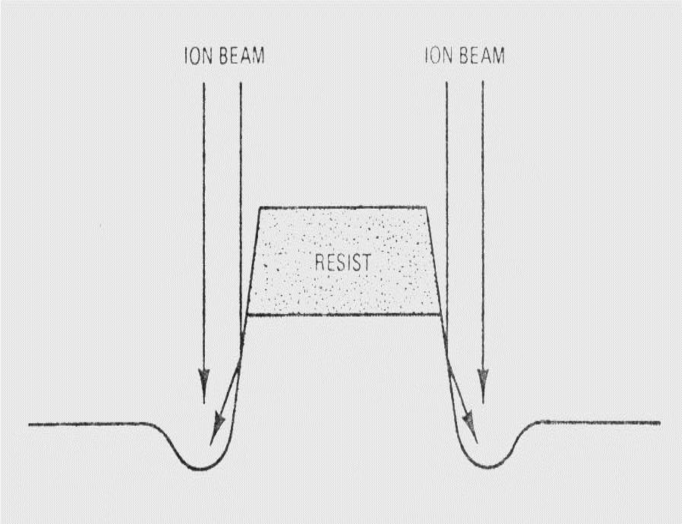
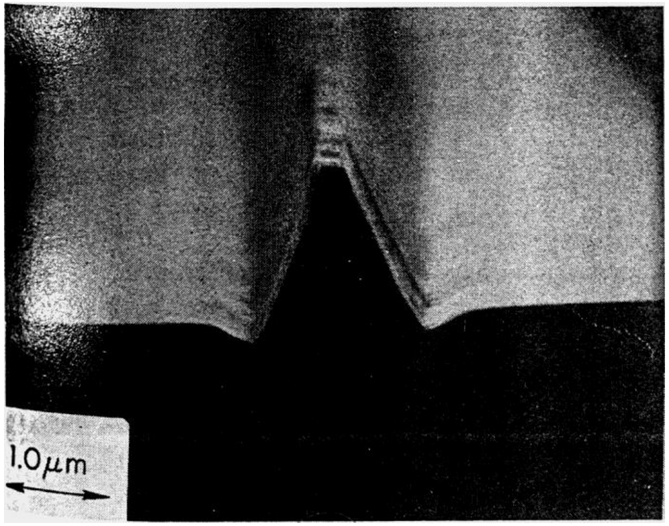
Trenching

- Trenching is formed by the effect No. 5
- Trenching can be easily eliminated by increasing the angle of incident ion beam (however, sputter etching can't)



D.Bollinger and R. Fink, Solid State Technology, 1980.



P.G. Gloersen, J. of Vac. Sci. Tech., 1975.

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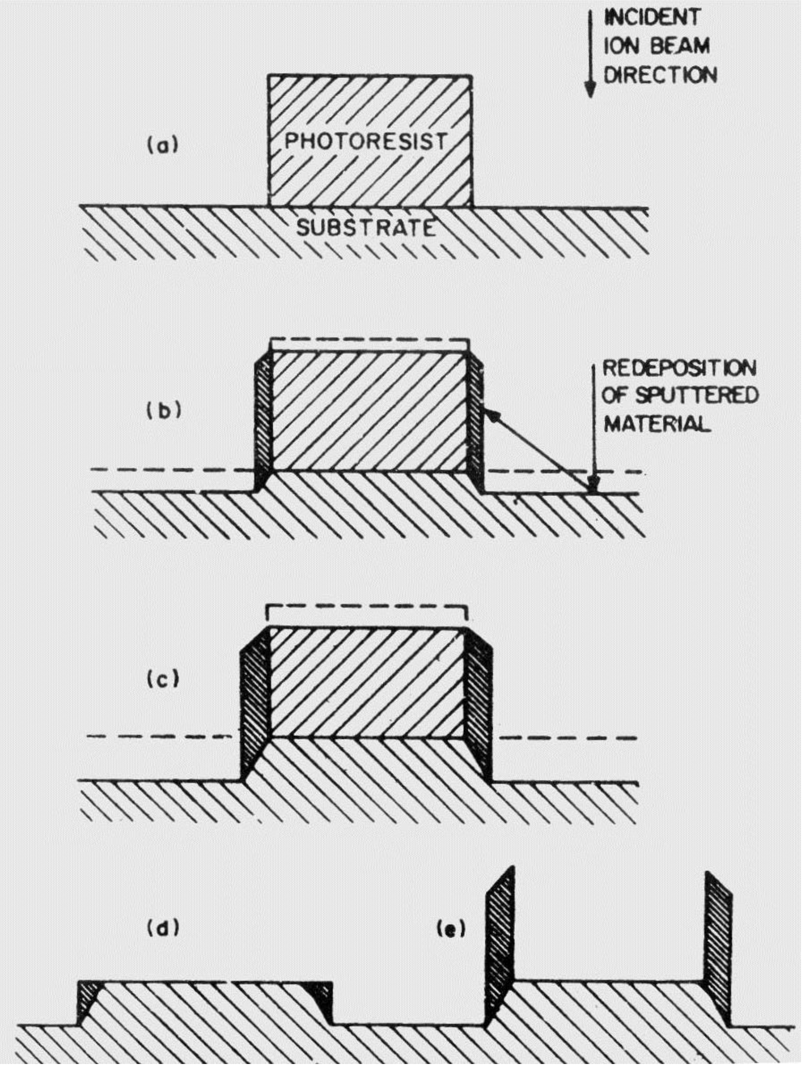
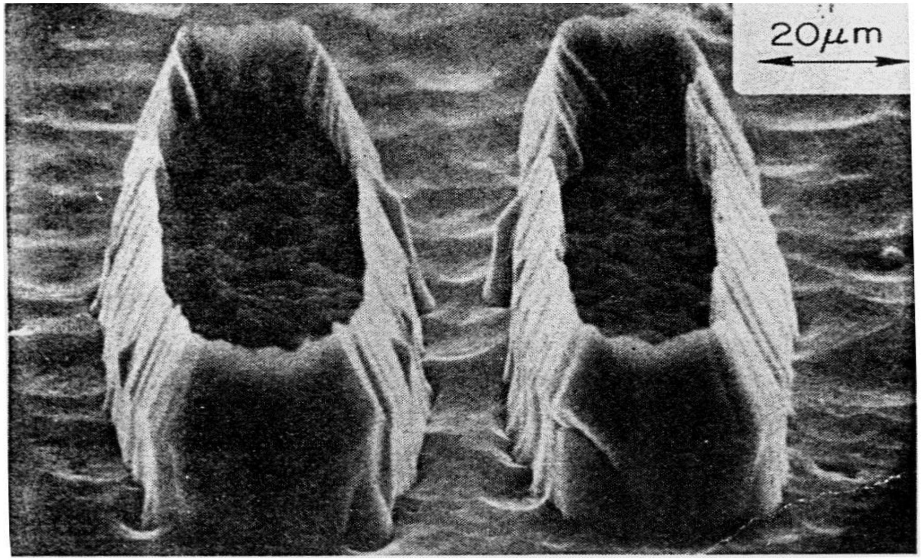
Redeposition



