Outline

1 Introduction

2 Basic IC fabrication processes

3 Fabrication techniques for MEMS

4 Applications

5 Mechanics issues on MEMS

2. Basic IC fabrication processes

2.1 Deposition and growth

2.2 Photolithography

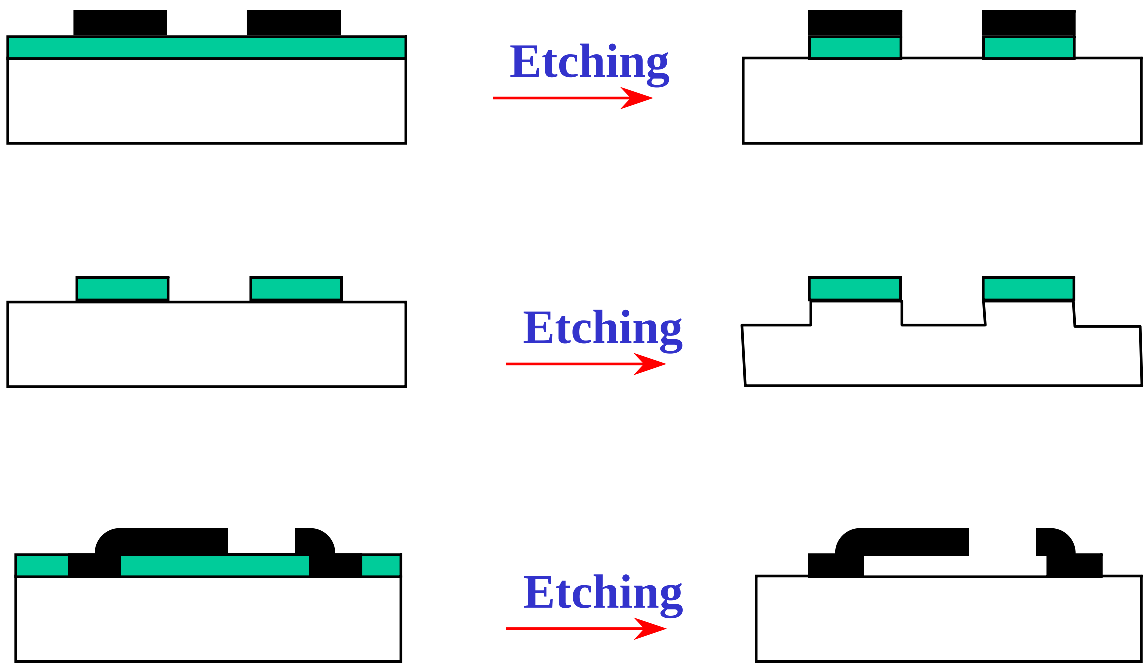
2.3 Etching

2.4 Bonding

2.3 Etching

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

- **Etching is the processes to remove unwanted thin film or substrate**



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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

- 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 - polycrystal or armorphous
  - Etching rate is crystal plane independent

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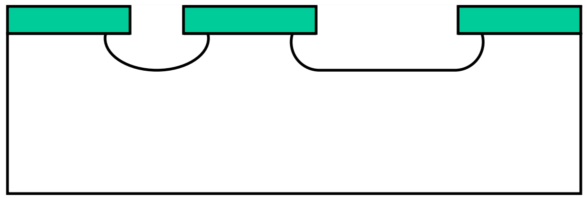
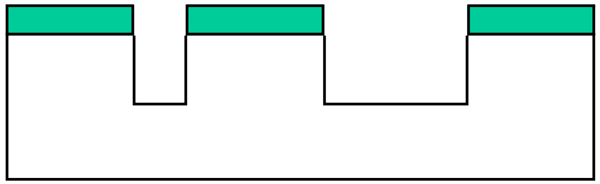
- **Isotropic and anisotropic**

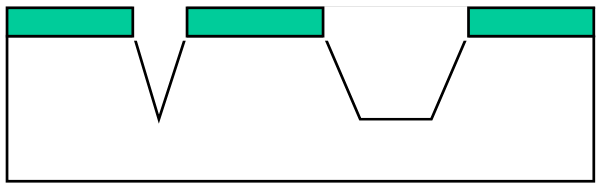
  + **Isotropic**



  + **Anisotropic**



Substrate Orientation



Crystal plane Orientation

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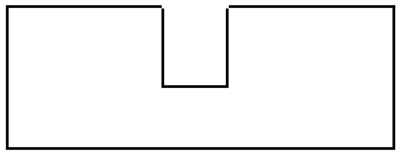
- **Selectivity**

  + **High selectivity**

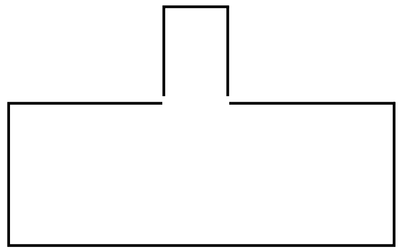
  + **Low selectivity**

- **Aspect ratio**

  + **High aspect ratio**

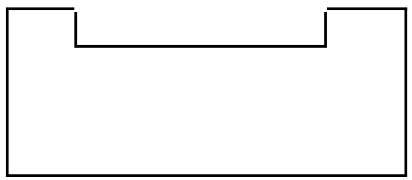


trench



post

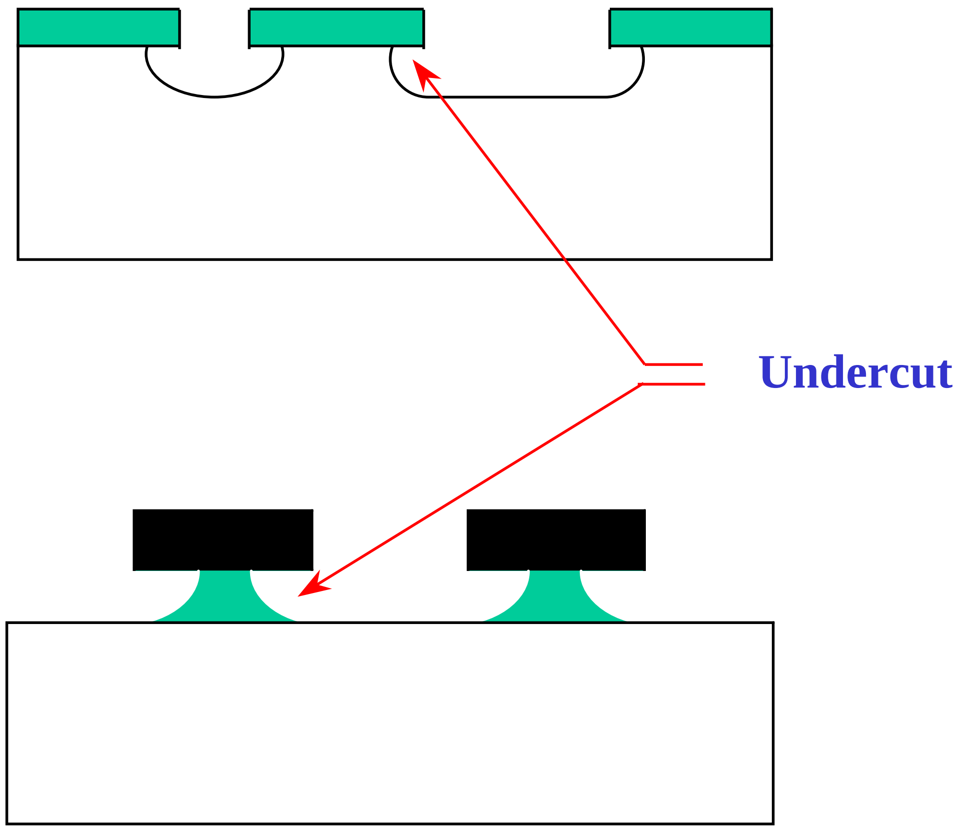
  + **Low aspect ratio**



recess

mesa

- **Undercut**



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- **Etching techniques can be characterized as :**

  + **Wet chemical etching**

  + **Dry etching**

    Ion etching - ion milling and sputter etching (physical)

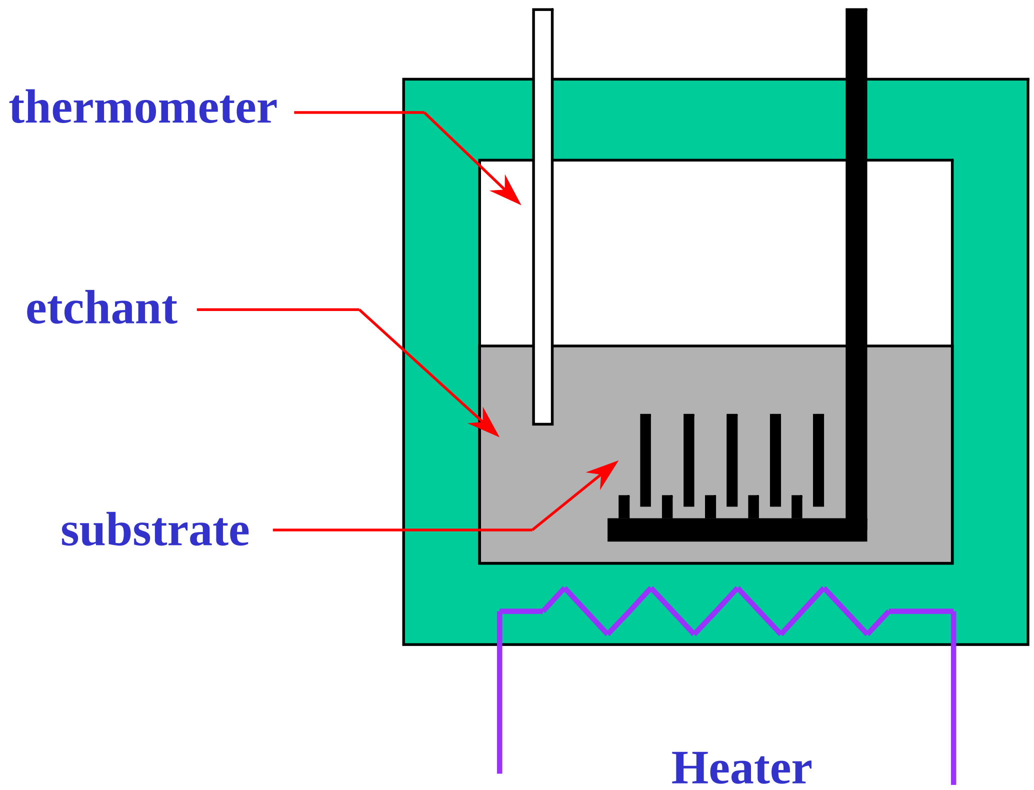
    Plasma etching (chemical)

    Reactive ion etching (RIE) (physical + chemical)

  + **Lift off**

2.3.1 Wet Chemical Etching

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



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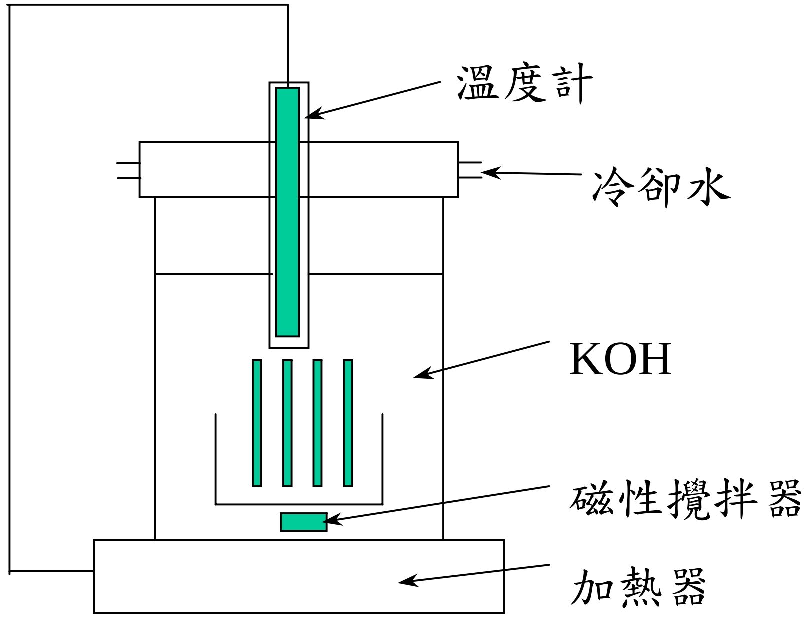

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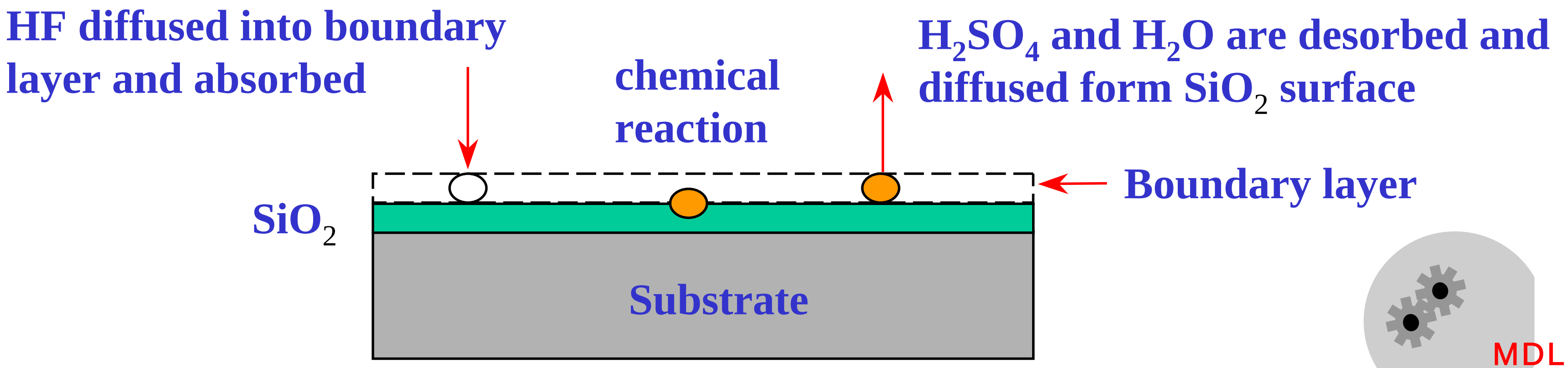
Etching Mechanism

- 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

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



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Etching Rate

- **Since the five steps of 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**

  + **The etching rate can be increased by increasing temperature if it is surface reaction rate limited**

  + **The etching rate can be increased by agitation if it is mass transportation rate limited**

- **Ultrasonic excitation is a very common agitation source**

- **The etching rate is also etchant solution dependent**

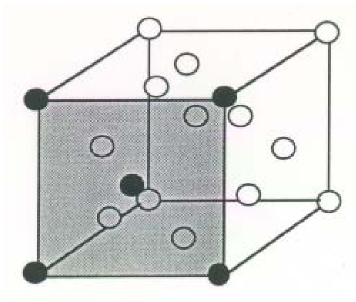
- **Single Crystal Silicon**

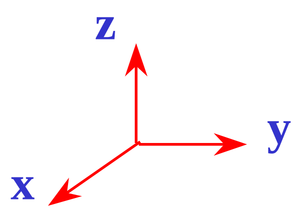
- **Thin films**

Single Crystal Silicon

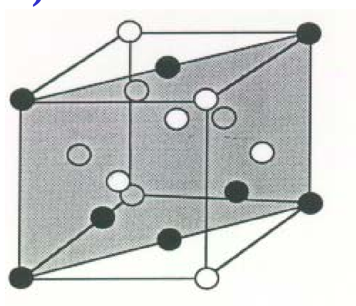
- Three important crystal planes in the silicon unit cell

(100)

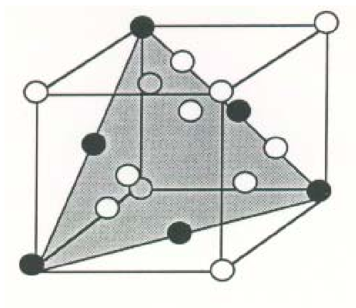




(110)

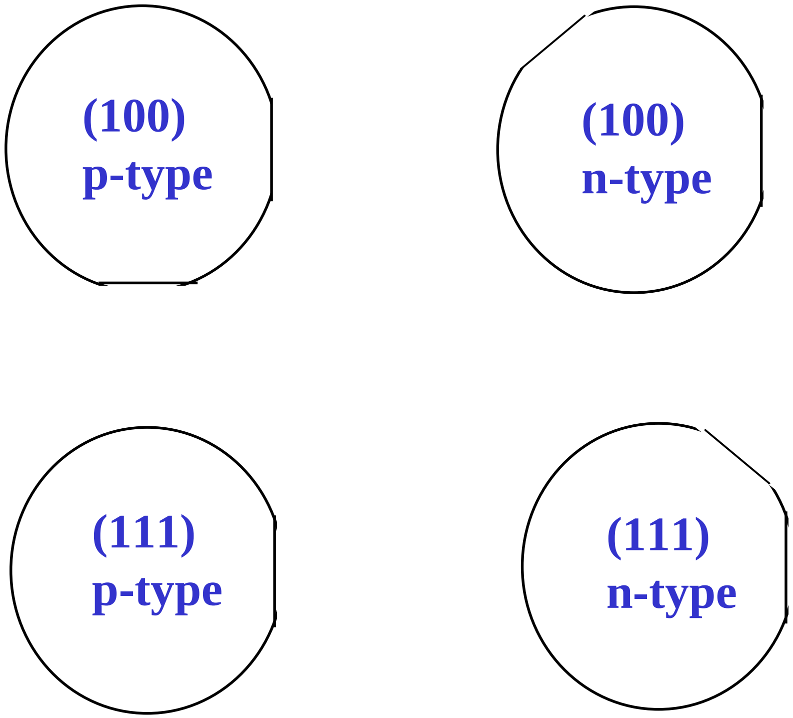


(111)