Thin Film Processes edited by J.L. Vossen and W. Kern, 1985.

- If redeposition rate by effect No. 6 is higher than the direct etching rate by effect No.2, thin layer will be left on sidewall
- Redeposition can be adjusted by:
  + Choosing the angle of ion beam such that the etch rate on wall slightly exceeds the redeposition rate
  + Removing the thin film left on the sidewall by etching with a very oblique ion beam at the end of ion milling



P.G. Gloersen, J. of Vac. Sci. Tech., 1975.

Advantages Over Sputter Etching

- Independent control over ion beam parameters
- Collimated ion beam - gives higher resolution
- Substrate etched outside of plasma region - no high energy electron bombardment
- Lower work chamber pressure - less contamination

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Ion Etching (physical) vs Wet Etching (Chemical)

- Advantages of ion etching over chemical etching
  - + Less resist undercutting, no limit to pattern size
  - + Insensitive to materials - any materials such as alloy or combination of material layers may be etched
  - + Dry process - less contamination, no capillary force
  - + Resist defects (eg. lack of adhesion) have little effect
- Disadvantages of ion etching over chemical etching
  - + Low selectivity
  - + Expensive equipment
  - + Lower throughput
  - + Sidewall redeposition

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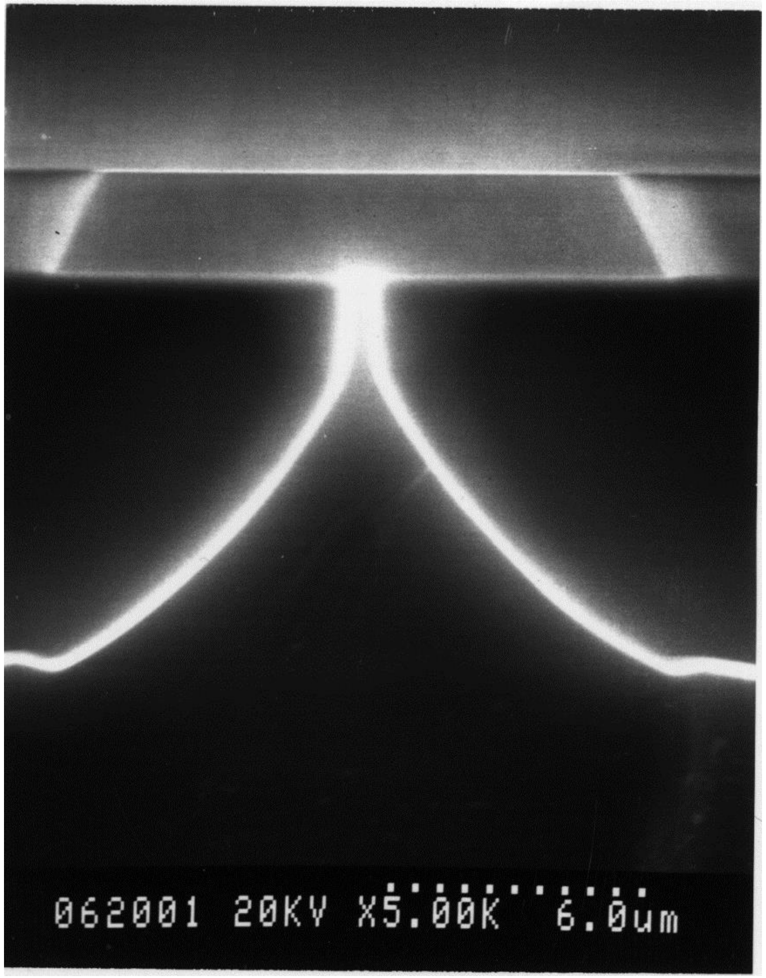

W. Fang, Ph.D. thesis, 1995

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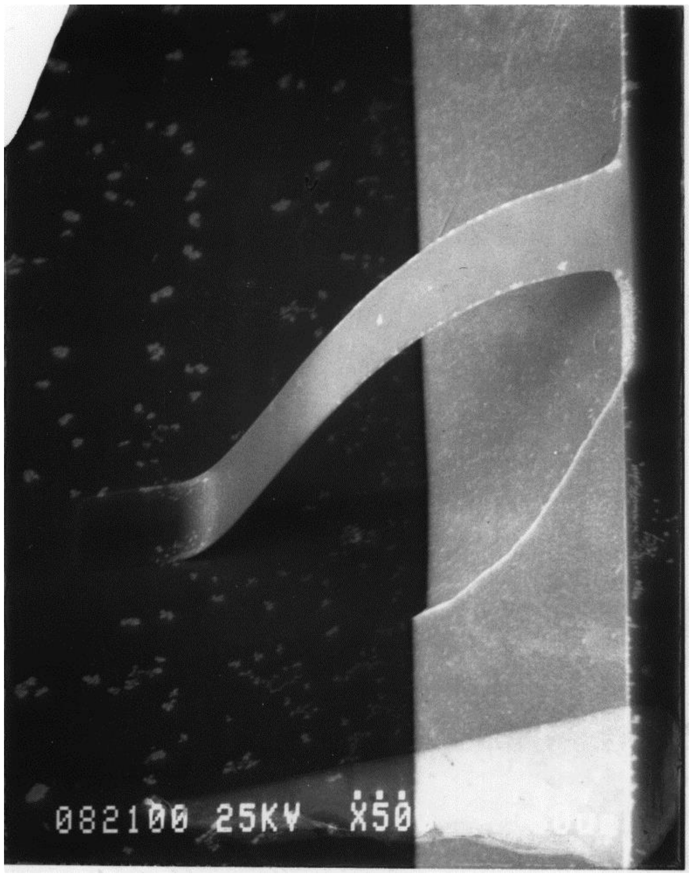

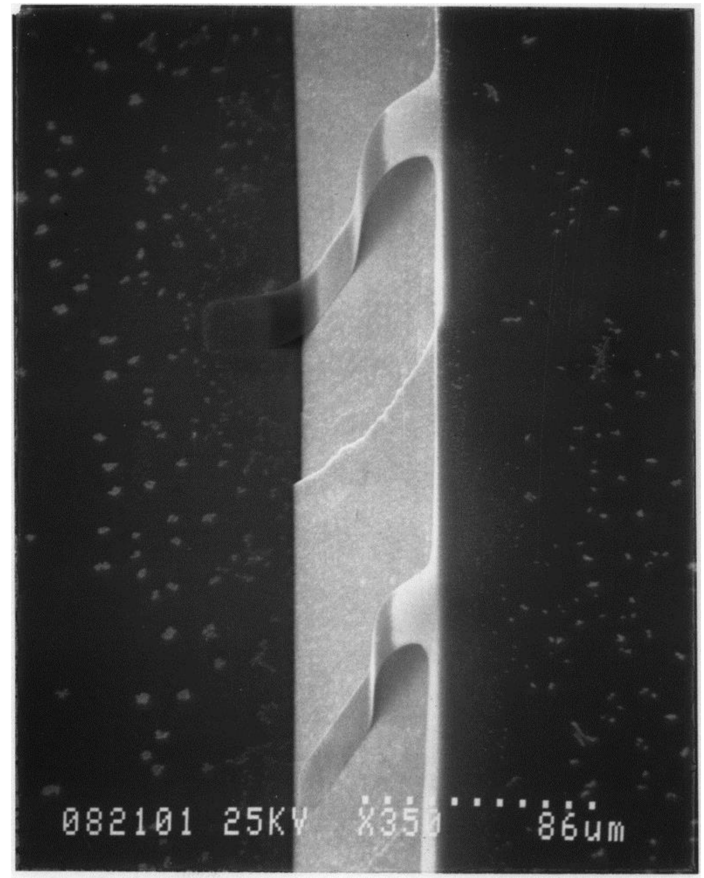

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When to Use Ion Etching

- When **undercutting** is not tolerable
- When **chemically inert materials** need to be etched (eg. gold)
- When a **combination of materials** need to be etched (eg alloys)
- When pattern geometry in the micron to sub-micron range