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

- **Flat edge indicate the crystal orientation of the Si substrate**



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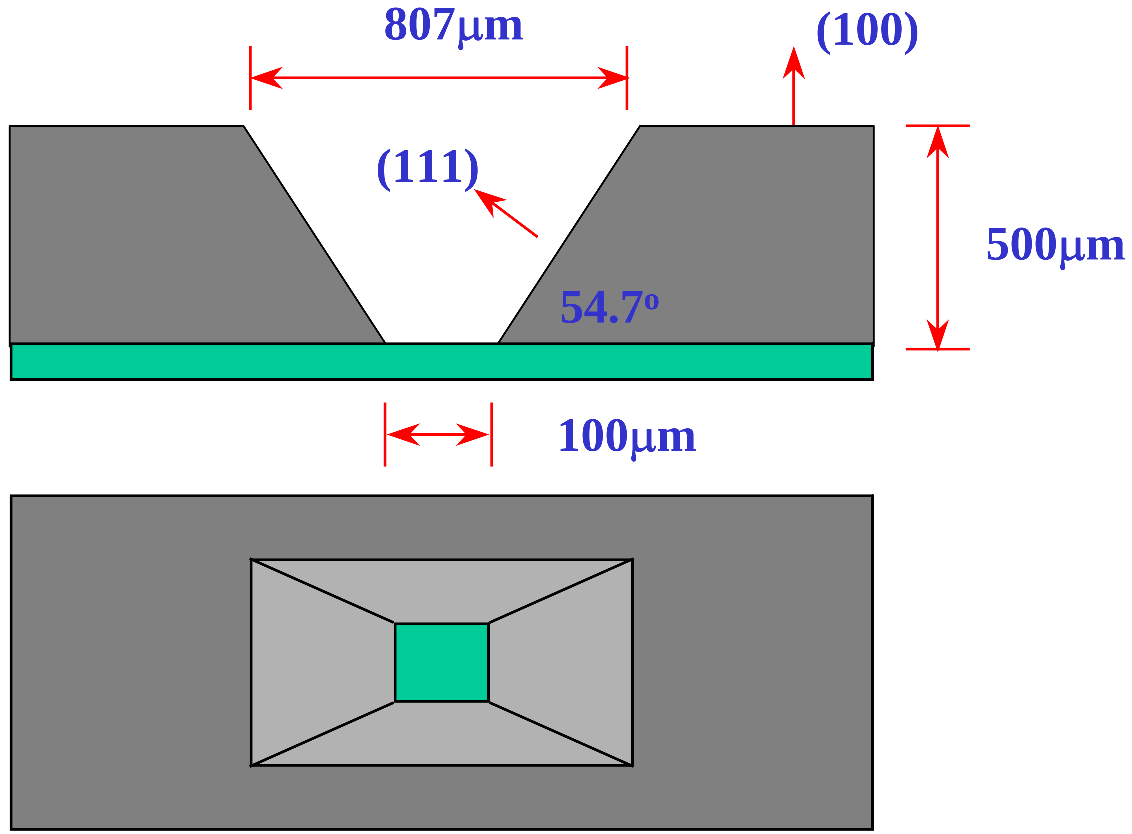
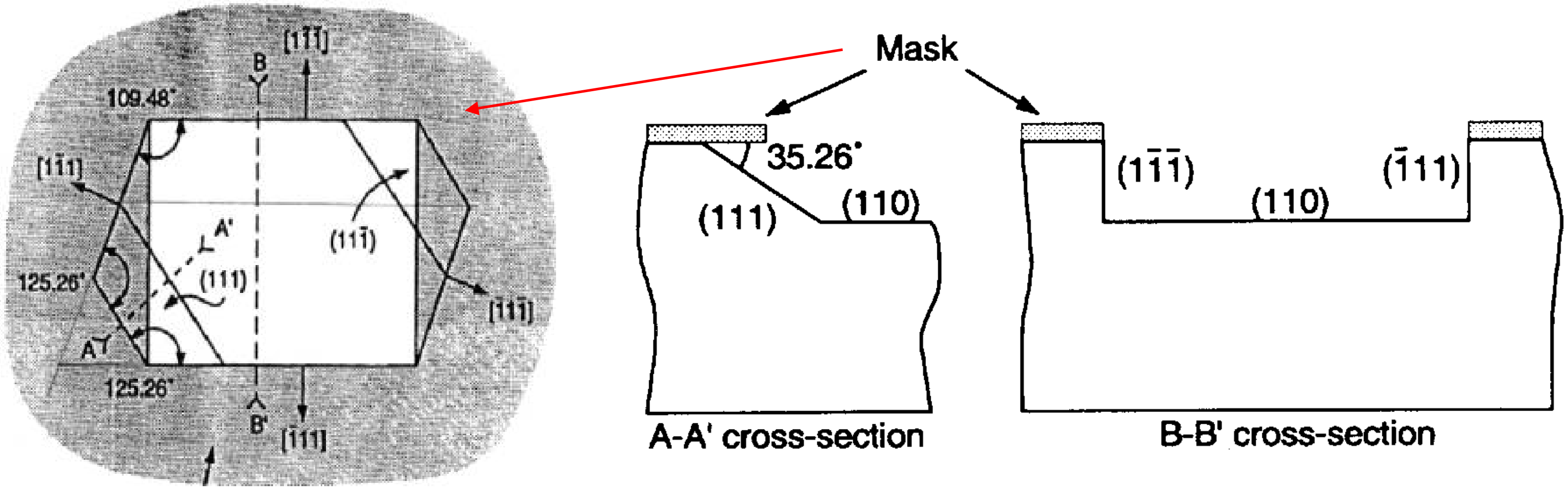
Anisotropic Etch

- Shape of (100) Si substrate after anisotropic etch



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



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

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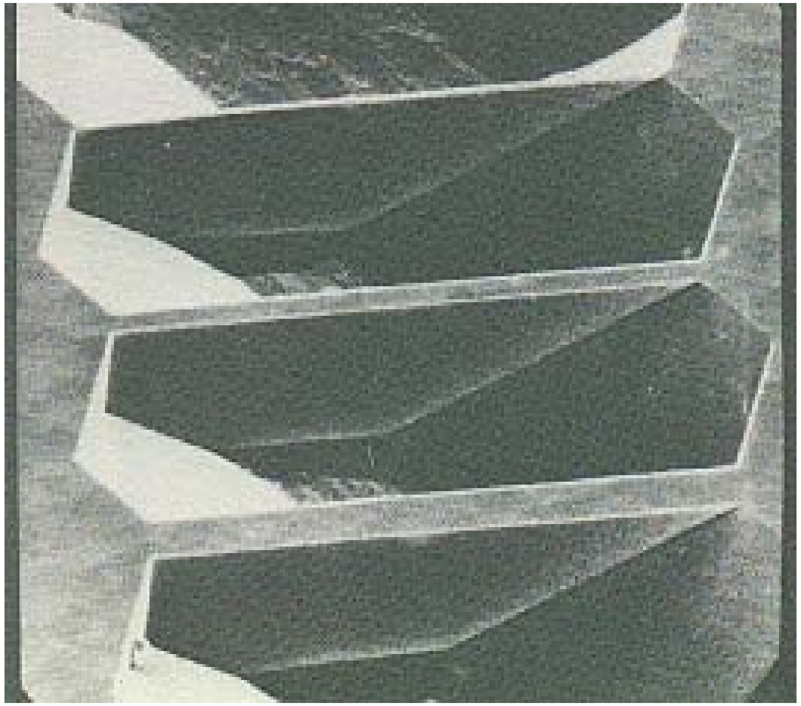

B. Hok, Integrated micro-motion systems, edited by F. Harashima, 1990.

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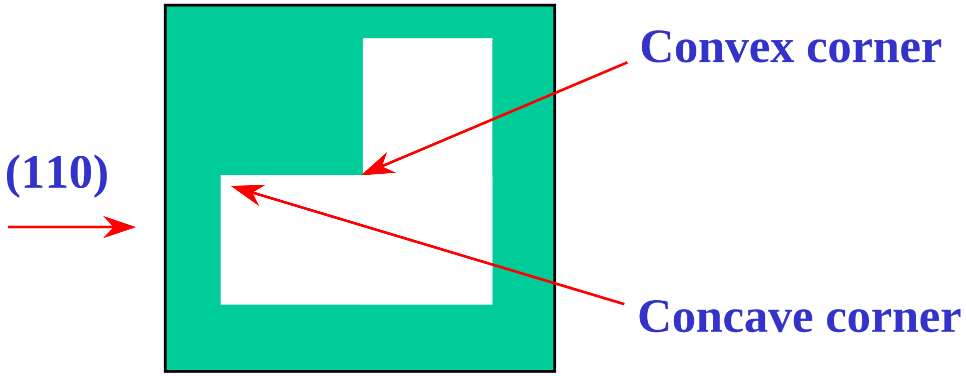
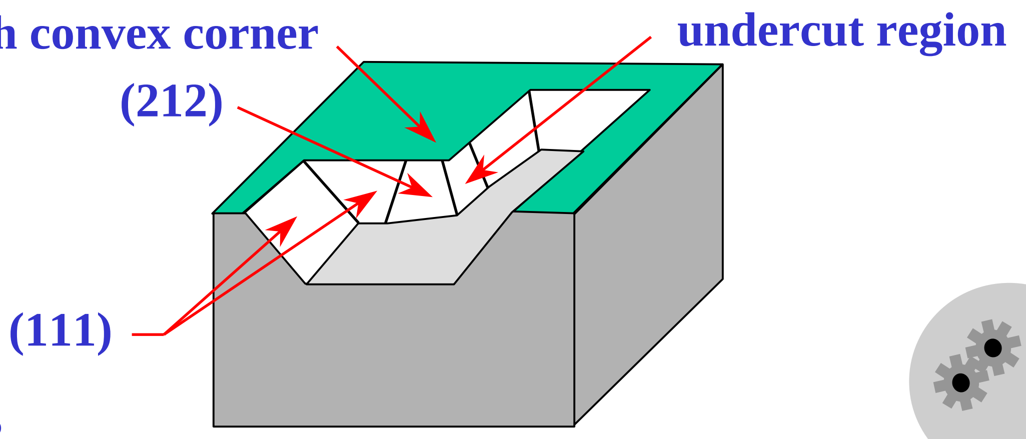
Convex Corner Undercut

- Convex corner



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



W. Fang, Ph.D. Thesis, 1995

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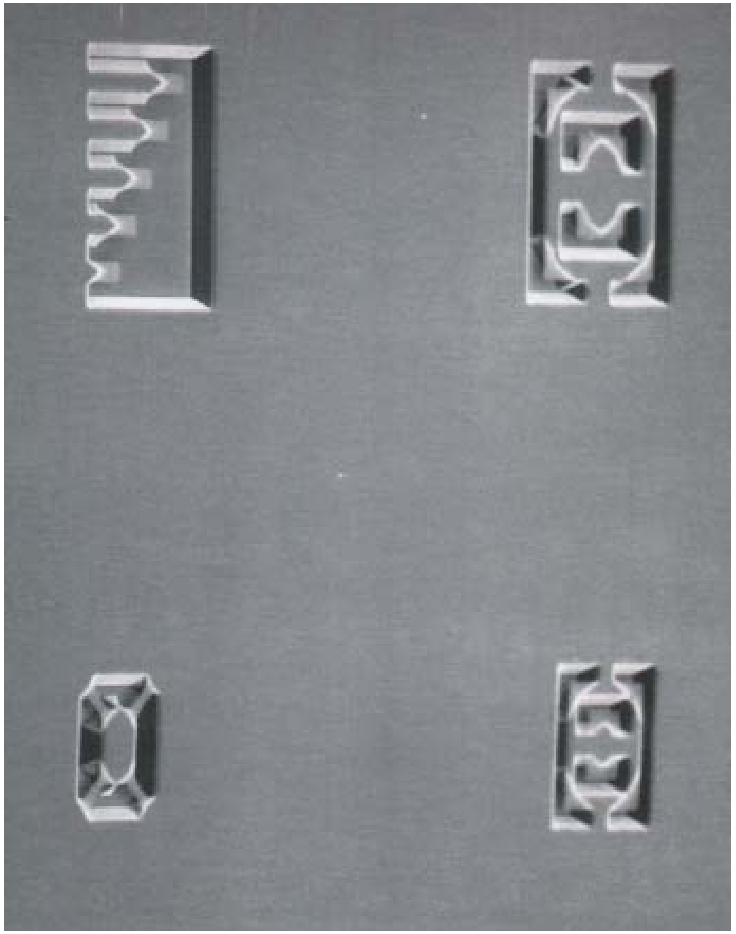

W. Fang and J.A. Wickert, DSSC annual report, 1993

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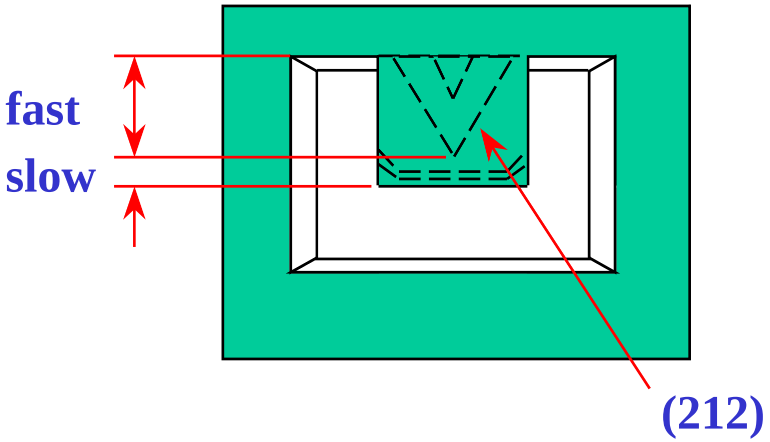
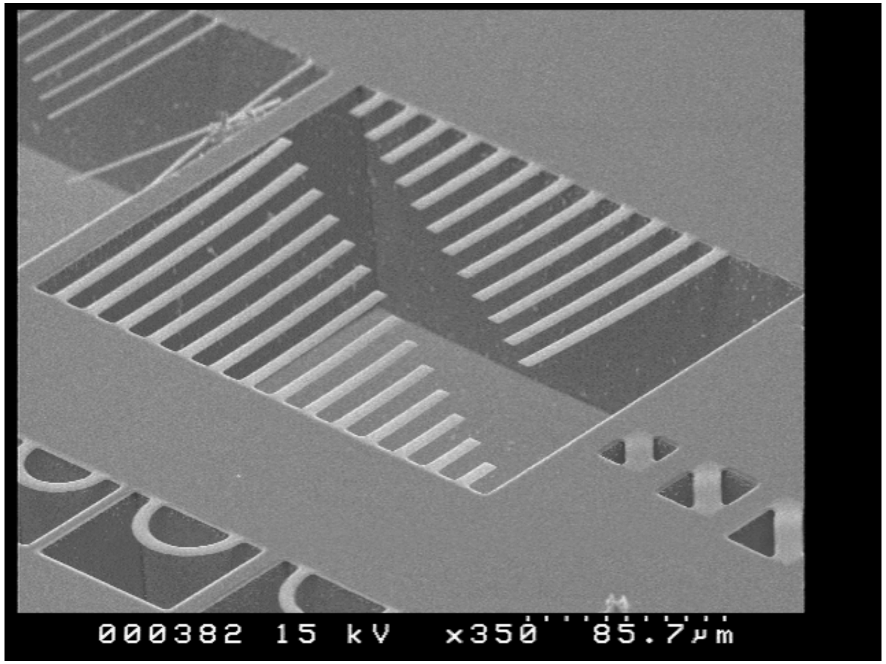
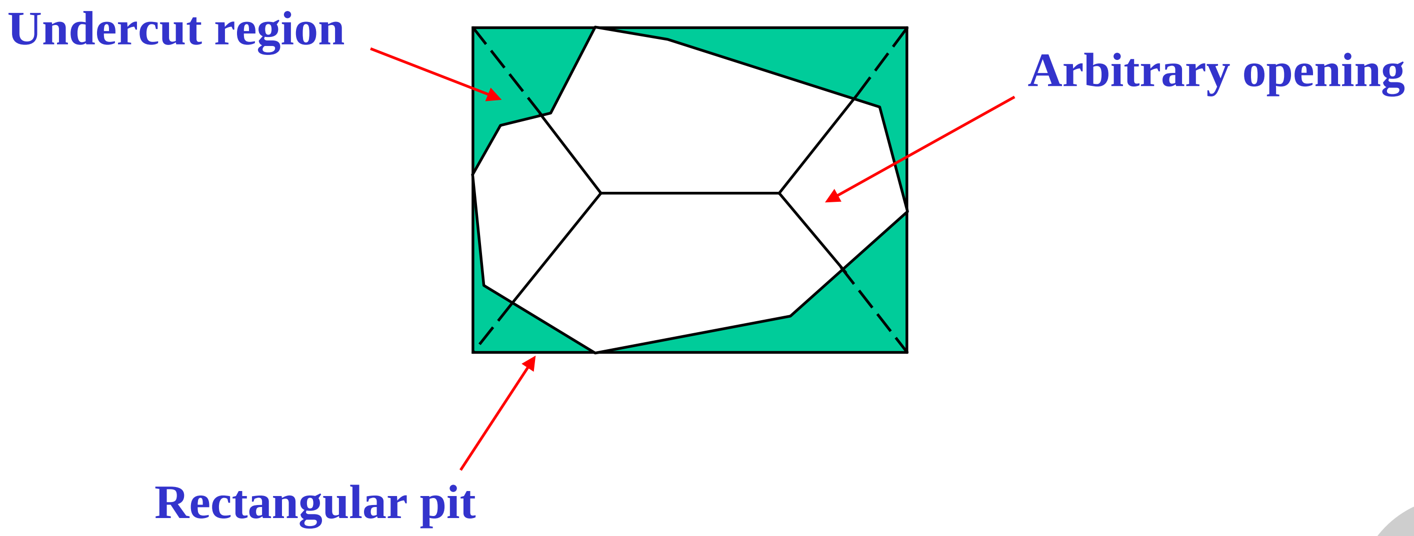
- **The undercut effect is exploited to make micromachined structures such as beams, suspensions, etc.**



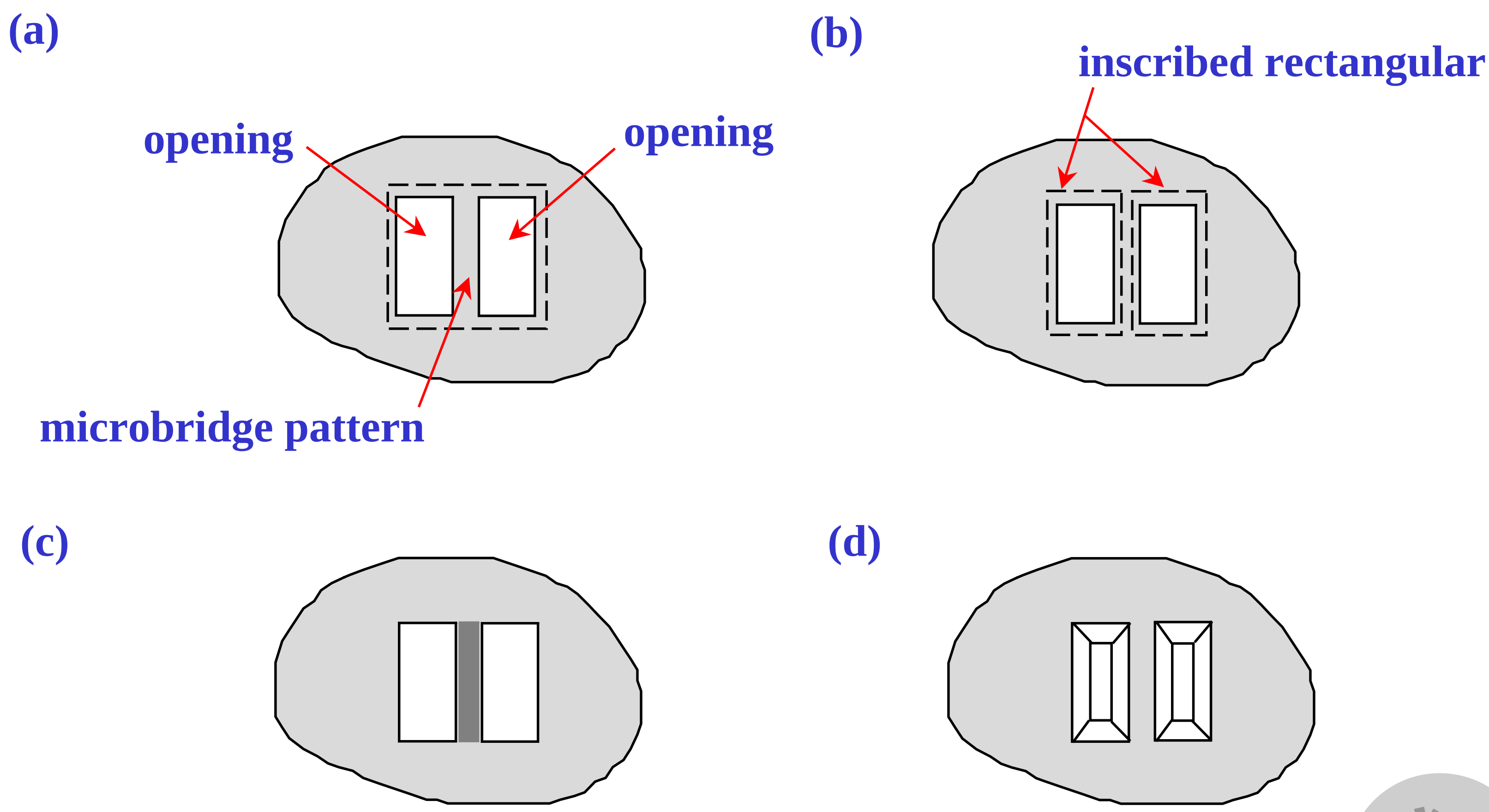


- If the Si wafer is etched long enough, any **arbitrary opening** on the mask will result in a **rectangular pit** in the wafer