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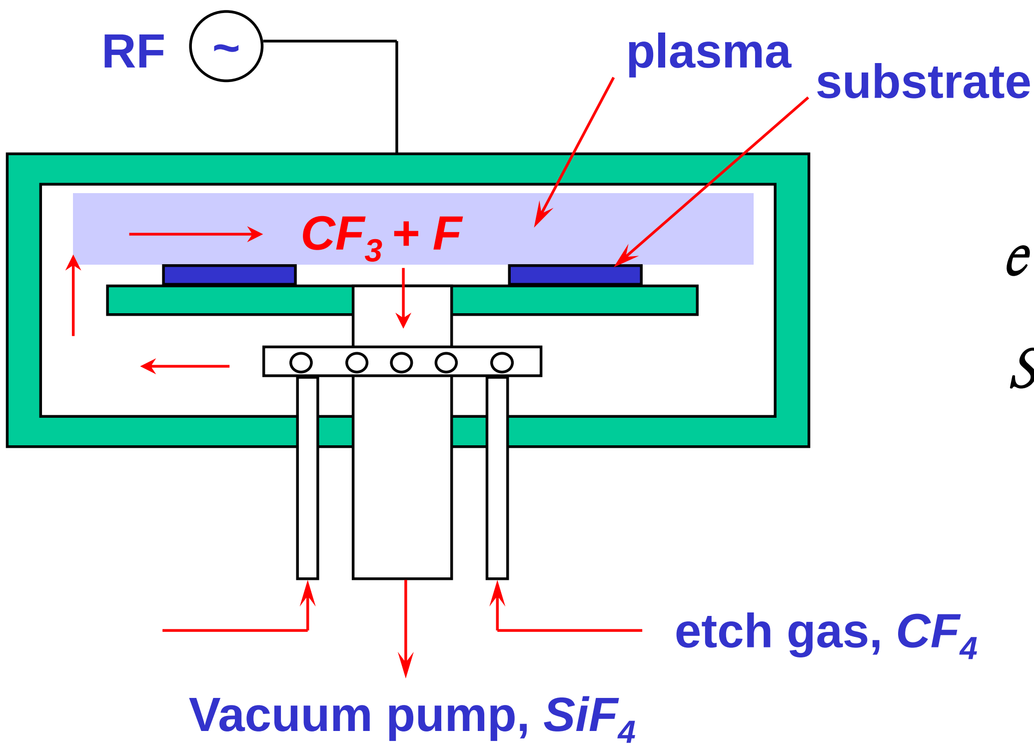
2.3.3 Plasma Etching (Chemical)

- Plasma etching - exploit plasma to generate active species (e.g. atoms, radicals) from a relatively inert molecular gas
  The active species will then react with the substrate to produce volatile products



$$e + CF_4 \rightarrow CF_3 + F + e$$

$$Si + 4F \rightarrow SiF_4$$

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Basic Steps in Plasma Etching

- Reactive species generated by plasma
- Species diffuse to the surface to be etched
- Species adsorbed by the surface
- Chemical reaction, formation of volatile by-product
- The by-product desorbed from the surface
- The desorbed by-product diffuse to the gas

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Plasma Etching vs Ion Etching

- Advantages

  + High selectivity (chemical)

  + Higher etching rate (chemical)

- Disadvantages

  + Undercut due to isotropic etch (chemical)

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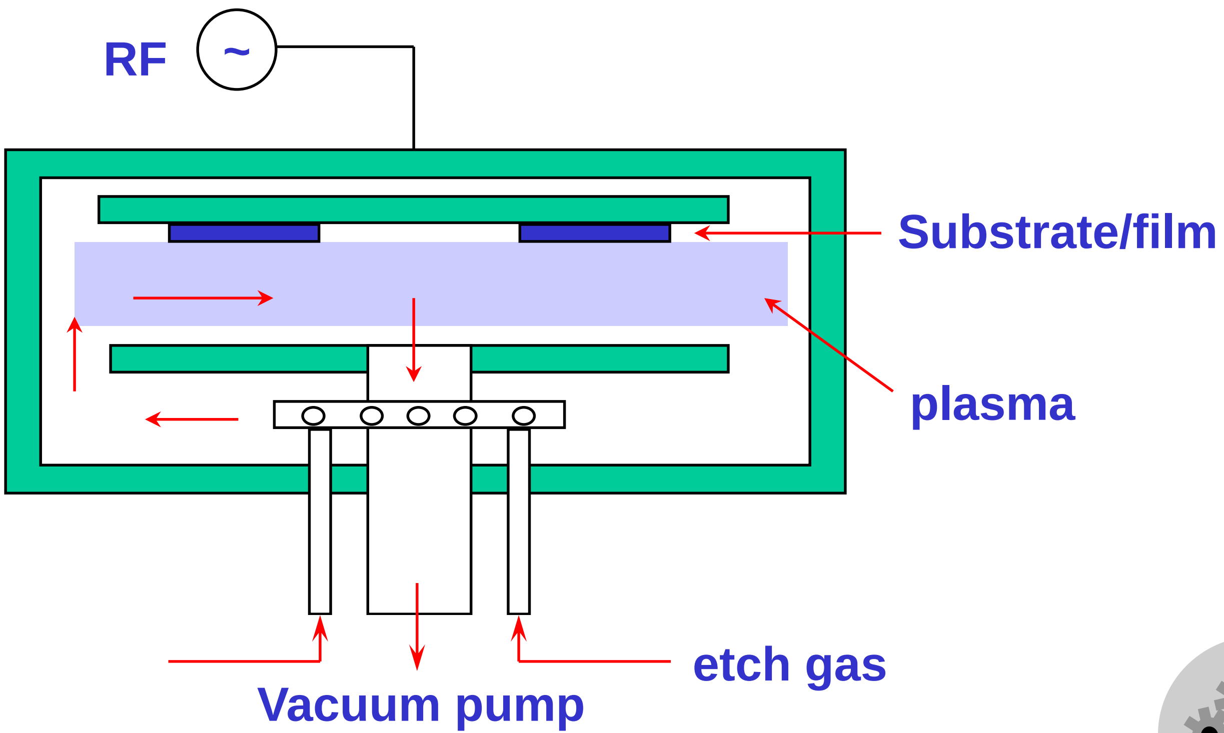
2.3.4 Reactive Ion Etching (RIE)

- RIE – the etching process including (1) ions reacting with substrate/film and remove atoms **chemically**, and (2) ions impact on substrate/film and remove atoms **physically**



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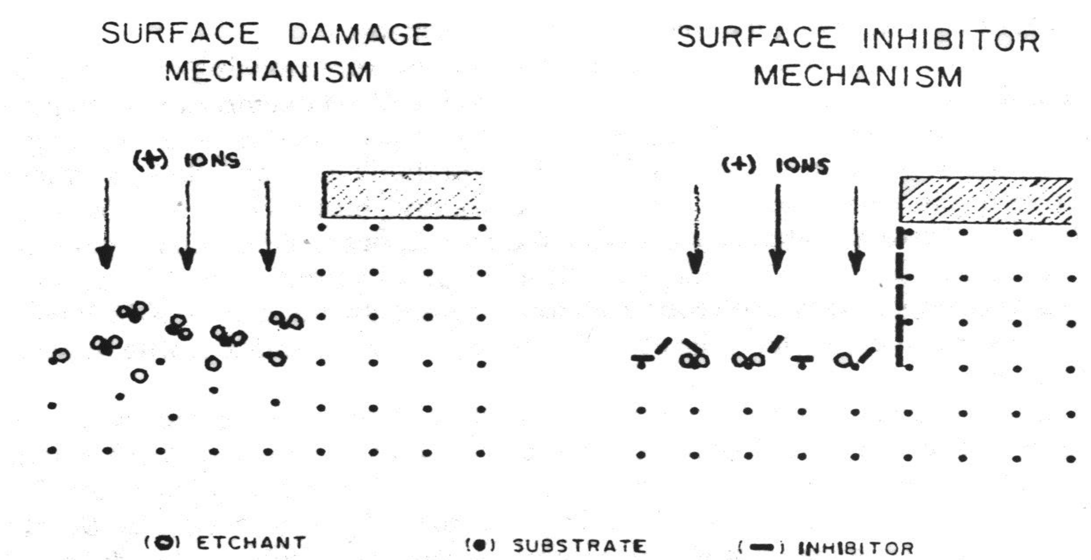
- **Two mechanisms to enhance the etching rate**

  + Surface damage - Relatively high energy impinging ions (> 50eV) cause lattice damage at the surface being etched
  -- Reaction at the damaged surface is increased

  + Surface inhibitor - Lower energy ions (< 50eV) provide enough energy to desorb nonvolatile polymer layers that deposit on the surface being etched



S. Wolf and R.N. Tauber, Silicon Processing for the VLSI Era Vol. 1, 1986.

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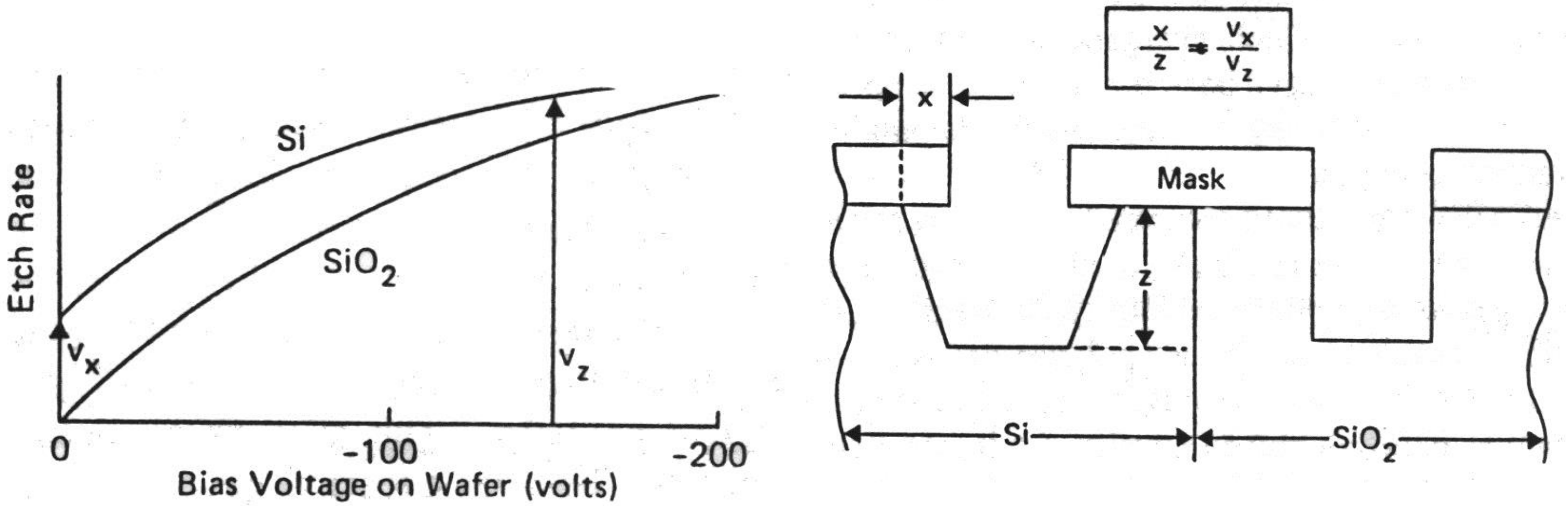
Control of Edge Profile

- The edge profile of etched wall can be controlled by the difference of etching rate in vertical and lateral directions