- The arbitrary opening is perfectly **inscribed** in the rectangle



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



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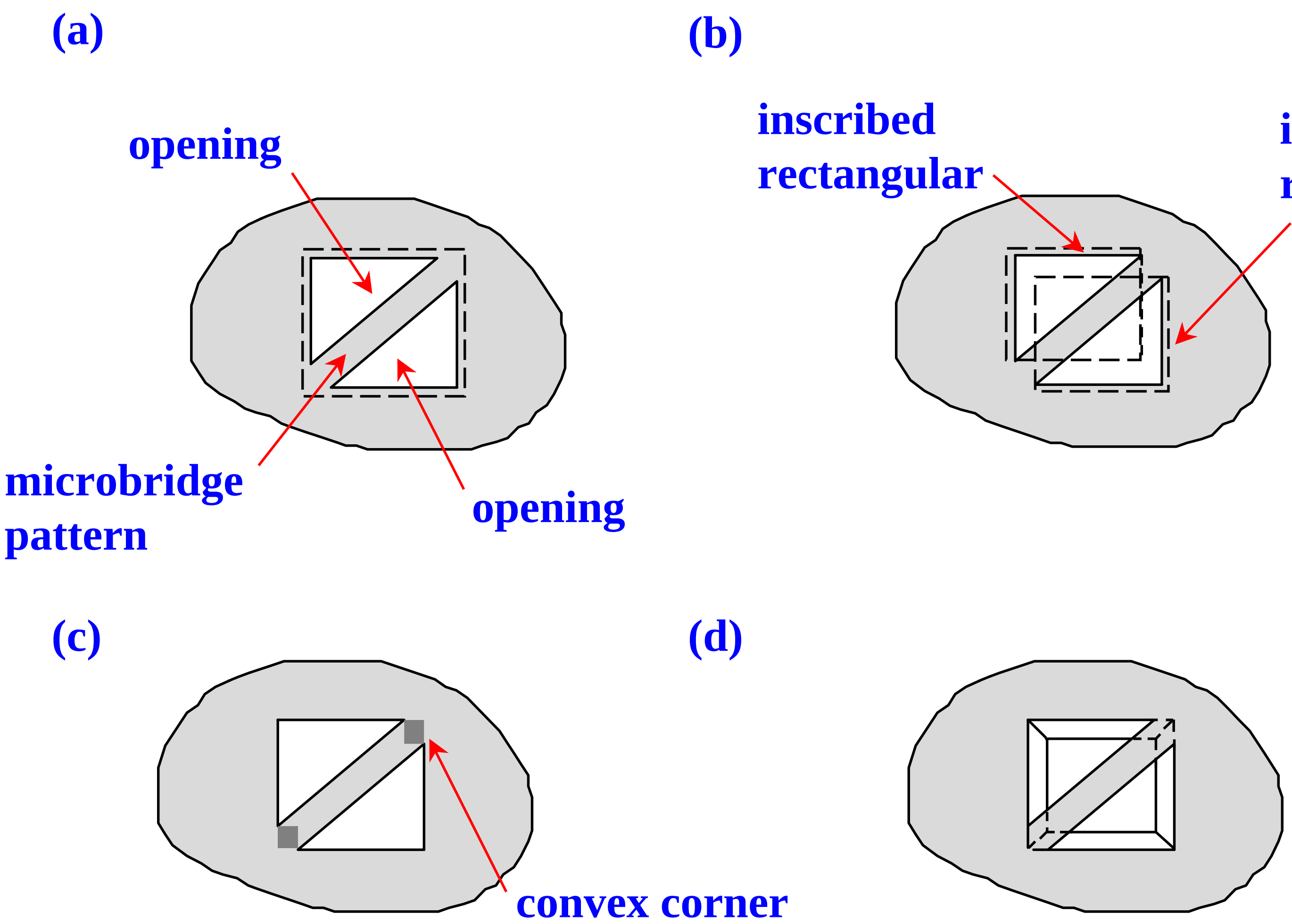
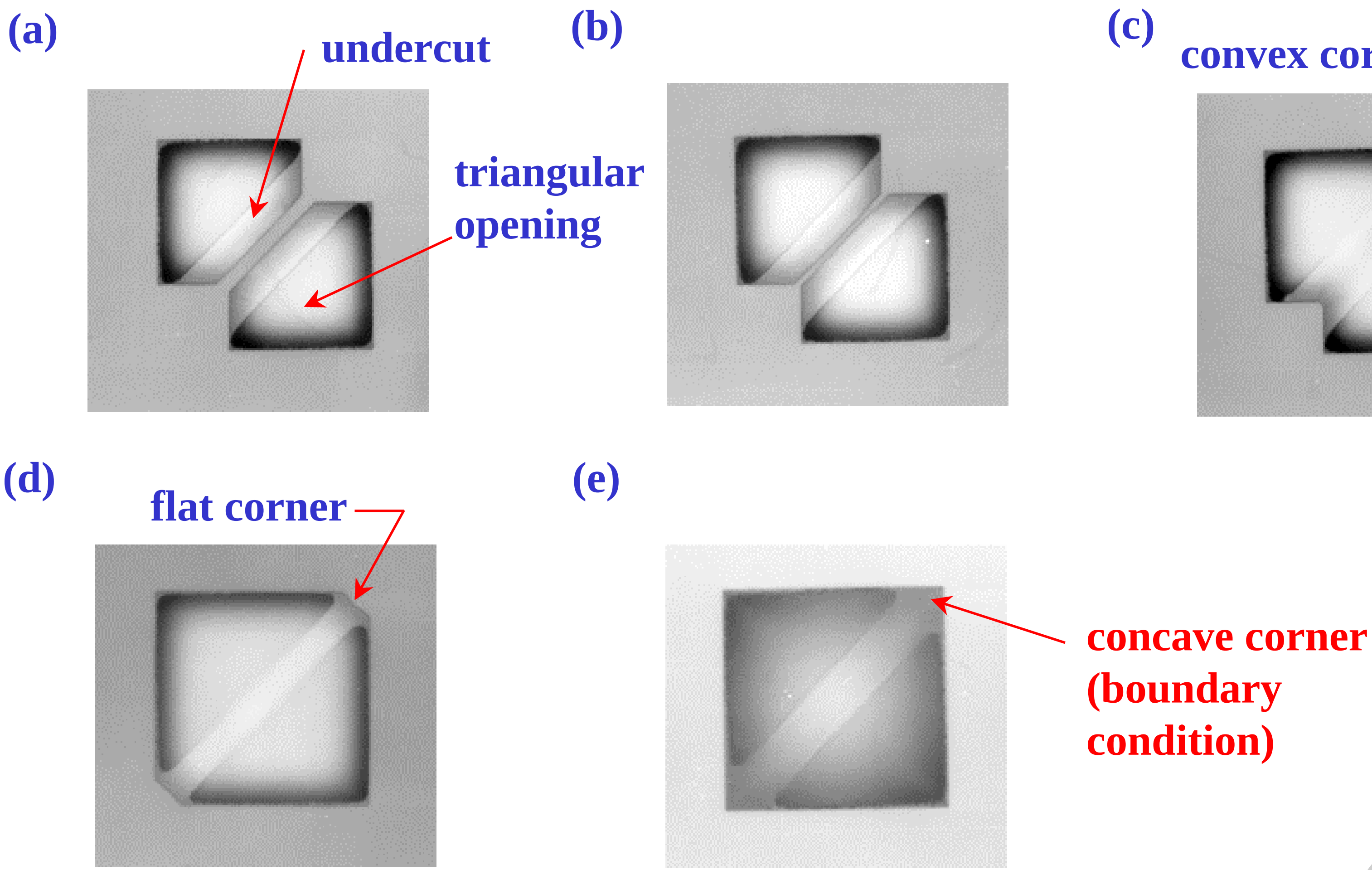


- The sequence of undercut



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

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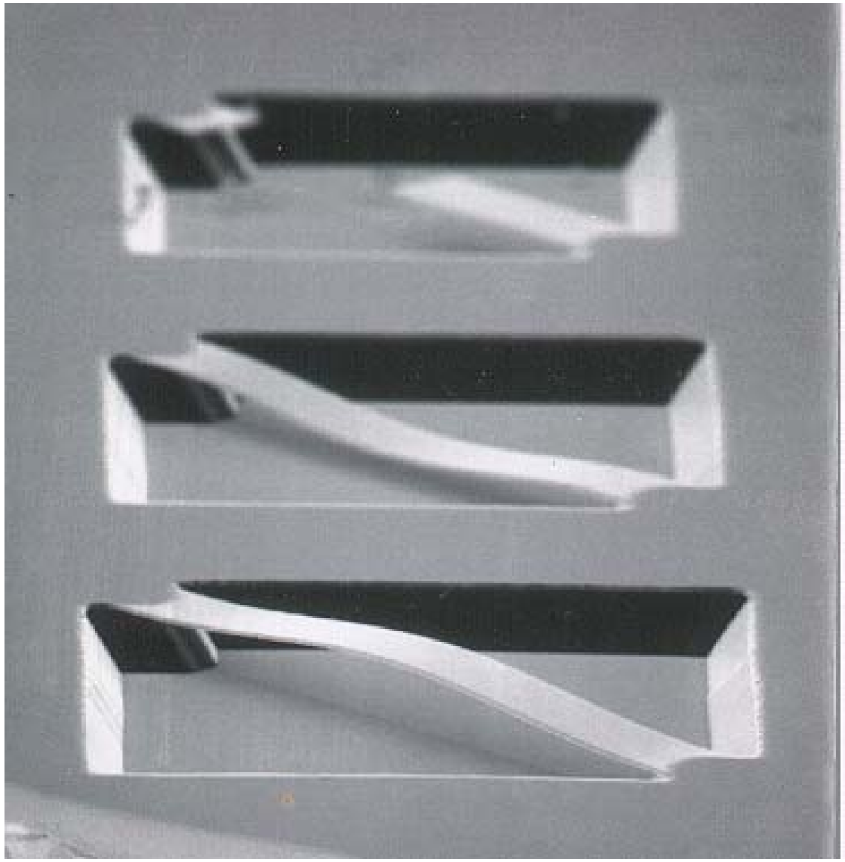

W. Fang and J.A. Wickert, DSSC annual report, 1993

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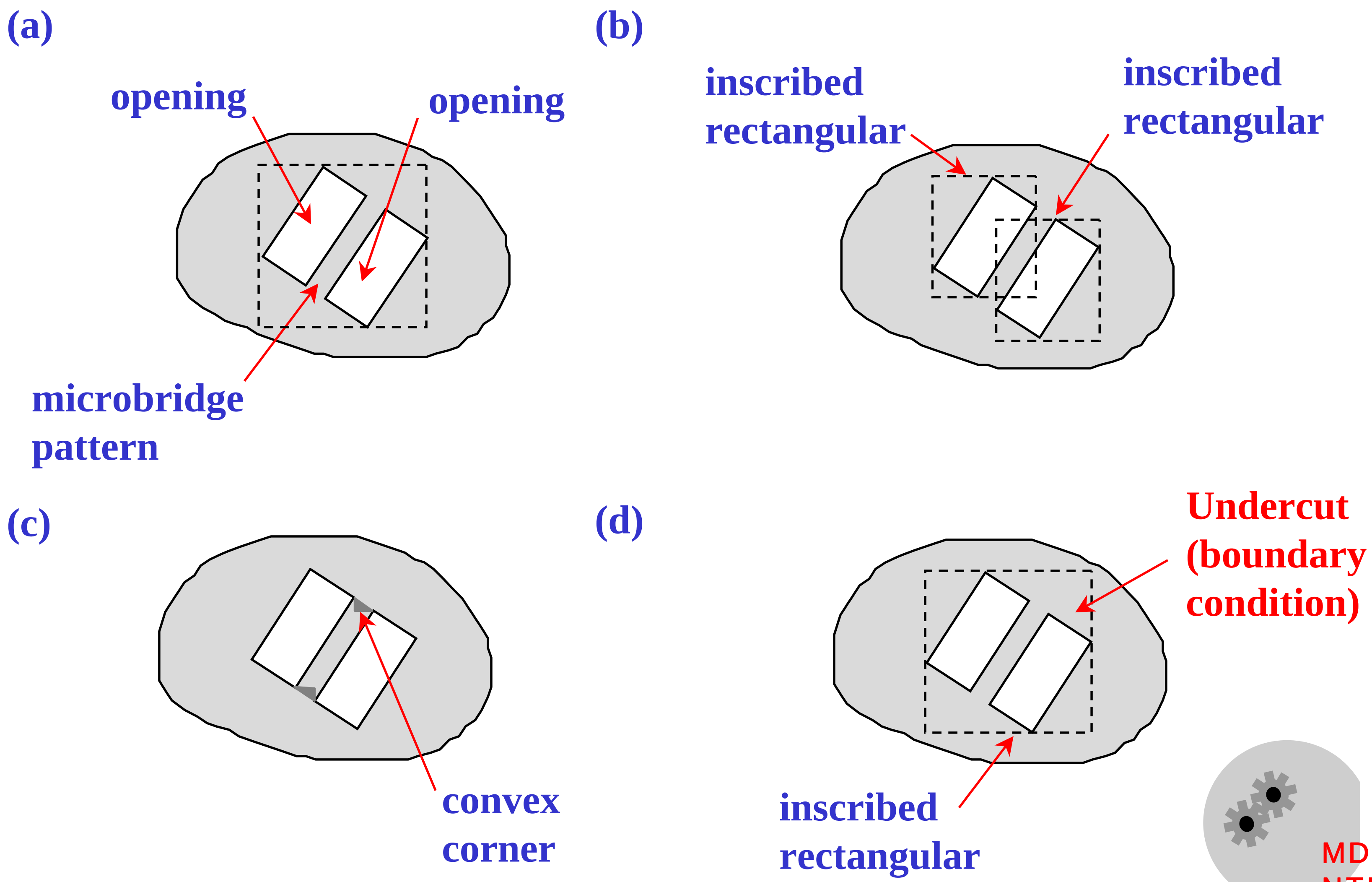
- **Another candidate design of the clamped-clamped beam (2 openings)**



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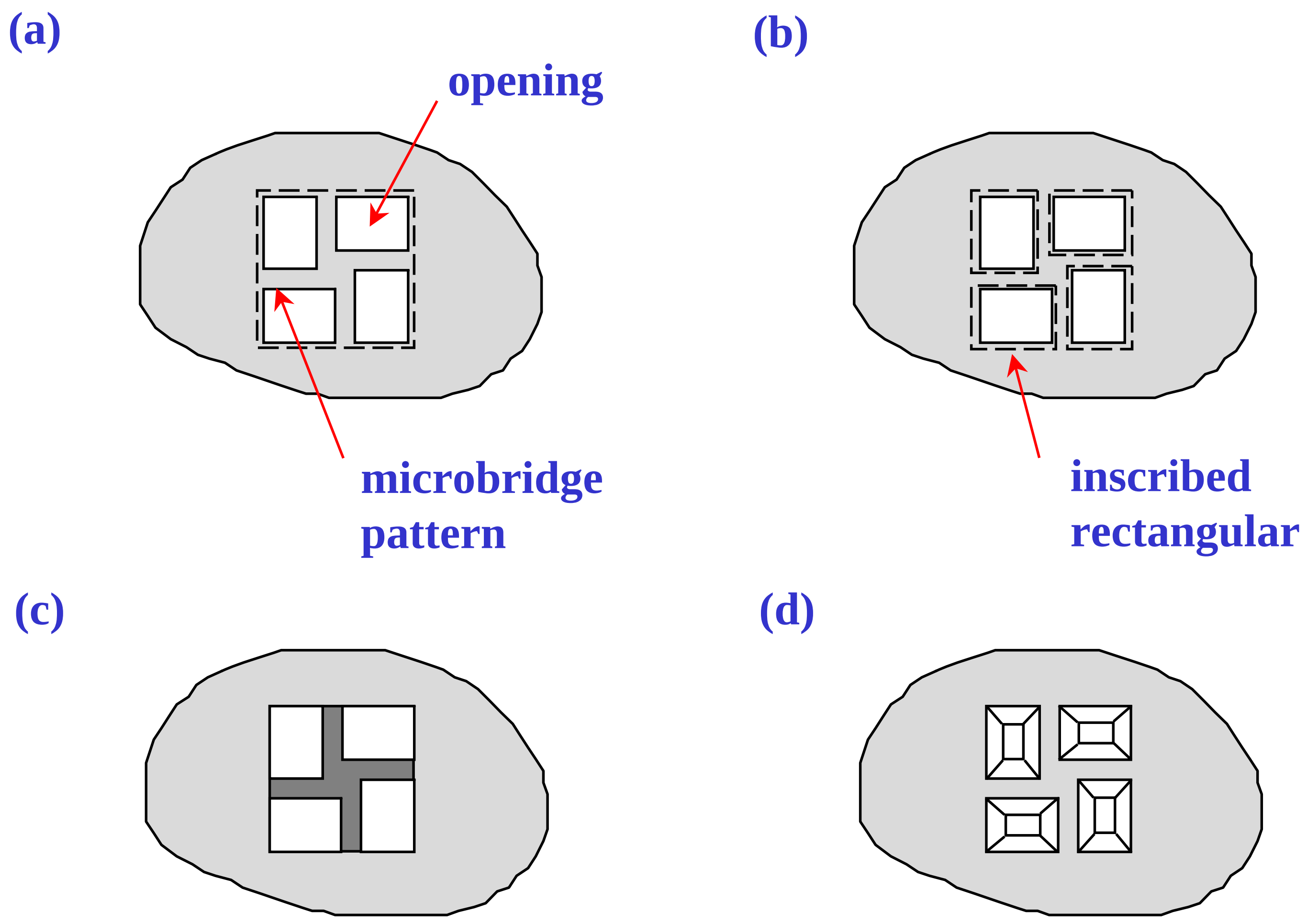
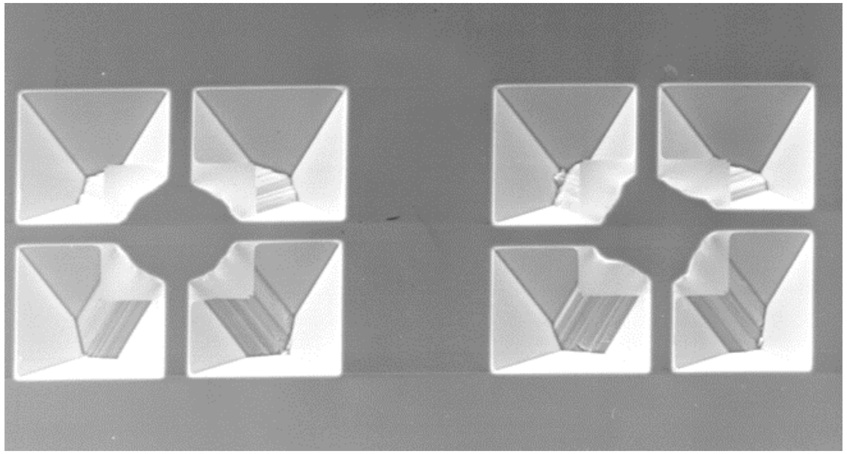
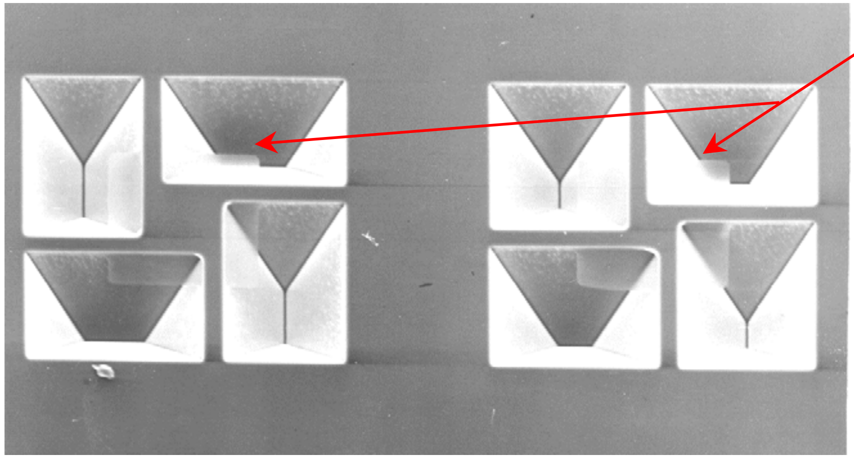
- **Similar effect is applied to design the micromachined suspensions (4 openings)**