- Example 1



S. Wolf and R.N. Tauber, Silicon Processing for the VLSI Era Vol. 1, 1986.

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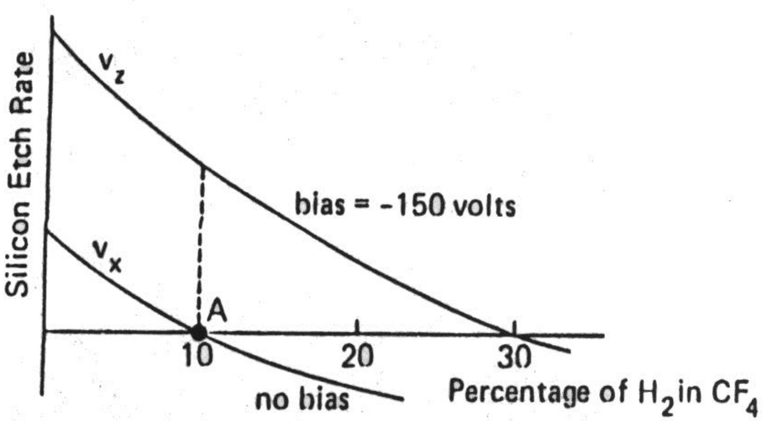
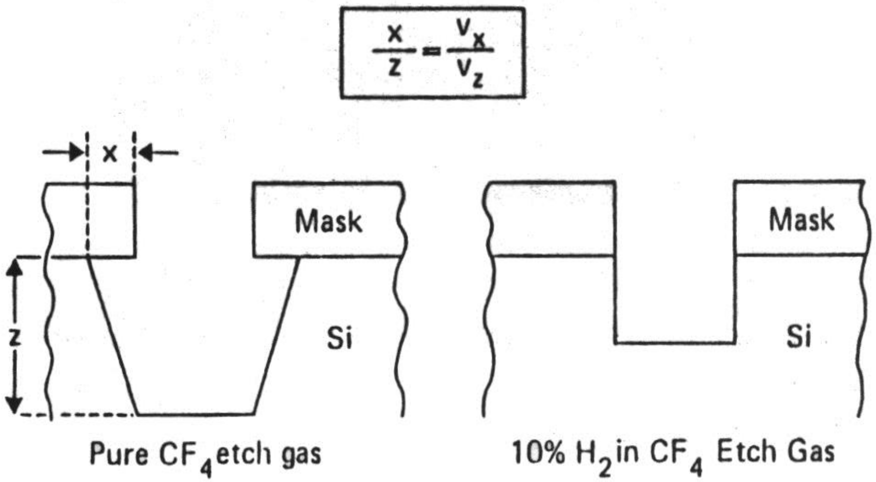
- **Example 2**

  + The Si etch rate is decreased if add H_2 to the feed gas

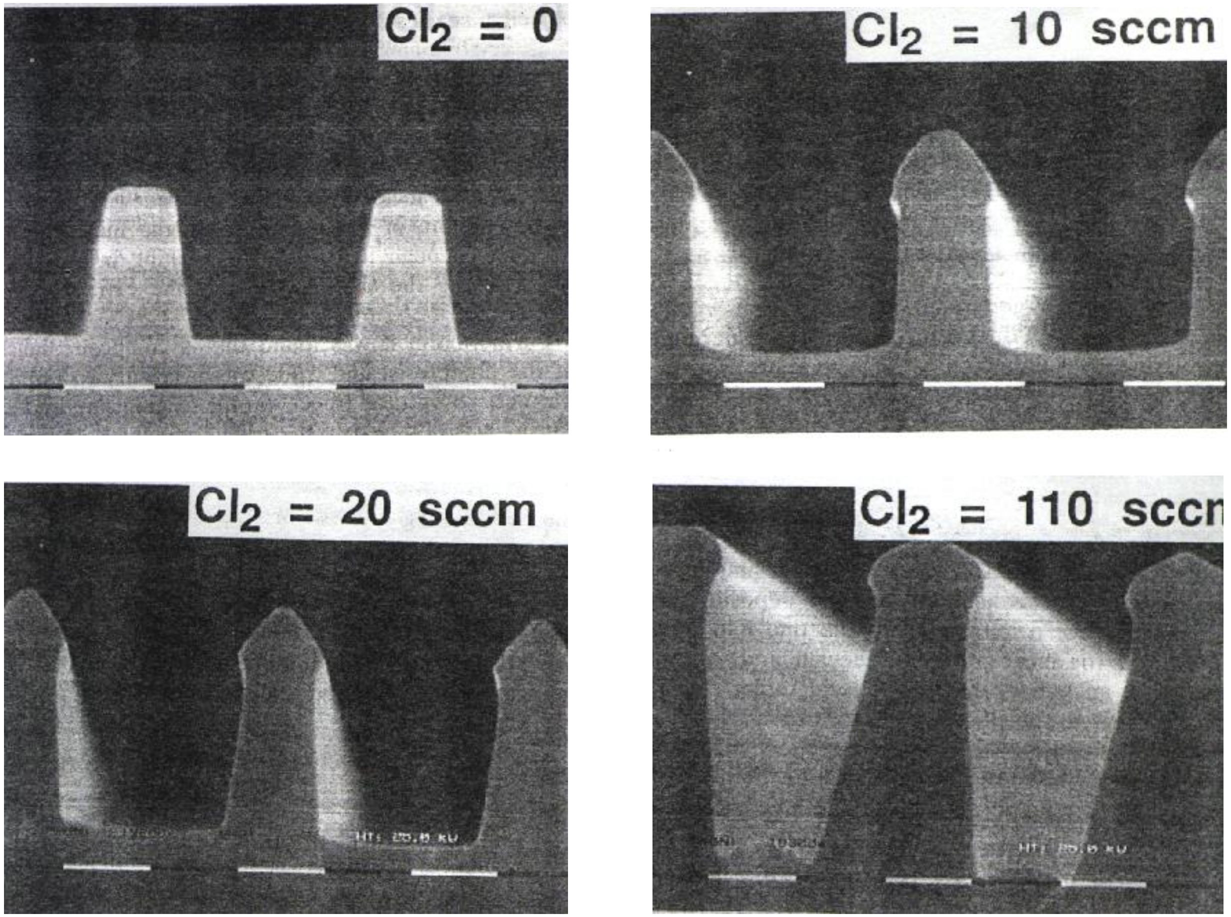
  + The etch rate of the surface without ion bombardment will decrease to zero at 10% value of H_2 concentration



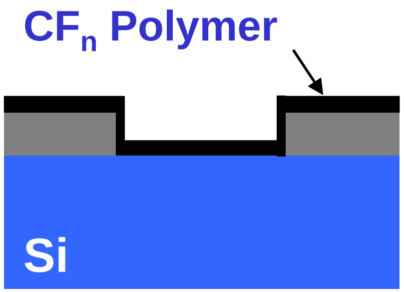


S. Wolf and R.N. Tauber, Silicon Processing for the VLSI Era Vol. 1, 1986.

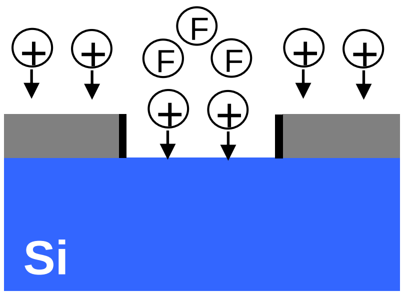
- **Variation of the edge profile with etching gas ($CF_4 + Cl_2$)**



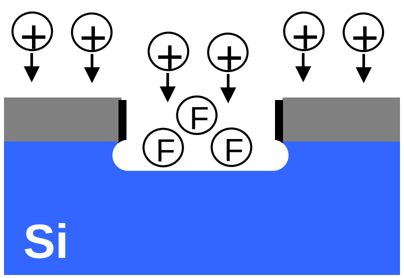
BOSCH DRIE Process



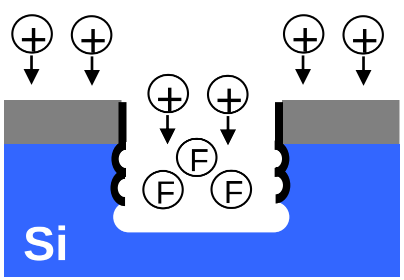
Passivation cycle: fluorcarbon polymer covers all surfaces. (Passivation gases: C_4F_8)



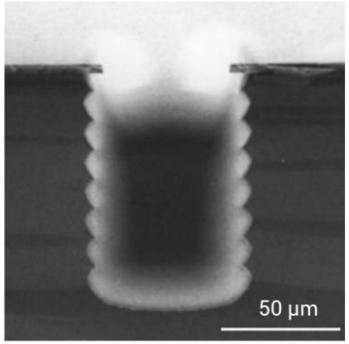
Etching cycle I: polymer removed from the base of trench by **ion bombardment.**



Etching cycle II: the exposed Si is etched **isotropically** by chemical reaction. (Etch gases: SF_6)



Continue passivation etching cycles



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RIE vs Plasma Etching and Ion Etching

- RIE is anisotropic etch
- RIE's selectivity is better than Ion Etching (chemical)
- RIE's etching rate is higher than Ion Etching (chemical)

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- **Etching techniques can be characterized as**

  + Wet chemical etching

  + Dry etching

  Ion etching - ion milling and sputter etching (physical)