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





can not be fully undercut

W. Fang, SPIE conference, 1997

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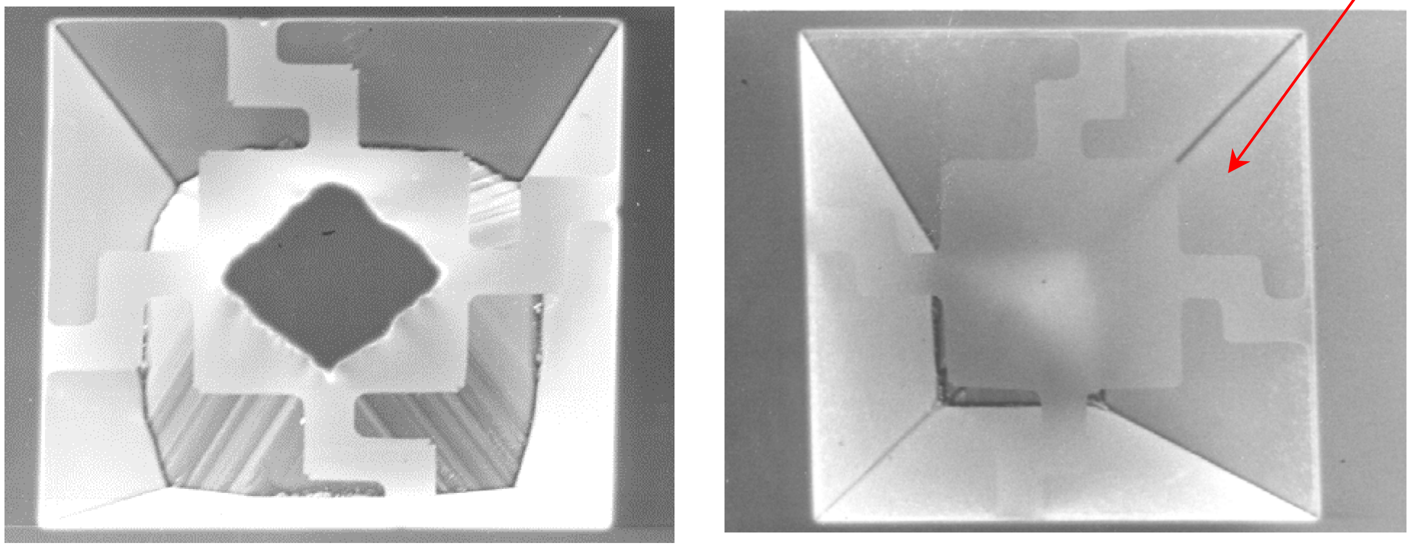
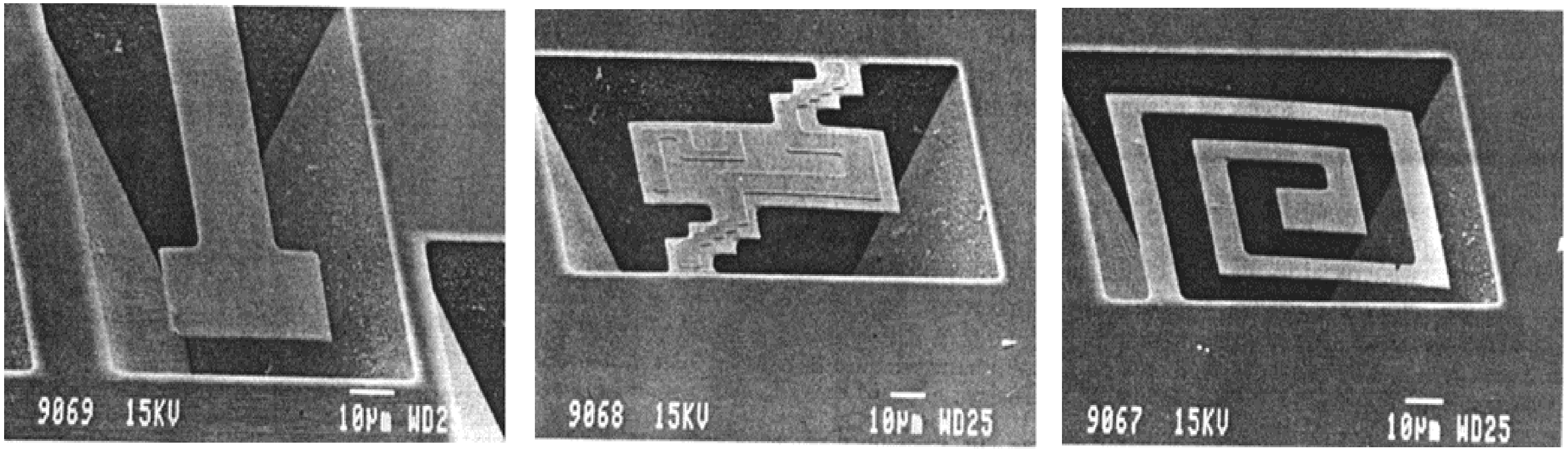
- **Mask pattern which can be fully undercut**

be fully undercut



W. Fang, SPIE conference, 1997

- **Other examples**



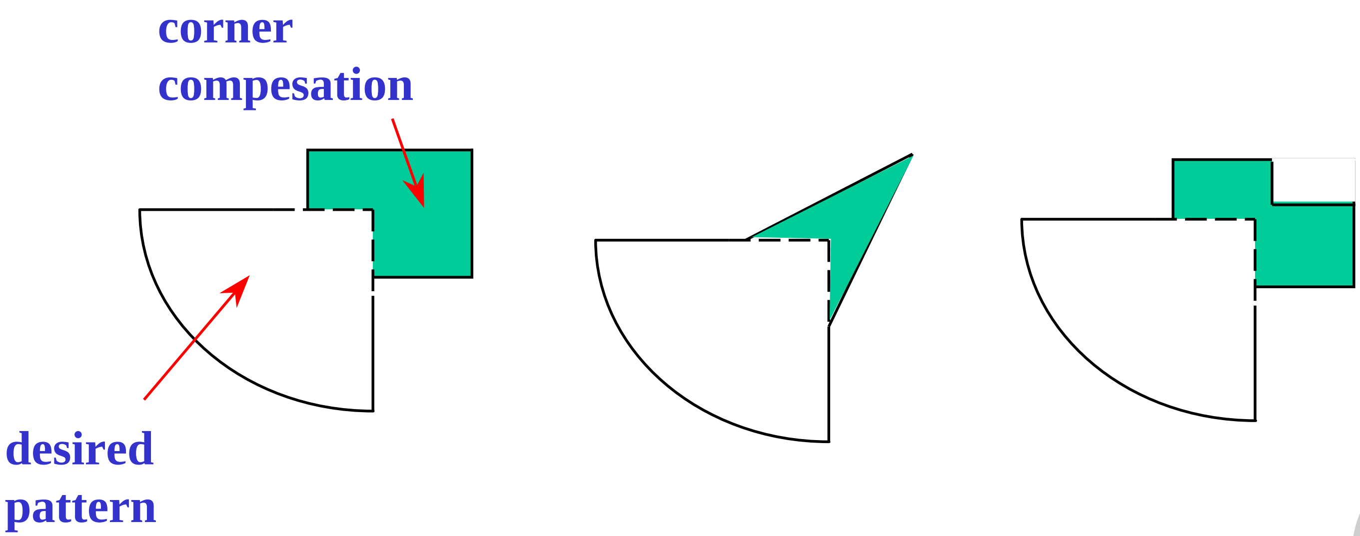
10 μm

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

Convex Corner Compensation

- If a square block (mesa) structure is required for the device, an extra pattern can be added to the convex corner to prevent the undercut

- The shape of the corner compensation is determined by (1) shape of the corner, and (2) depth of the mesa



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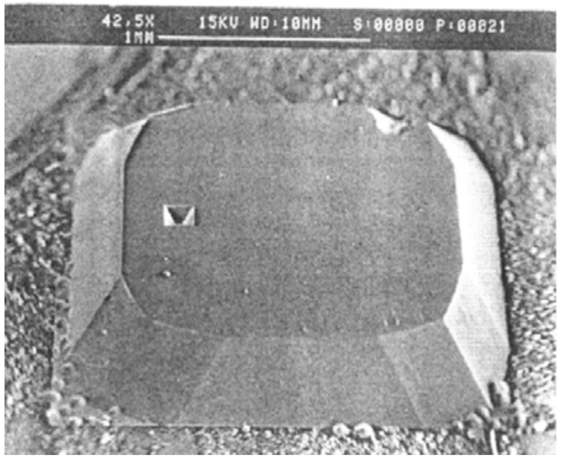
- **Mesa**

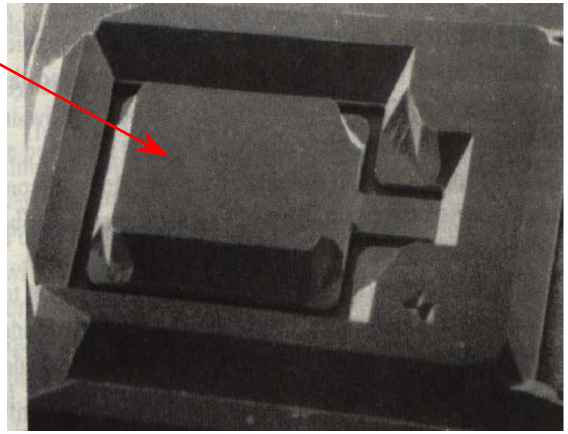


1 mm

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 85º C

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

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

  + selectivity is ~ 500:1 for SiO_2 : Si

  + add isopropyl alcohol (IPA) to get 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 115° C

  + selectivity is ~ 35:1 for (100):(111)

  + selectivity is ~ 5000:1 for SiO_2 : Si

  + may get rougher Si surface than KOH

  + etch rate decreases ~ 50x on boron doped Si

  + toxic

- **TMAH (anisotropic etchant)**

  + selectivity is >4000:1 for SiO_2 (or Si_3N_4) : Si

  + higher surface roughness than KOH or EDP

  + etch rate decreases ~ 50x on boron doped Si

- N_2H_4 (anisotropic etchant)

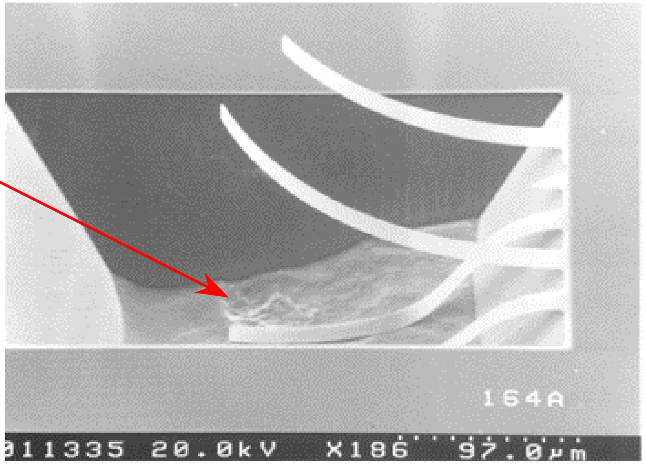
  + selectivity is good for SiO_2 : Si

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

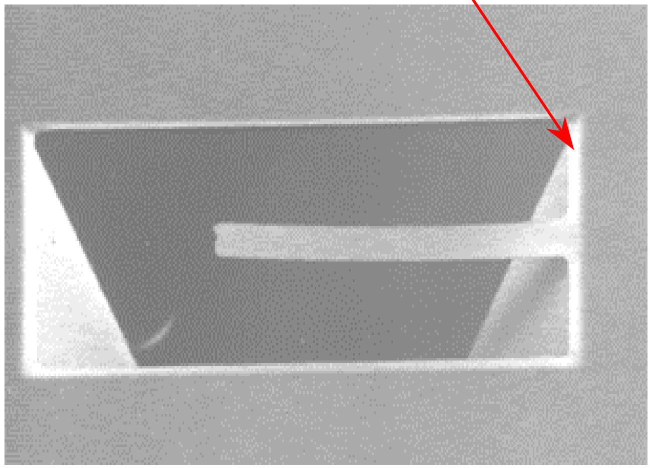
  + may get rougher Si surface than KOH

  + toxic

Flatness and roughness



Undercut



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

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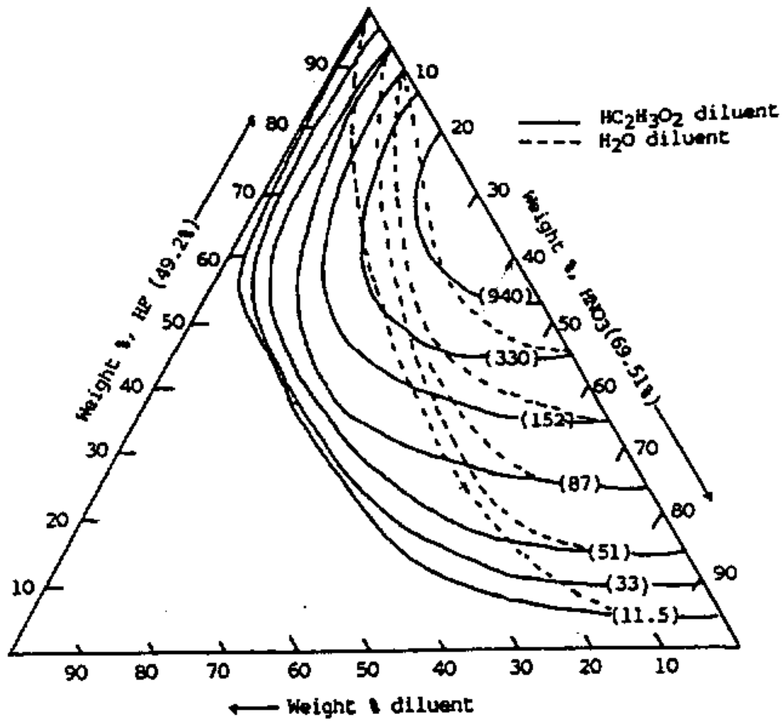
- HNA (isotropic etchant) : **H**ydroflouric acid (HF) + **N**itric acid (HNO_3) + **A**cetic acid (CH_3COOH)

+ 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 SiO_2 : Si



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

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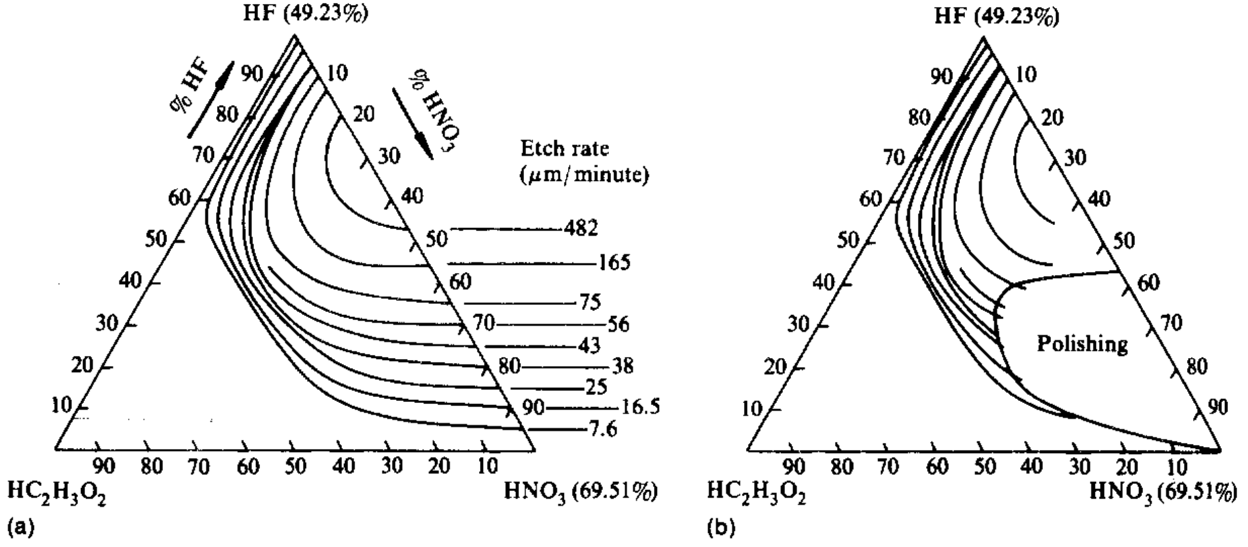
- The etching is a two-step process including : (1) the silicon is oxidized by HNO_3 first, and (2) the oxide is then dissolved by HF
- At high HF low HNO_3 concentration, the etching rate is dominated by process (1)
- At high HNO_3 low HF concentration, the etching rate is dominated by process (2),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



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

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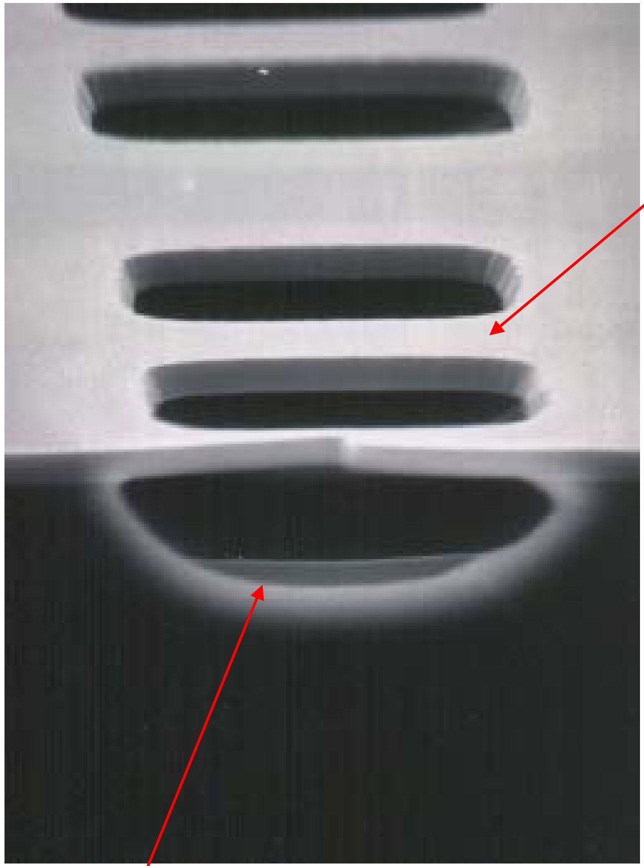

Clamped-clamped beam

isotropic etching

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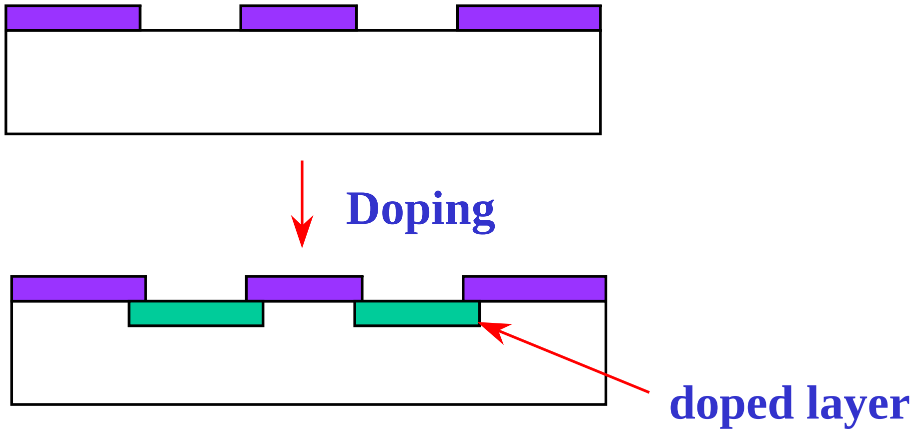
Dopant Dependent Etch Stop

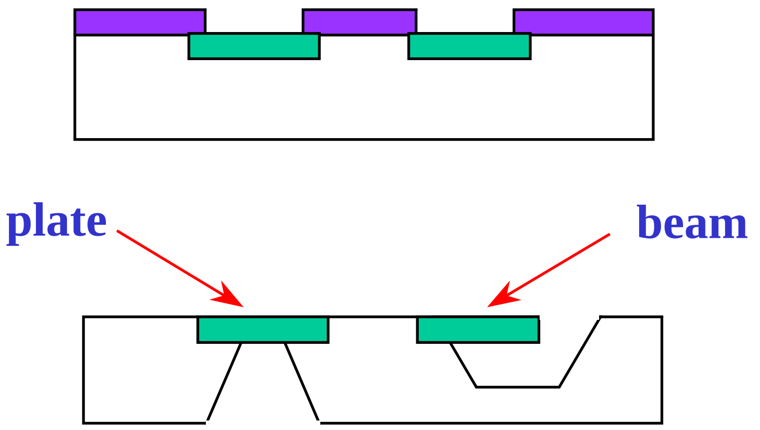
- Doping - doping is the process to add dopant into a silicon substrate by (1) diffusion, or (2) ion implantation



- Etch stop - if the silicon substrate is **heavily doped**, the etching rate for anisotropic etchants such as KOH and EDP will be reduced drastically

- The most common dopant for etch stop purpose is **boron**

- The purpose of doped etch stop layer is to precisely define the thickness of a beam, membrane, or plate



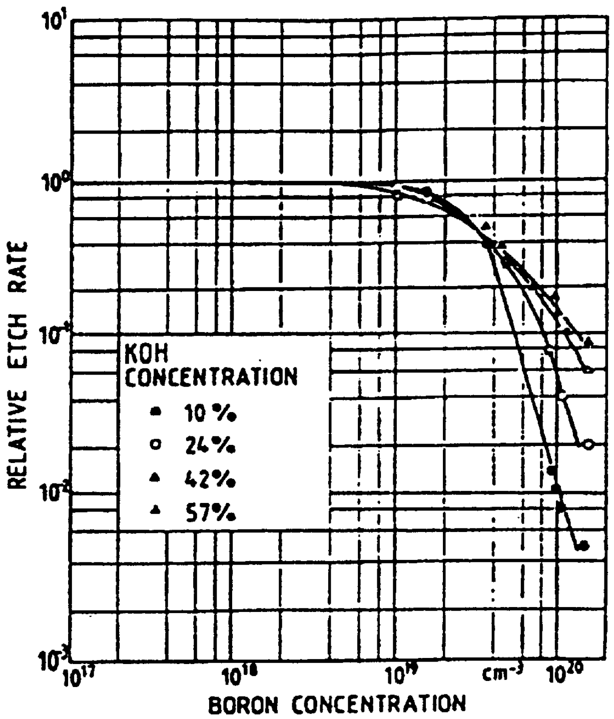
- If the silicon are doped with boron to about 10^{20} atoms/cm^3 , the etch rate will be reduced

  + For KOH - the etch rate become 1/20 if the doped boron ≥ 1×10^{20} atoms/cm^3

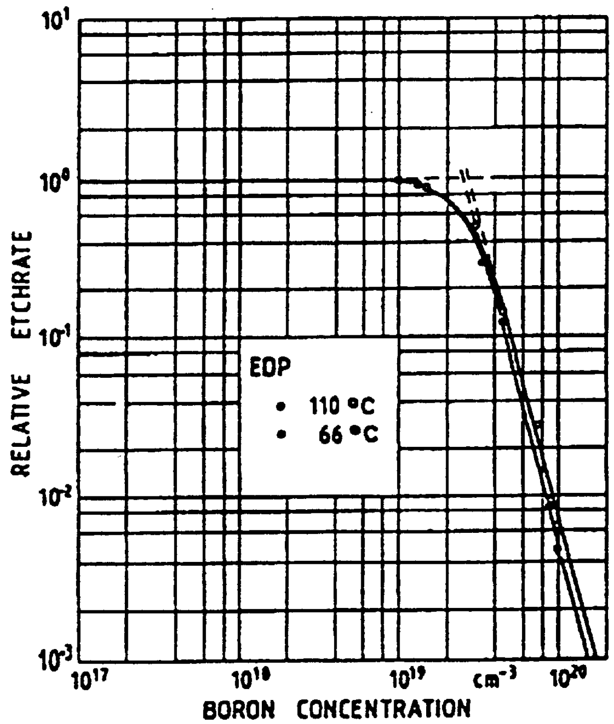
  + For EDP - the etch rate become 1/50 if the doped boron ≥ 7×10^{19} atoms/cm^3

- Variation of the boron concentration and 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 - this is a technique by which impurity atoms, traveling at high energy, are made to impinge on the substrate**

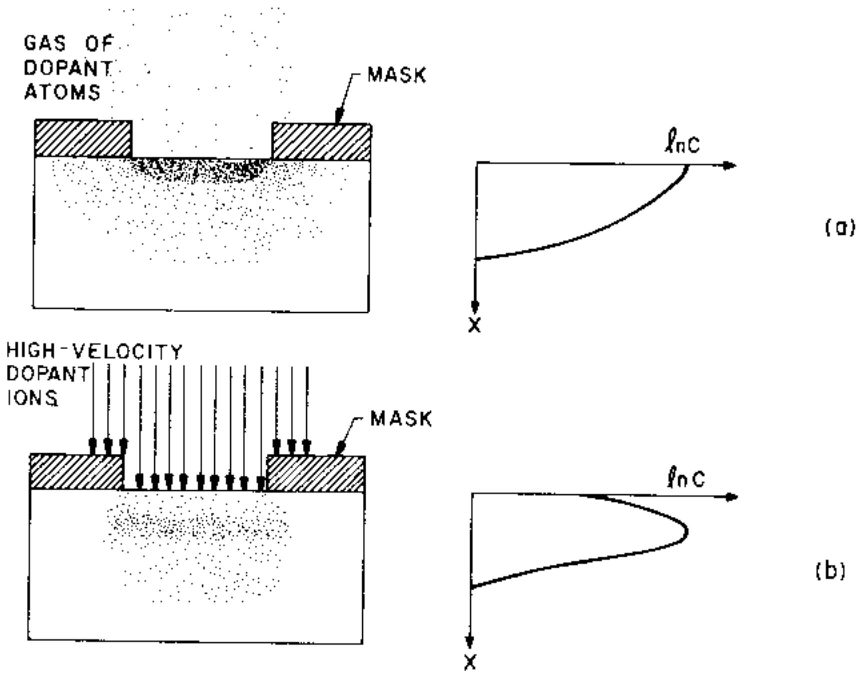
- **Comparison of diffusion and ion implantation method**

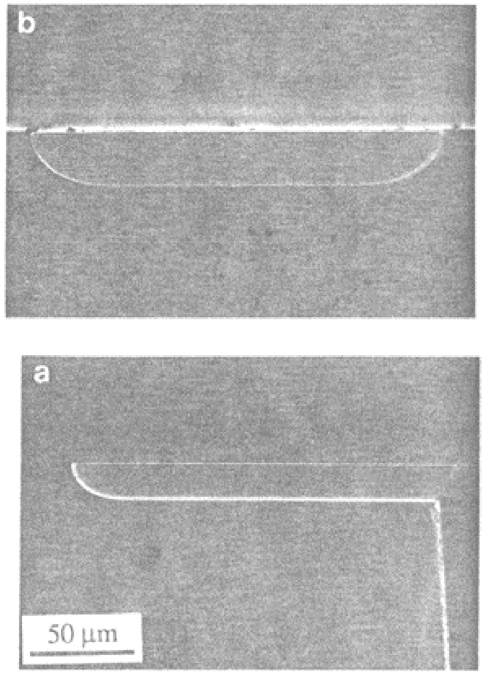
  + **In general, the thickness of the doped layer is approximate 10 ~ 20 μm by diffusion method, but only several microns by ion implantation**

  + **The equipment for ion implantation is very expensive**

  + **Although the diffusion method is less accuracy in controlling dopant concentartion and thickness of the doped layer, it still satisfied the requirement for MEMS**

- **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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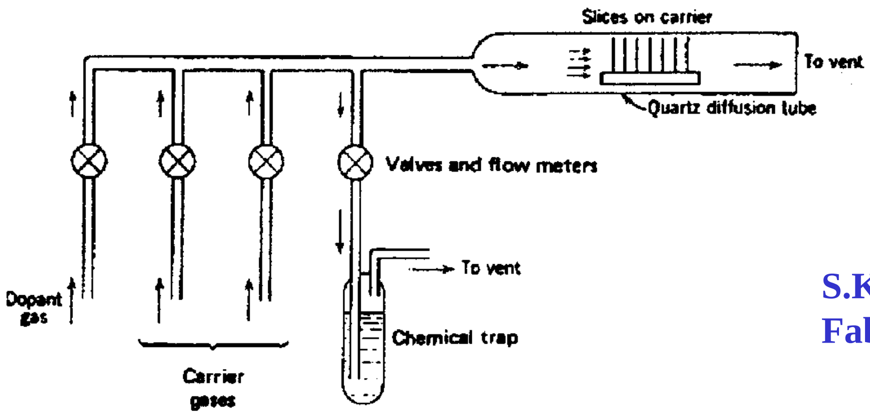
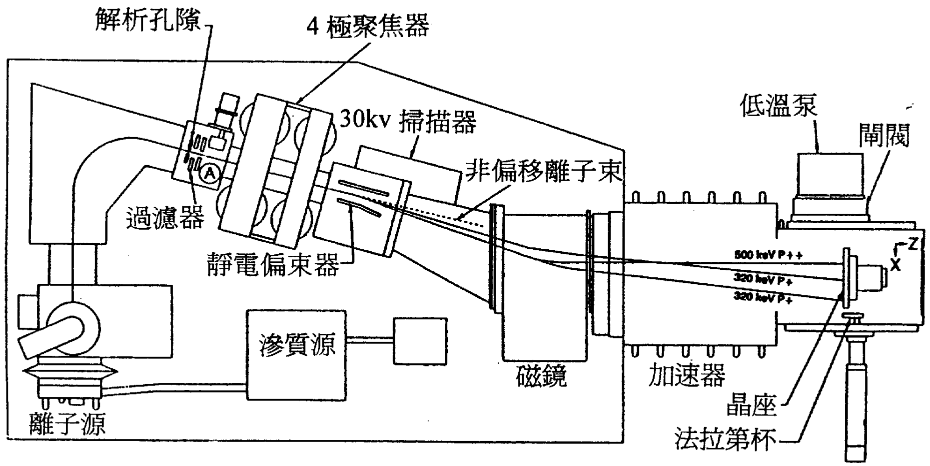
- **Devices for diffusion**



S.K. Ghandhi, VLSI Fabrication Principles, 1983

- **Devices for ion implantation**



莊達人, VLSI 製造技術, 1995

- **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**

- **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

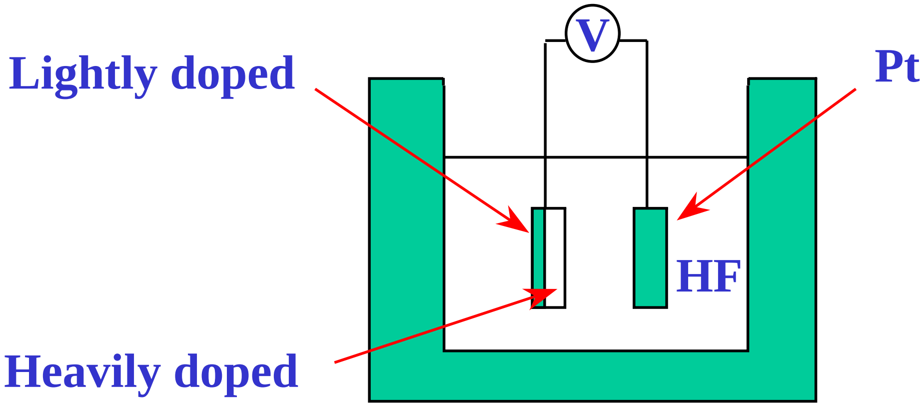
  Ion implantation - S.M. Sze Chap8, 莊達人 Chap 9, W.R. Runyan and K.E. Bean, Chap. 9

Electrochemical etch stop I

- The etching process includes two steps

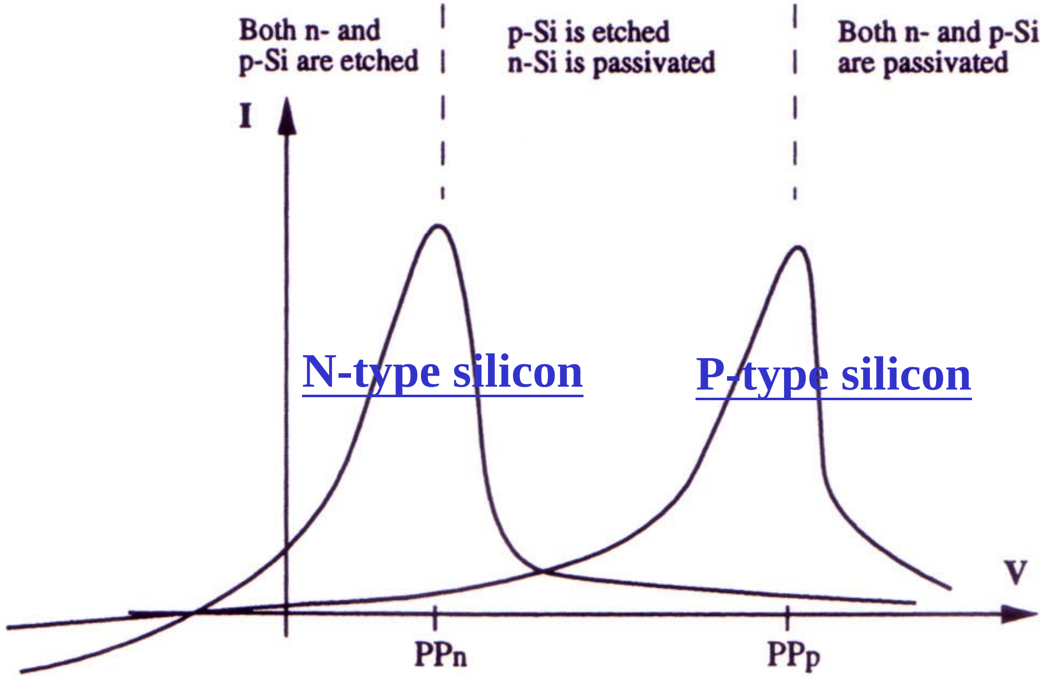
  + oxidation of the substrate by voltage

  + etching of the silicon oxide by HF

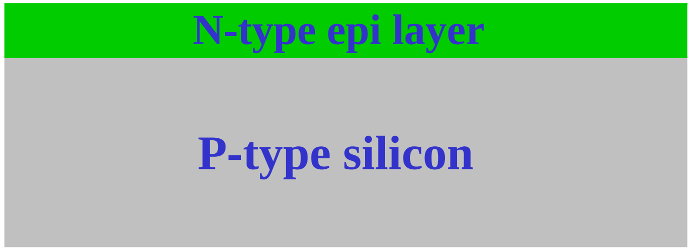


- The substrate contains two parts with different doped concentration
- The heavily doped part has higher conductivity and will be oxidized more quickly - the heavily doped Si will be etched faster than the lightly doped Si

Electrochemical etching stop II



Typical I-V plot for pn etch-stop



Epitaxial silicon wafer

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

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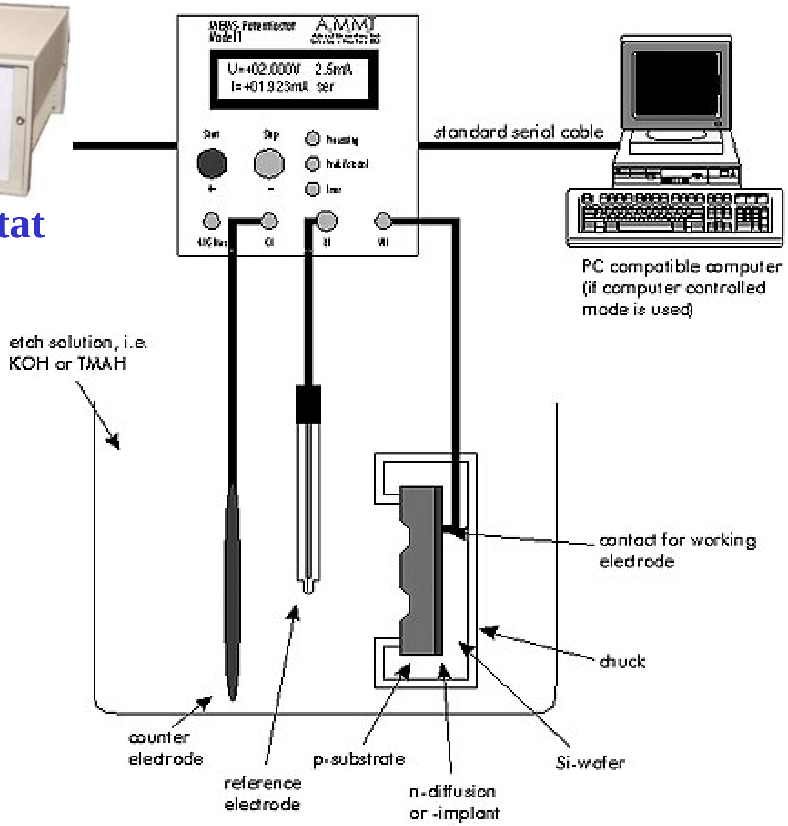
Equipment setup