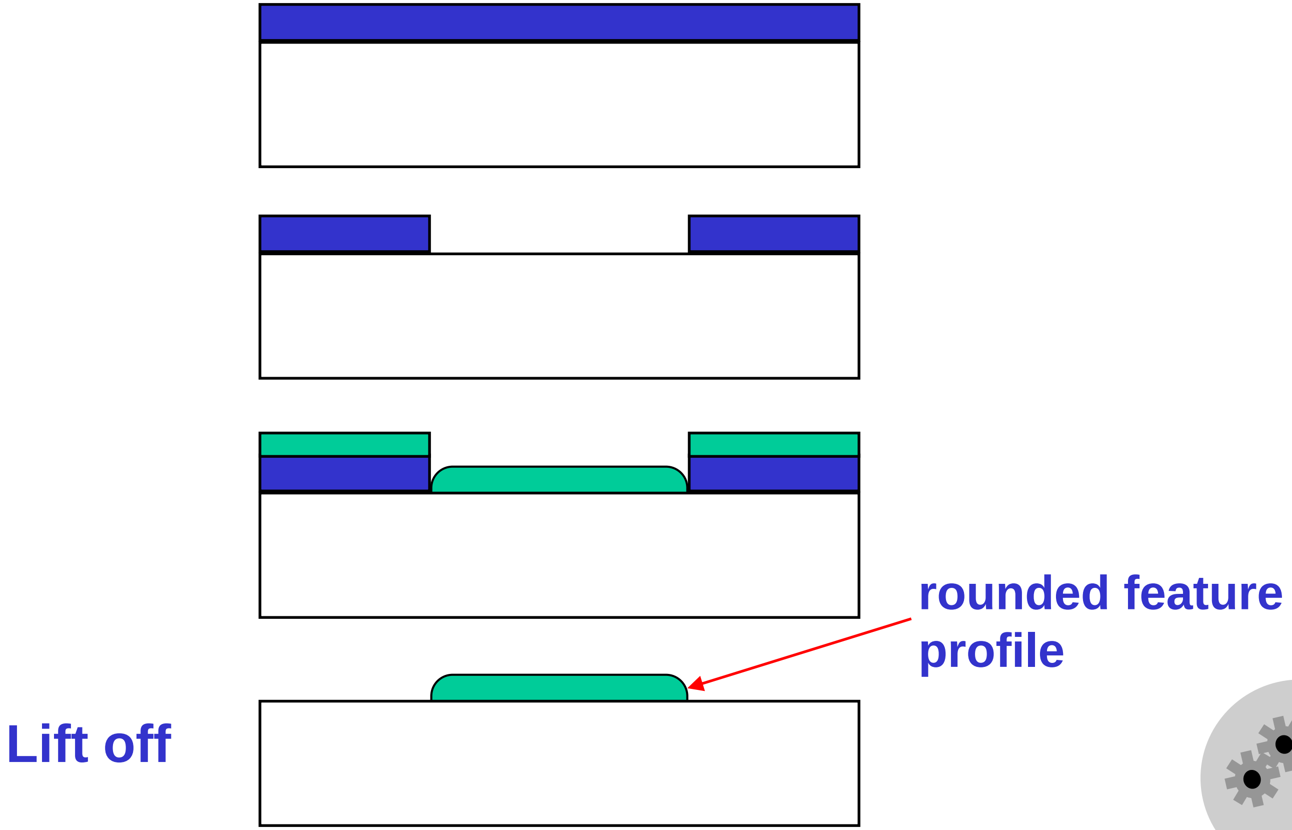
  Plasma etching (chemical)

  Reactive ion etching (RIE) (physical + chemical)

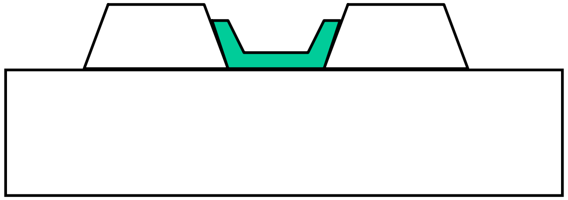
  + Lift off

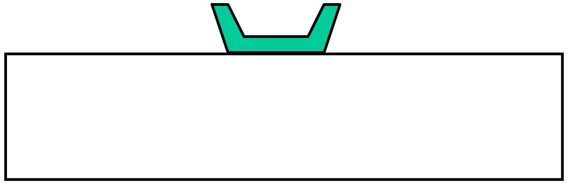
2.3.5 Lift off

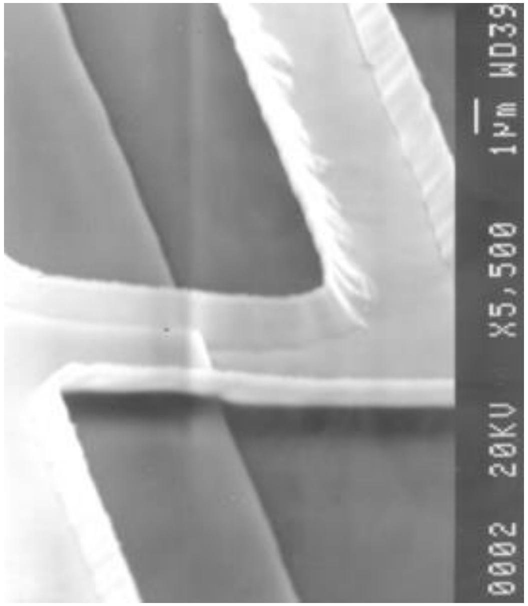
- **Lift off : to obtain the desired pattern by removing photoresist**
- **Disadvantages : (1) rounded feature profile, (2) temp. limitation**

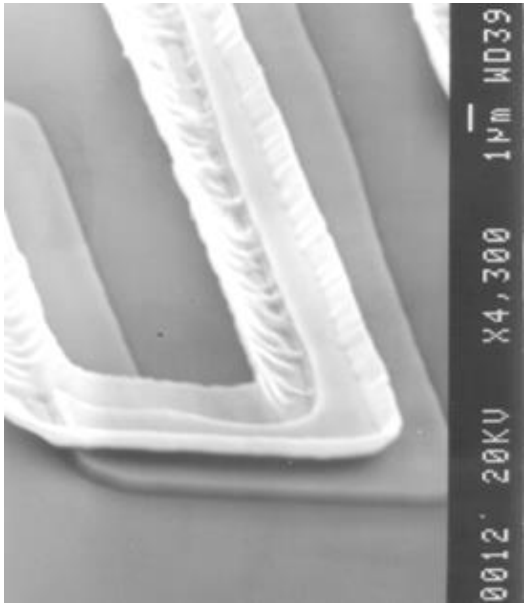


- **After lift off**









Conclusions

- Etching: key process to make 3-D micromachined structures
- Etching can be characterized as (1) dry and wet etching, and (2) physical and chemical etching
- Dry etching has the following advantages

  + thin film anisotropic etching available (physical)

  + no stiction

  + less contamination
- Wet etching has the following advantages

  + higher etching rate (chemical)

  + better selectivity (chemical)

  + cheap equipment

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