MEMS potentiostat



Wafer holder

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

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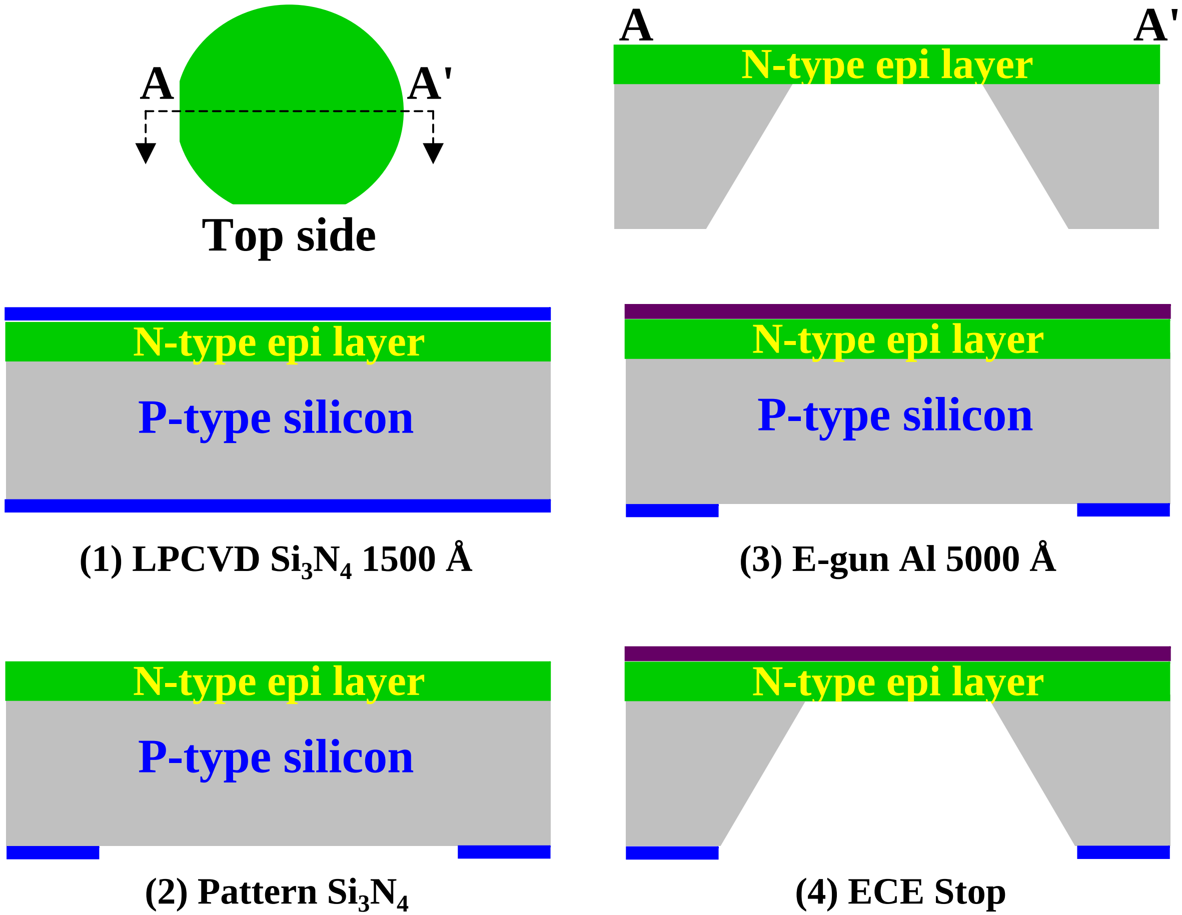
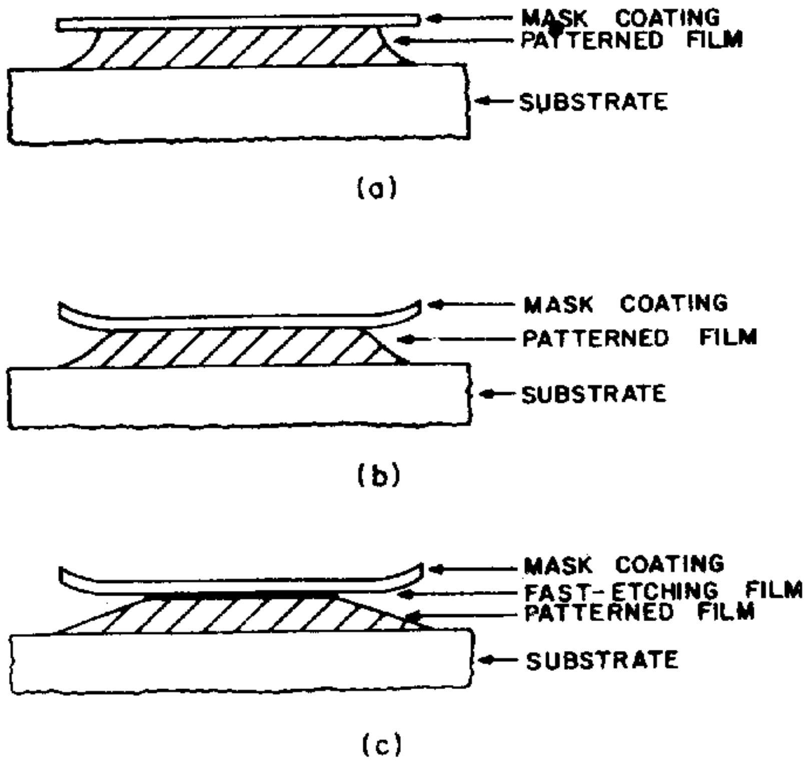

A
A'
Top side
A
A'
N-type epi layer
N-type epi layer
P-type silicon
(1) LPCVD Si_3N_4 1500 Å
N-type epi layer
P-type silicon
(2) Pattern Si_3N_4
N-type epi layer
P-type silicon
(3) E-gun Al 5000 Å
N-type epi layer
(4) ECE Stop

- **Single Crystal Silicon**
- **Thin films**

Common Etchant for SiO_2

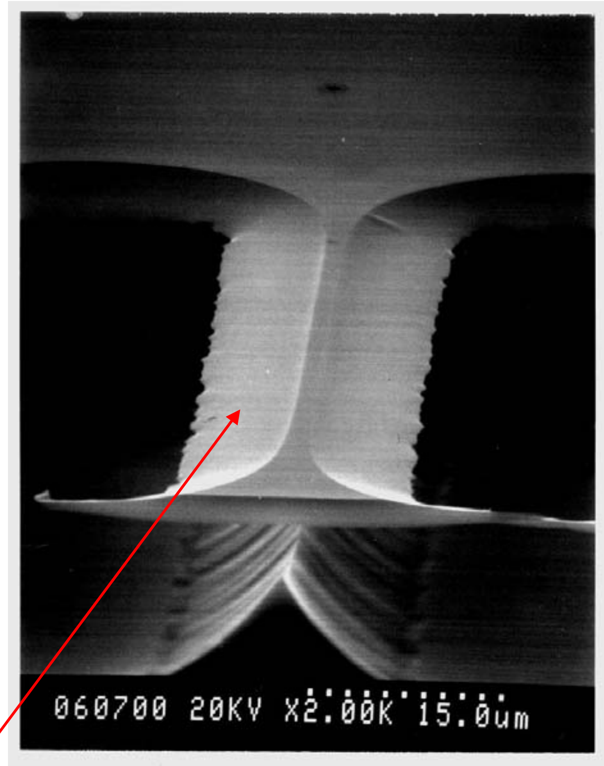
- **HF**
  - + **Buffer HF - add NH_4F to HF to control pH yield**
  - + **etching rate depends on density, residual stress, and microstructures of SiO_2**
  - + **toxic**
  - + **can not store in glass bottle**

- **Undercut of the thin film structure**



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

- If the SiO_2 film is very thick, it takes longer time to pattern the film. Thus, the undercut effect will destroy the micromechanical structure



height

width

Cross-section of the beam

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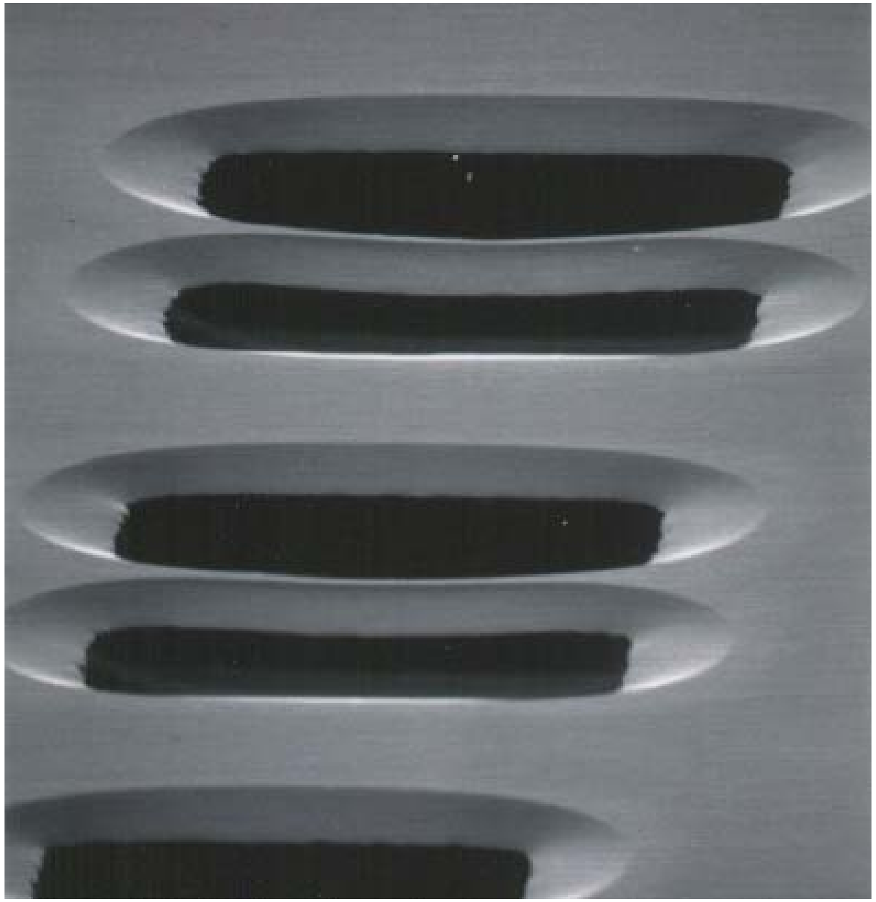

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- The undercut effect can be exploited to **prevent step coverage**, if additional layers are to be deposited subsequently
- The undercut effect can also be applied to **smooth the edge of the structure**

W. Fang, Ph.D. thesis, 1995

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**

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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**

2.3.2 Ion Etching

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

- Ion etching - Ion etching is the process to remove the atoms from the 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 - the ions are generated in a plasma remote from the substrates and subsequently accelerated towards them
- Sputter etching - the substartes are an integral part of the cathode of a parallel plate discharge
- Anisotropic etch (substrate orientation) and selectivity is low

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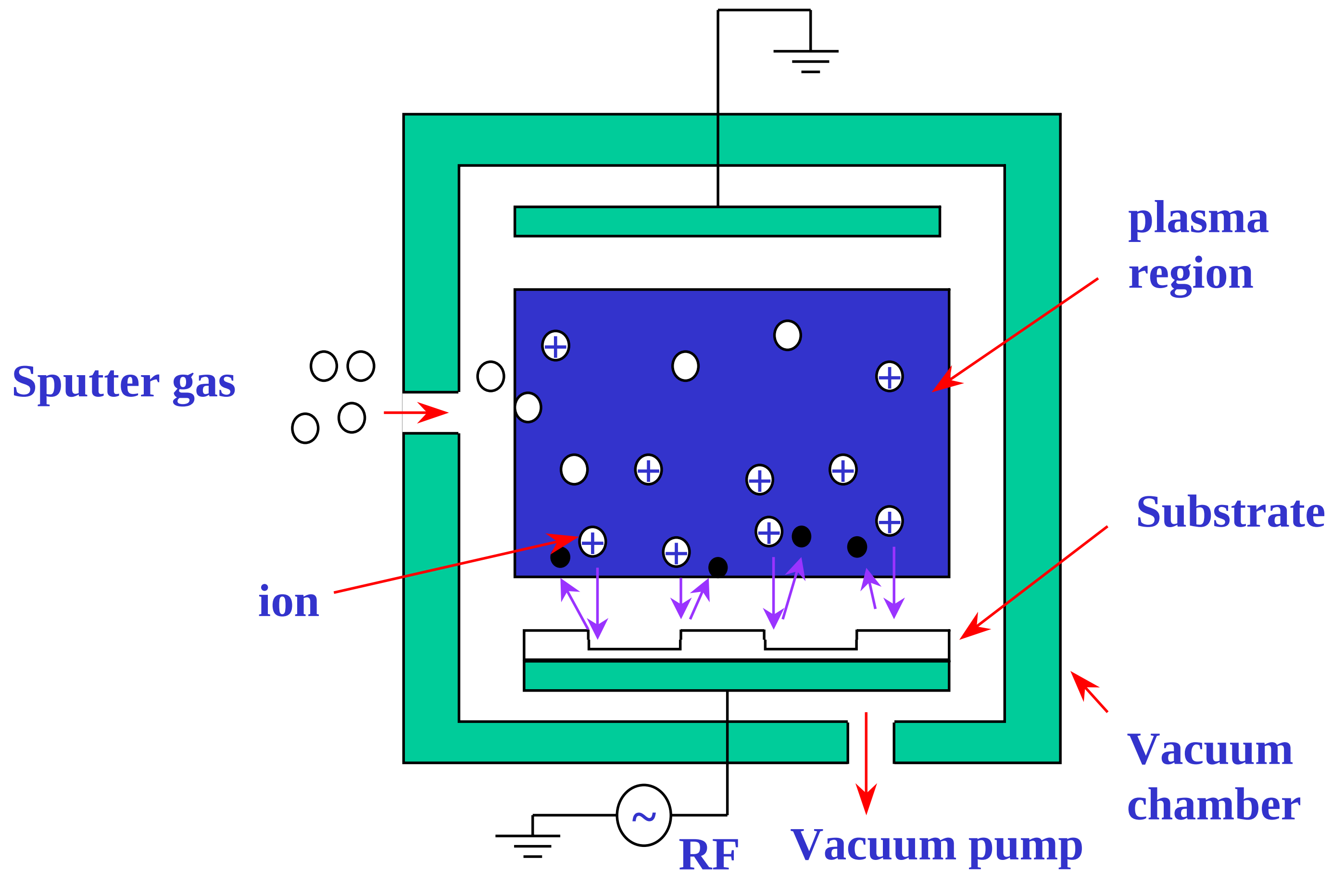
Sputter Etching

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



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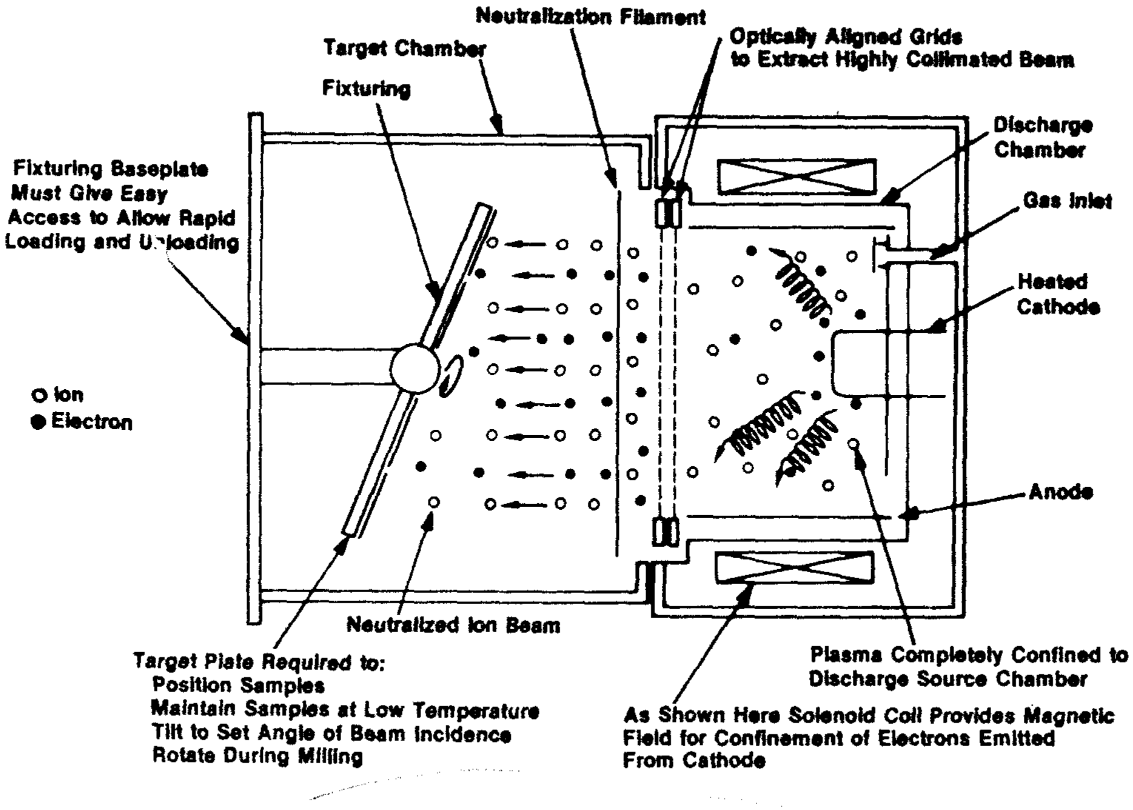
Ion Milling

- Ion milling - the ions are generated in a plasma remote from the 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
- These emitted electrons are accelerated toward the anode and their path length is increased by the magnetic field
- The neutral gas atoms in discharge chamber will then be impacted and ionized by these accelerated electrons
- The ions created in the discharge chamber are extracted and formed into an ion beam by a set of grids
- An electric potential corresponding to the ion beam energy required for ion milling is applied across a parallel set of grids
- The accelerated ions are neutralized by a neutralization filament to prevent space charge effect

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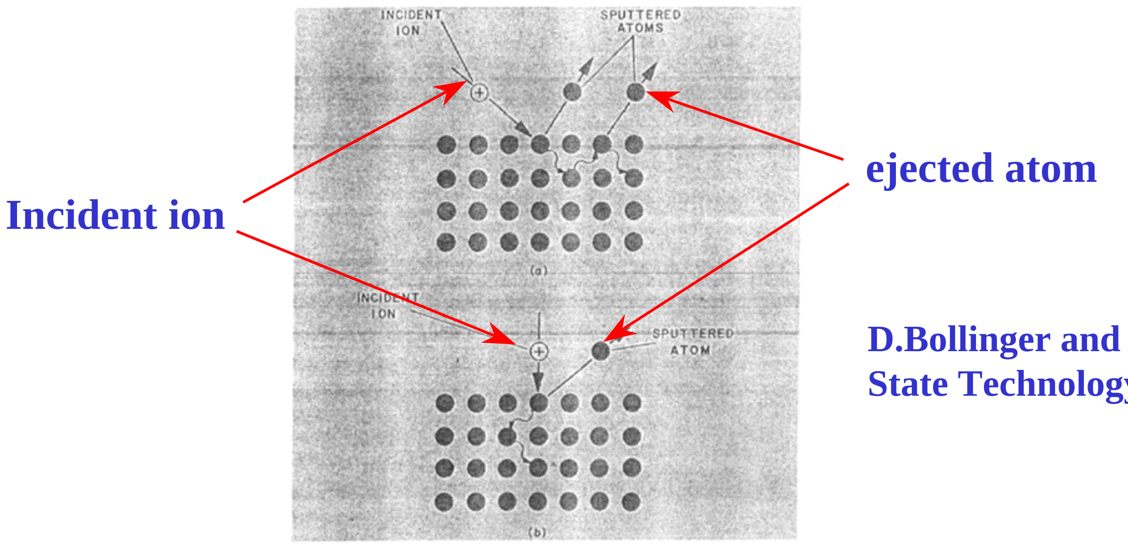
Etching Rate

- 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.

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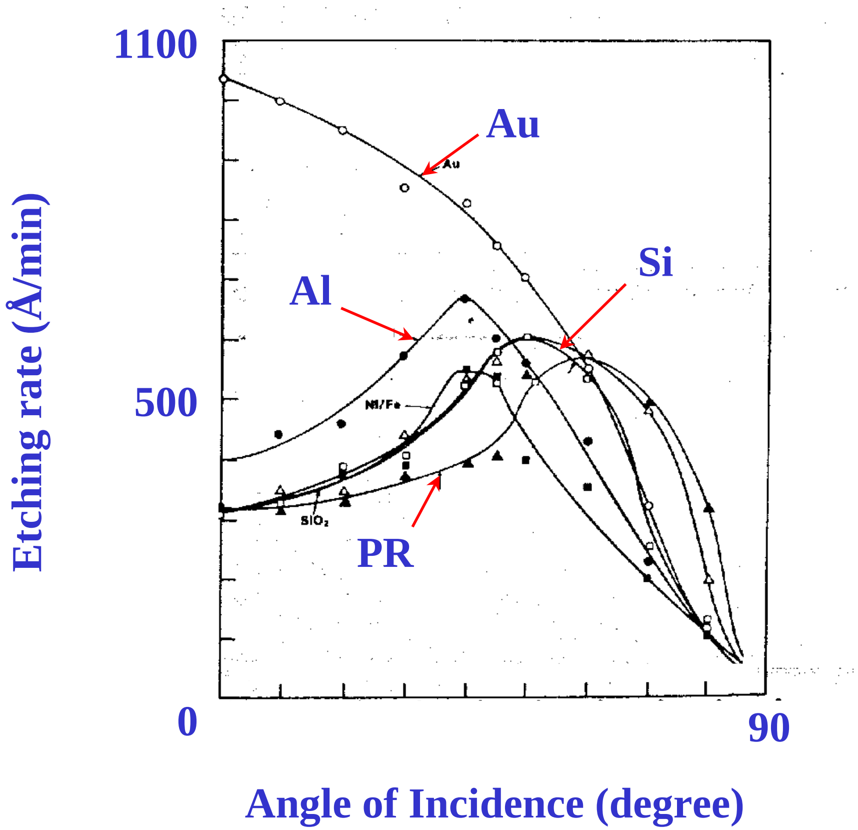
- **Etching rate vs Impact angle for different materials**



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

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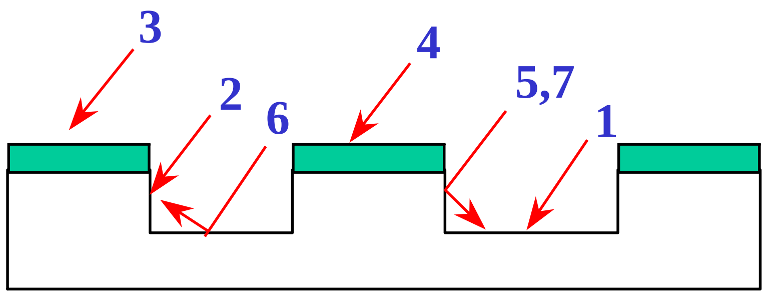
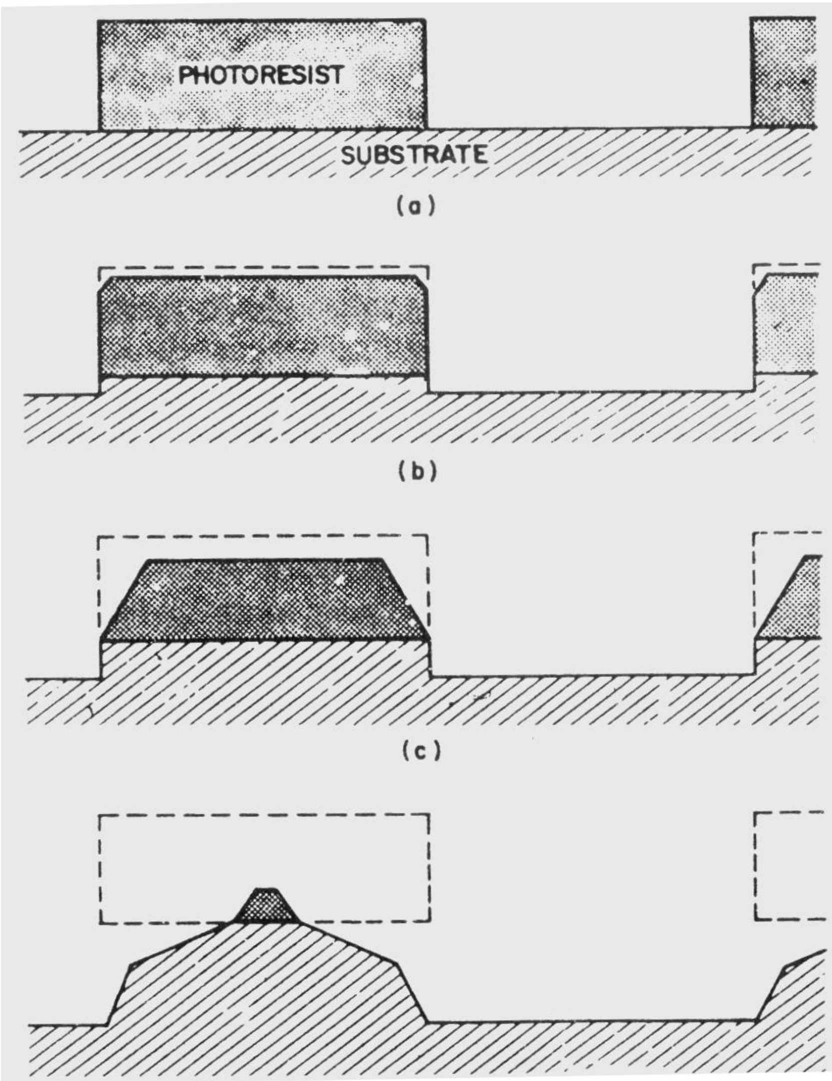
Basic Physical Effects during Impact

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 the wall is shadowed by etching mask and step
5. Etching rate of the base near the 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



Facets



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

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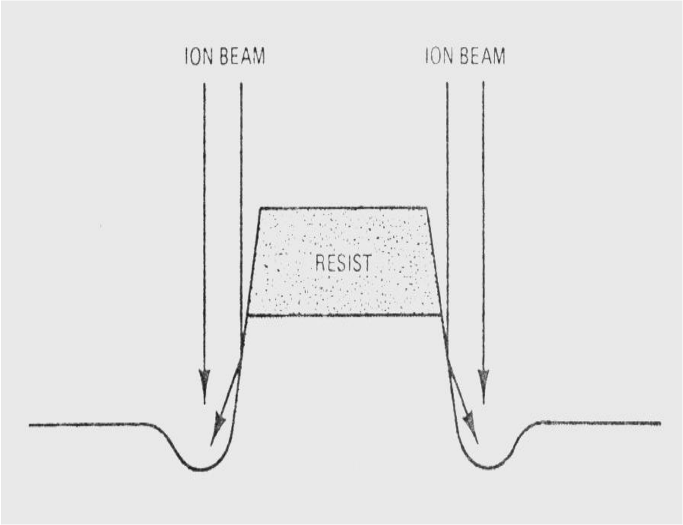
- **Facets is due to the effect No. 3**
- **The angle formed on the photoresist is the angle of maximum etching rate with respect to the beam**
- **The thin film can be etched even when much of the resist remains**
- **The angle formed on the thin film is also the angle of maximum etching rate with respect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

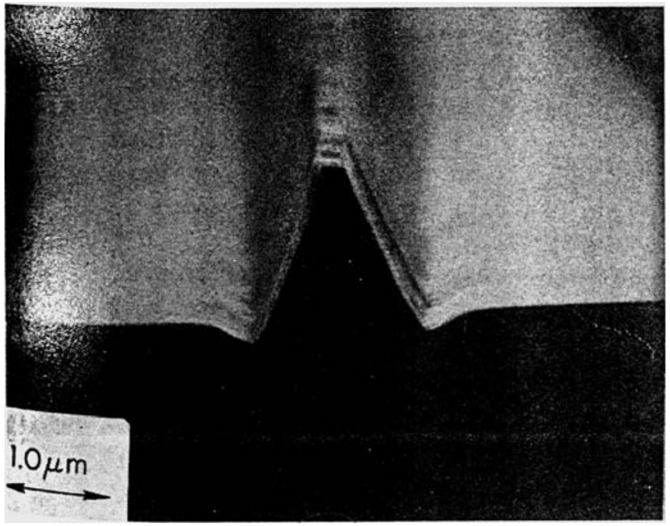
Trenching

- 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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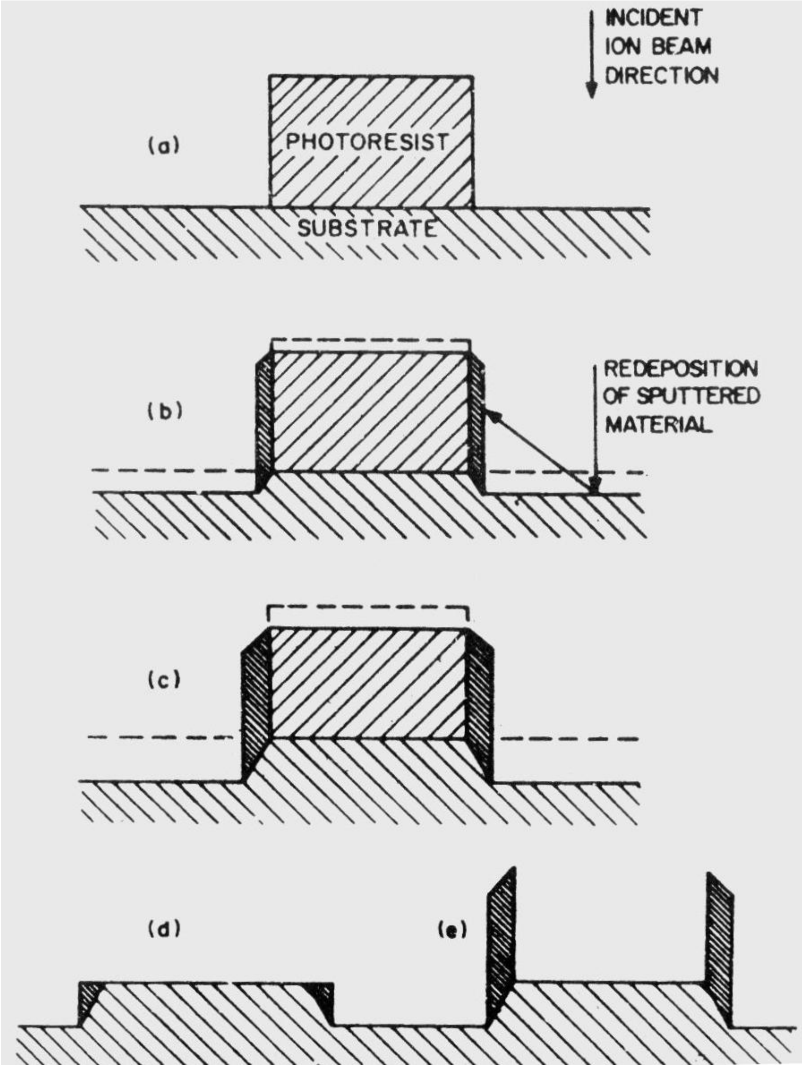
Redeposition



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

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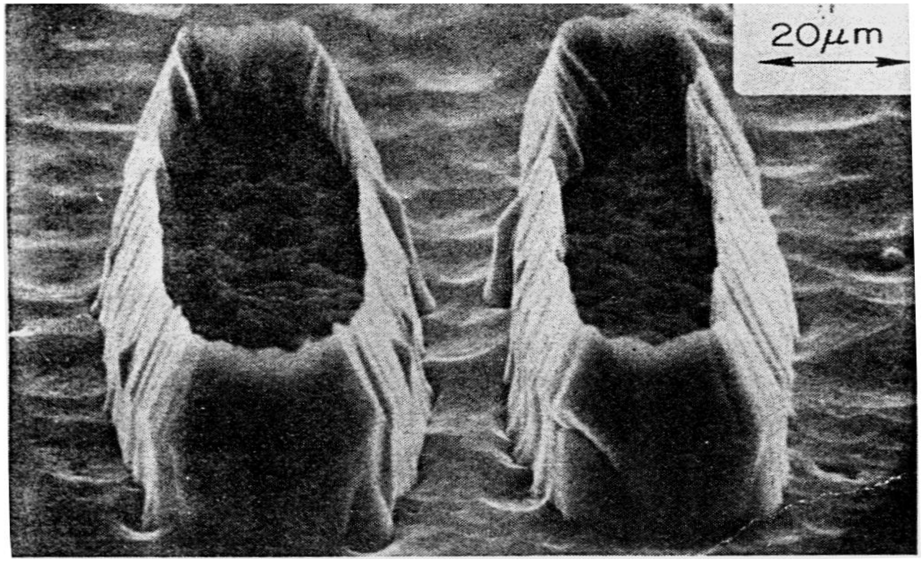
- If the redeposition rate by effect No. 6 is higher than the direct etching rate by effect No.2, the thin layer will be left on the sidewall
- Redeposition can be adjusted by:

  + Choosing the angle of ion beam such that the etch rate on the 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.

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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

Ion Etching (physical) vs Chemical Etching

- **Advantages of ion etching over chemical etching**

  + No 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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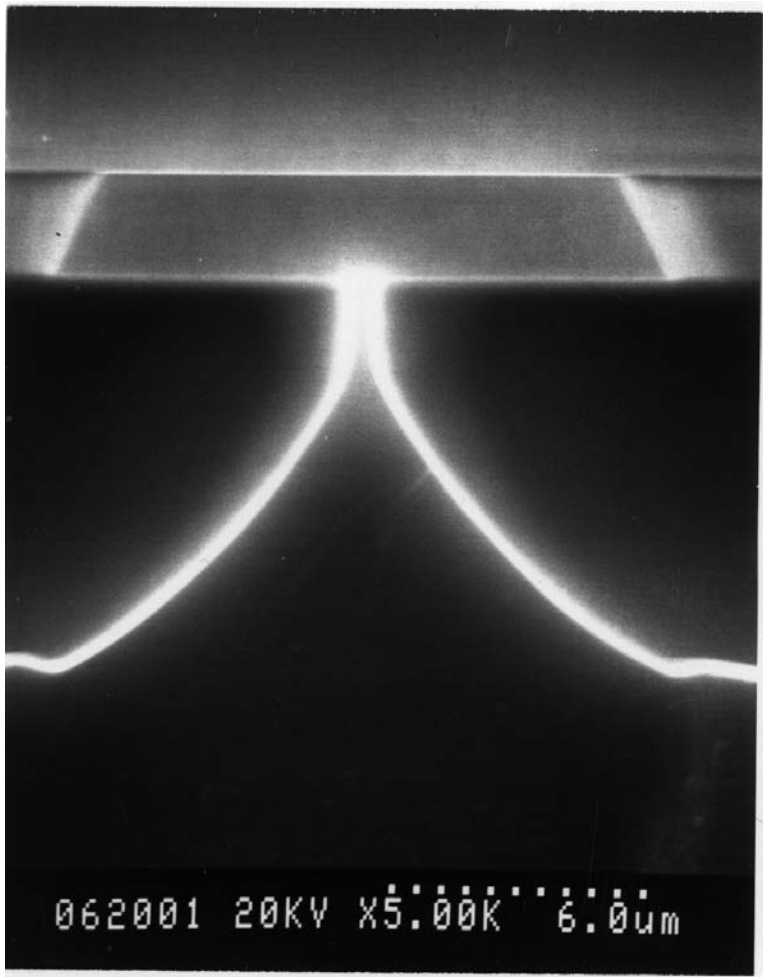

W. Fang, Ph.D. thesis, 1995

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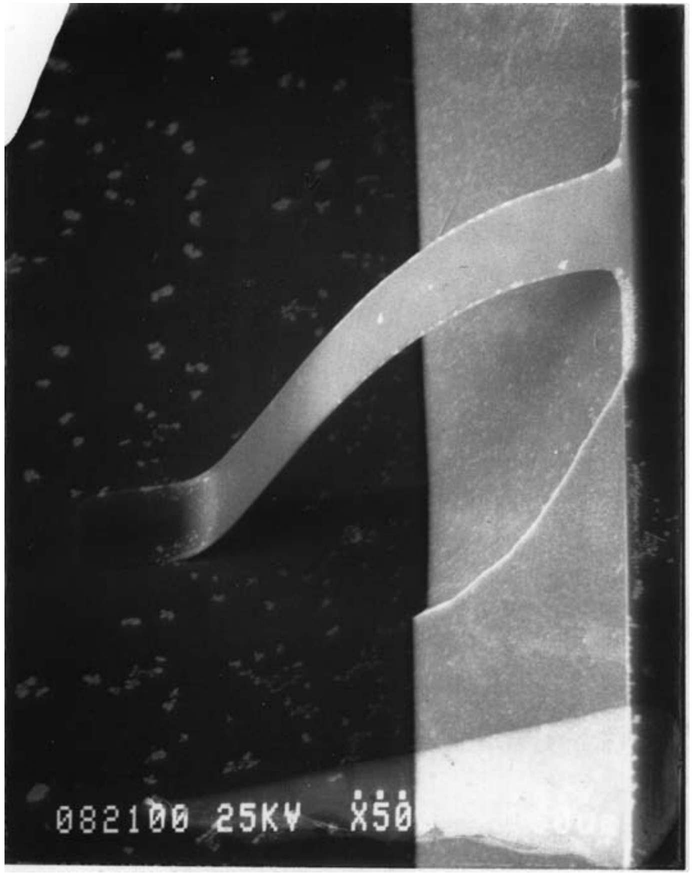
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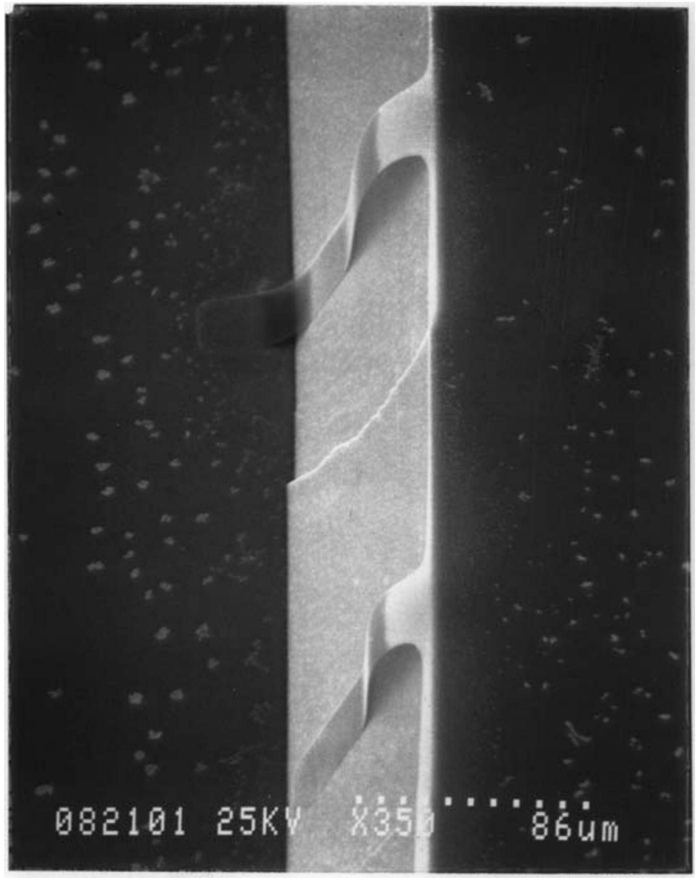
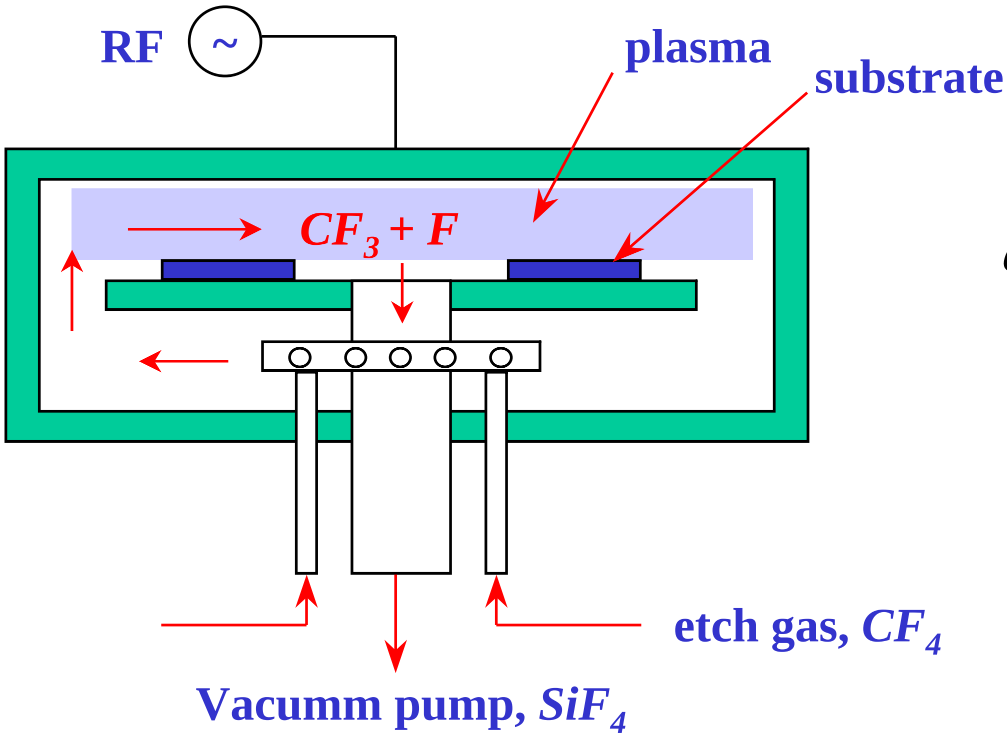

082101 25KV X350 86um

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**

2.3.3 Plasma Etching

- **Plasma etching - Plasma etching is the process to use plasma to generate active species (such as atoms and 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**

Plasma Etching vs Ion Etching

- **Advantages**

  + High selectivity (chemical)

  + Higher etching rate (chemical)

- **Disadvantages**

  + Undercut due to isotropic etch (chemical)

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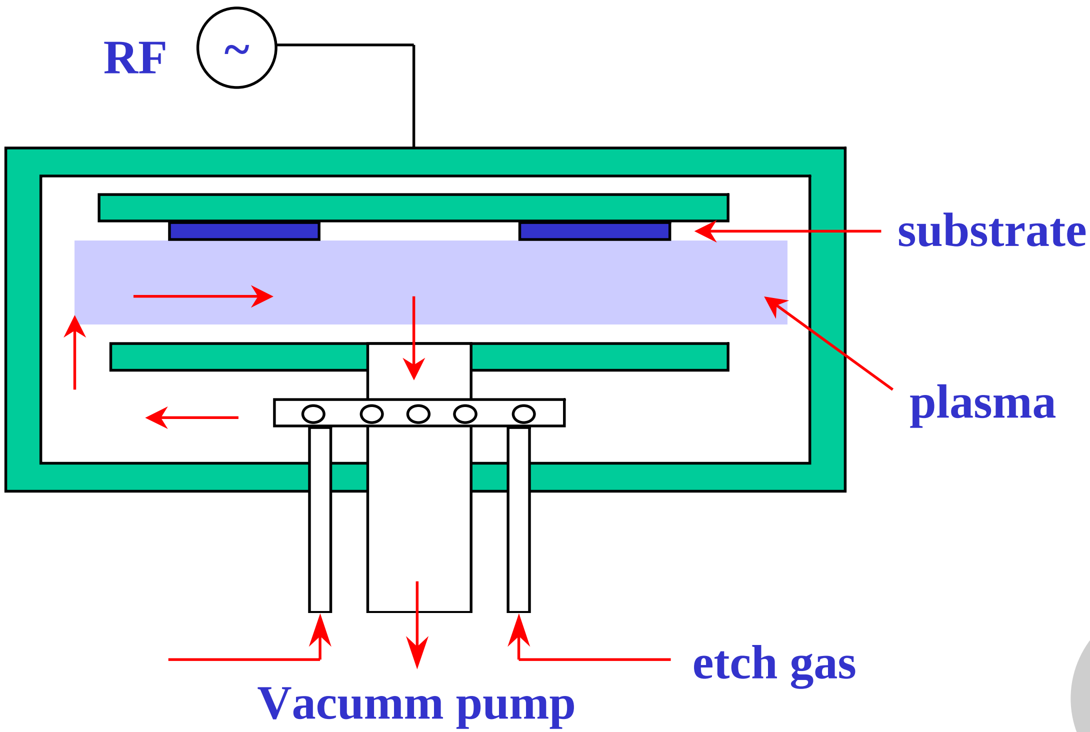
2.3.4 Reactive Ion Etching (RIE)

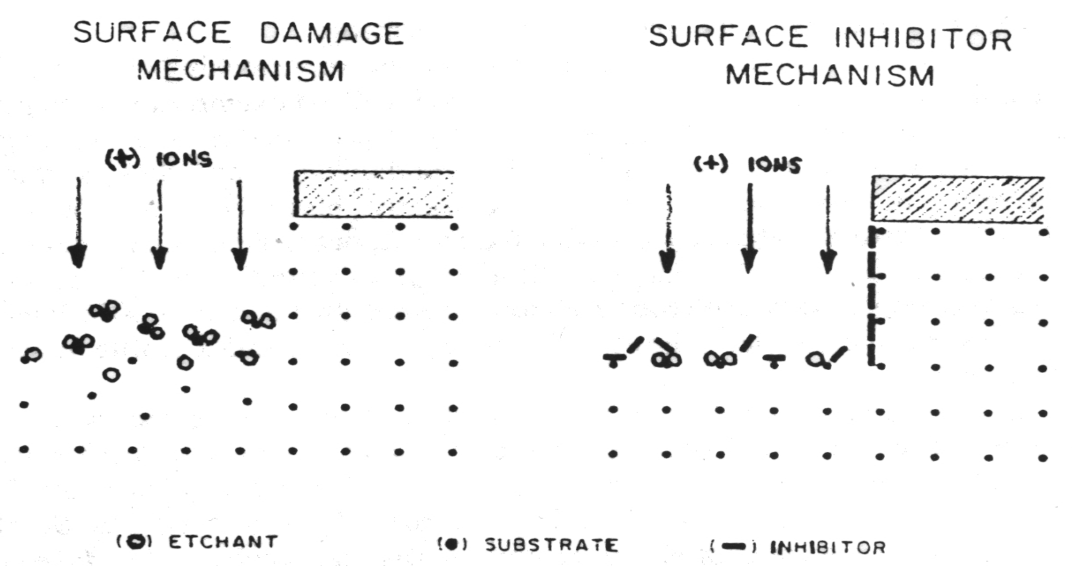
- **RIE – RIE is the etching process including (1) ions reacting with the substrate and remove the substrate atoms chemically, and (2) ions impact on the substrate and remove the substrate atoms physically**



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

  + **Surface damage - Relatively high energy impinging ions (> 50eV) produce 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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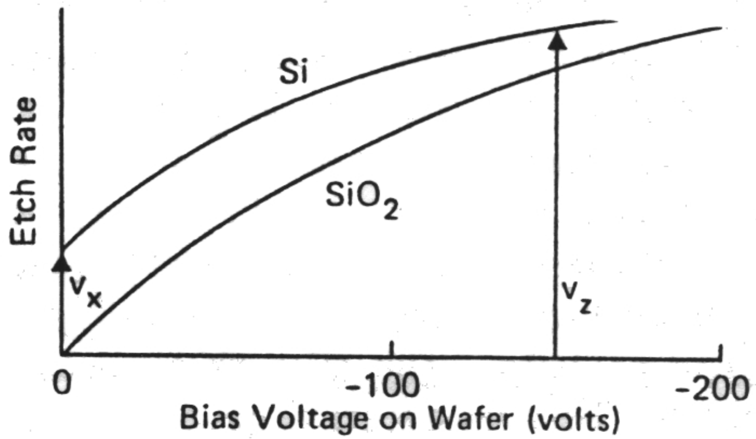
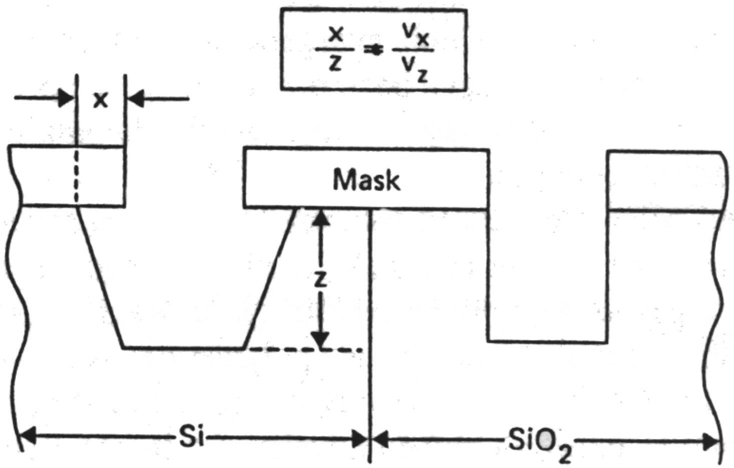
Control of Edge Profile

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

- Example 1





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

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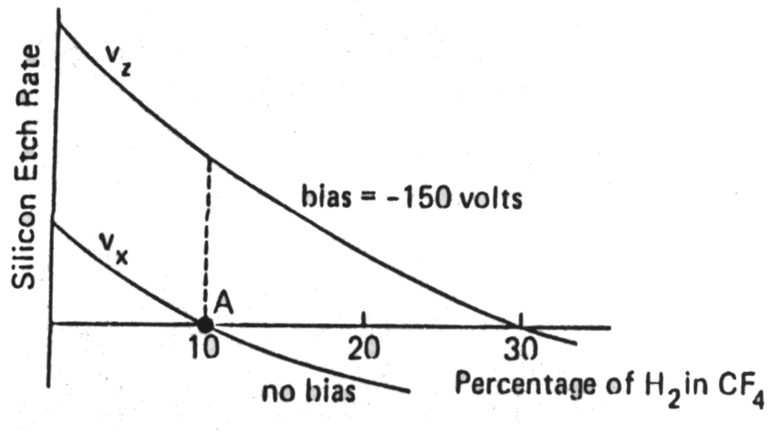
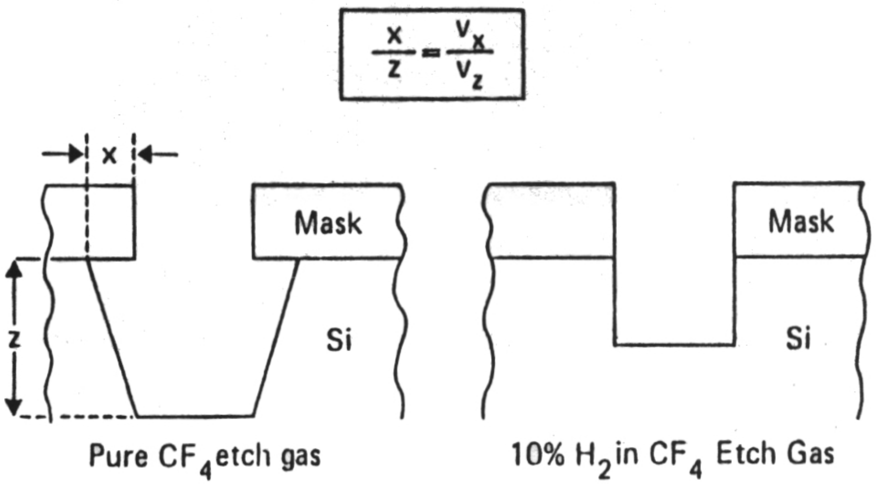
- **Example 2**

  + **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.

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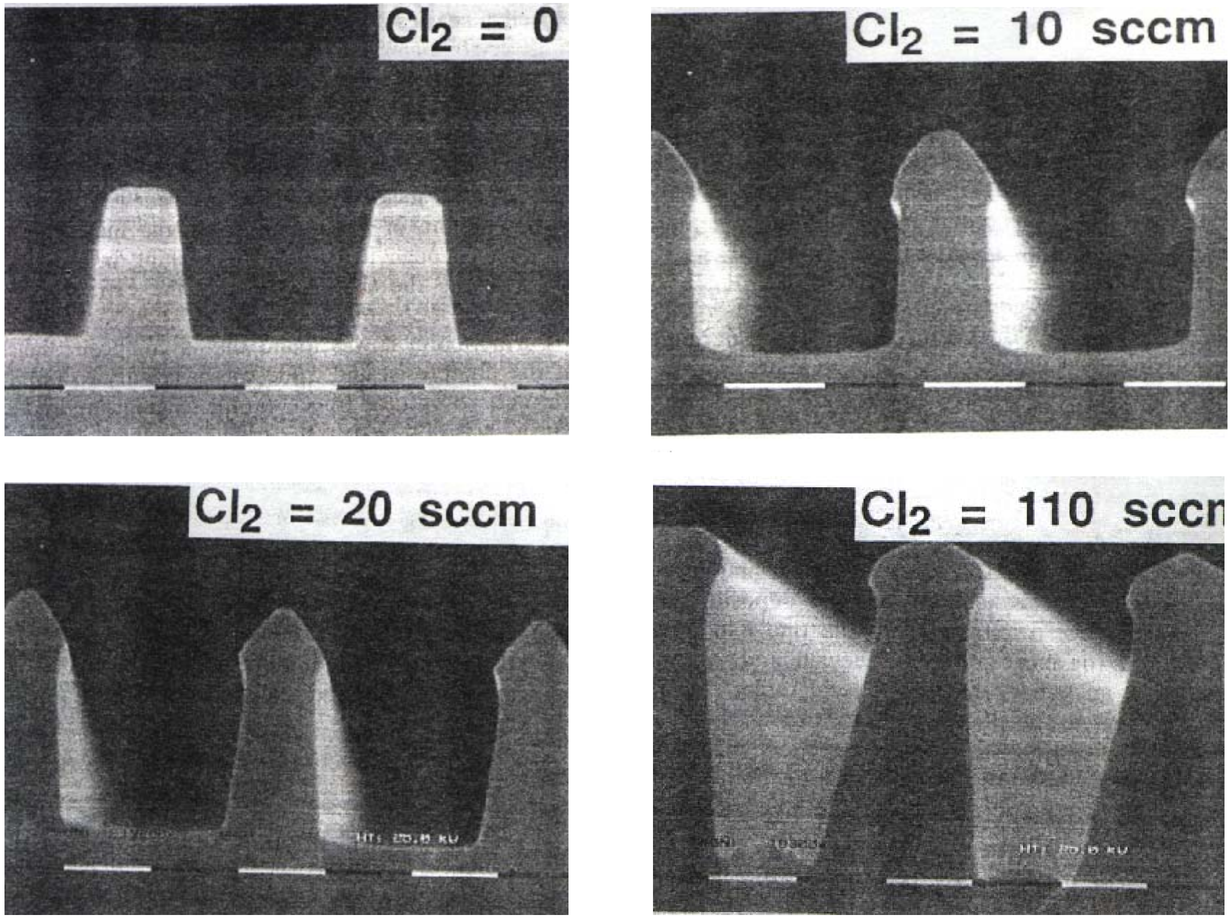
- **Variation of the edge profile and the etching gas (CF_4 + Cl_2)**



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RIE vs Plasma Etching and Ion Etching

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

- **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

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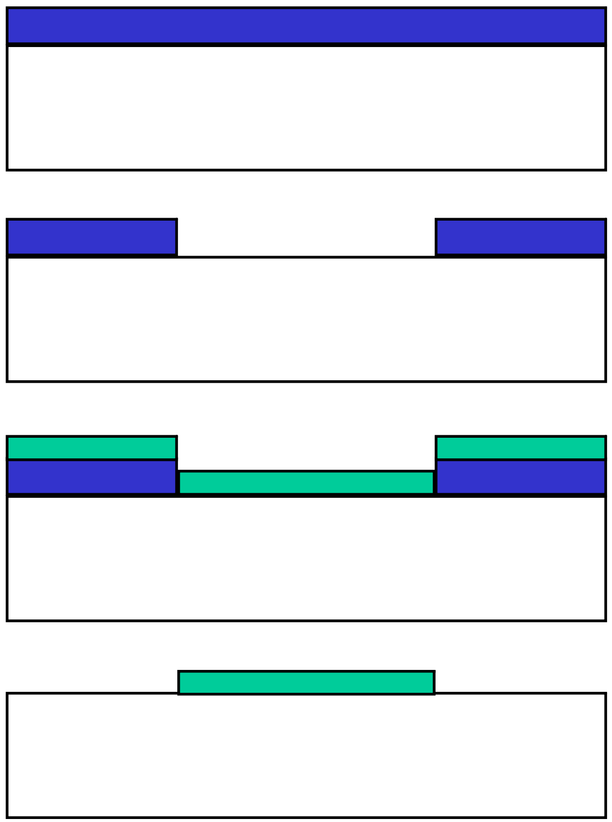
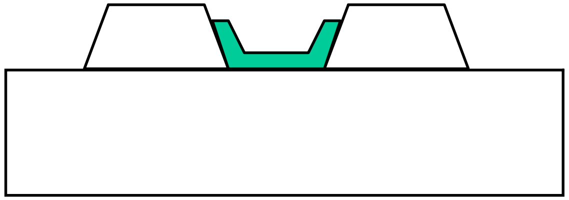
2.3.5 Lift off

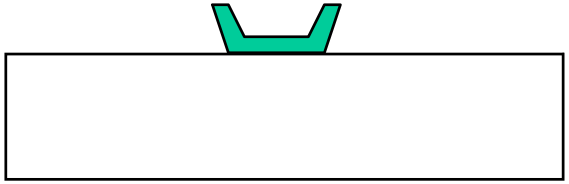
- **Lift off : to obtain the desired pattern by removing the photoresist**
- **Two disadvantages : (1) rounded feature profile, (2) temperature limitation**

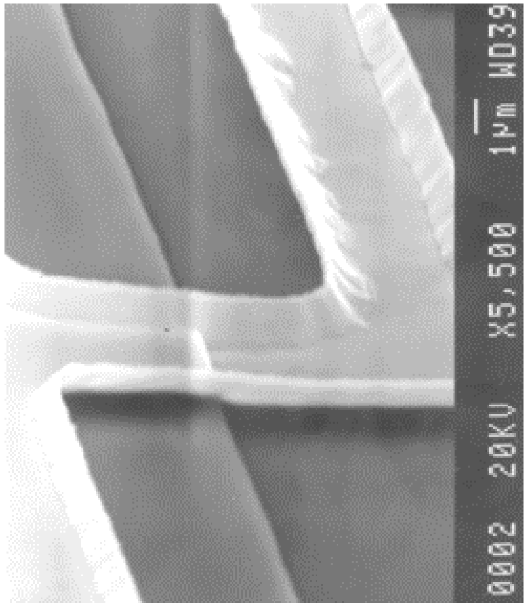


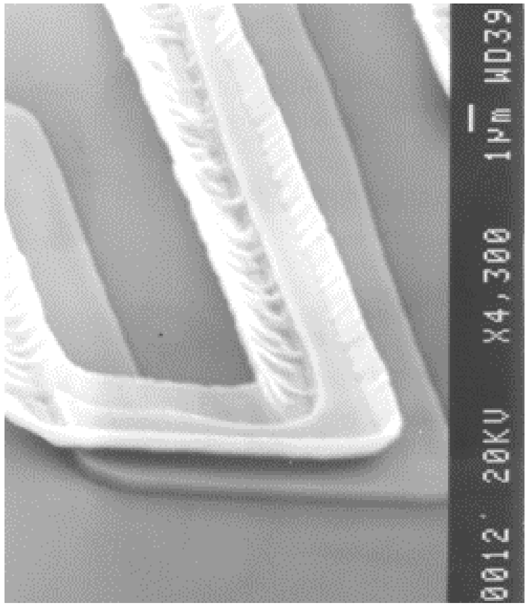
Lift off

- **After lift off**









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Conclusion

- **Etching is the 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**

  + anisotropic etching

  + less contamination
- **Wet etching has the following advantages**

  + higher etching rate

  + better selectivity

  + cheap equipment

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