Lecture 14

Microfabrication
– Pattern Transfer (VII)

- Dry Etching
  - Vapor Etching
    - Xenon Difluoride Etching
    - Vapor Phase Etching of Silicon Oxides
  - Plasma-Assisted Etching
    - Dry Etching
    - Ion Milling
    - Ashing
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    - Dry Etching
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Vapor Phase Dry Etching

- Plasma/RIE etching과 같이 복잡하고 비싼 장비 없이 plasma/RIE etching과 같은 특성을 얻음.
- 온도나 반응 가스의 분압을 조절함으로써 반응을 조절할 수 있다.
- 반면에 plasma etching에서는 많은 변수들이 조절가능하기도, 그렇지 않기도 하다. 즉, 가스 조성, 입력 전력 등이 복합적인 형태로 기판의 온도나 반응 가스 농도 등에 영향을 준다.
- Plasma etching과 다른 점은 자연 발생적인 non-plasma 반응은 모두 등방적이라는 점이다.

Xenon Difluoride Etching

- XeF_2 : Silicon non-plasma isotropic dry etching이 가능.

  Aluminum, silicon dioxide, silicon nitride, photoresist에 대해 높은 선택성을 갖고 있다.

- Hoffman : 간단한 bell-jar setup으로 1 Torr XeF_2로 상온에서 실험.
- Etch rate : 1~3 μm/min.
- Aluminum을 다치지 않으므로 mount하거나 DIP 패키징한 채 etching할 수 있다.
- 식각된 면은 거칠어서 깨끗한 면으로 쓰기 어렵다.
- 반응 속도가 조절되지 않으면 발열반응에 의해 발생한 열이 마이크로 구조물에 악영향을 줄 수 있다.
- XeF_2가 물(또는 수증기)와 반응해서 Xe과 HF를 발생시킨다. HF는 toxic하며 oxide를 식각한다.

Etching Mechanism

- 주된 반응

$$2XeF_2 + Si \rightarrow 2Xe + SiF_4$$

(1) non-dissociative adsorption of XeF_2 at silicon surface.

(2) dissociation of the absorbed gas, F_2.

(3) reaction between the adsorbed atoms and silicon surface to form an adsorbed product molecule, SiF_4 (ads).

(4) desorption of product molecule into the gas phase.

(5) the removal of non-reactive residue from the etched surface.

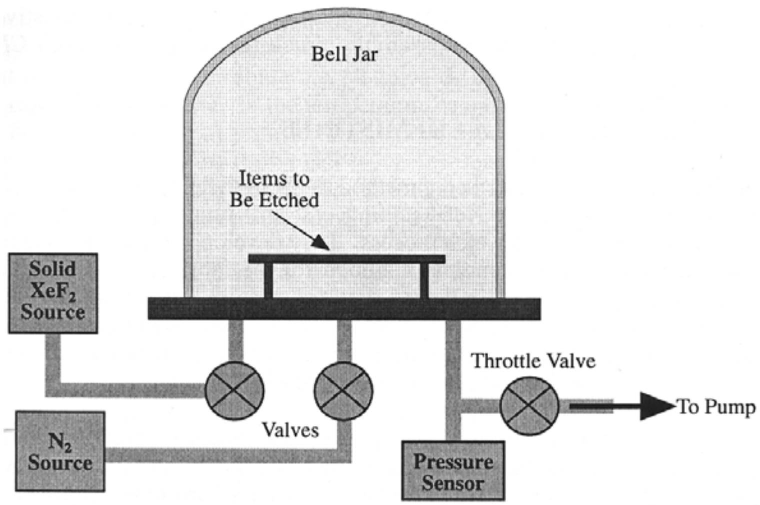


Illustration of an XeF_2 etch system. After Hoffman, et al.(1995). During etching, the XeF_2 valve is opened and the pump is throttled to achieve a pressure of 1 Torr to sublimate the XeF_2 . Etching is done in cycles to allow generated heat to dissipate. After etching is completed, N_2 is used to purge the system.

XeF_2 Pulse Etching

- Chang : Dehydrated in an oven at 120°C for at least 5 min.

이것이 잘 안되면 식각 시작 후 뿌연 막이 생기고 식각이 늦어지며 중지된다.

이 막은 XeF_2와 silicon사이의 반응으로 생긴 silicon fluoride polymer막이다.

또한, 수분은 XeF_2와 반응하여 HF를 만들고 이는 oxide를 식각한다.

발열량 : 1 W/cm^2. 대면적 (a few cm^2) 식각시 1 μm/pulse의 식각율.

소면적 (hundreds of μm^2) 식각시 40 μm/pulse의 식각율.

따라서, pulse etching을 시도. 20 mTorr까지 진공을 만든 후 2.5 Torr까지 XeF_2 주입.

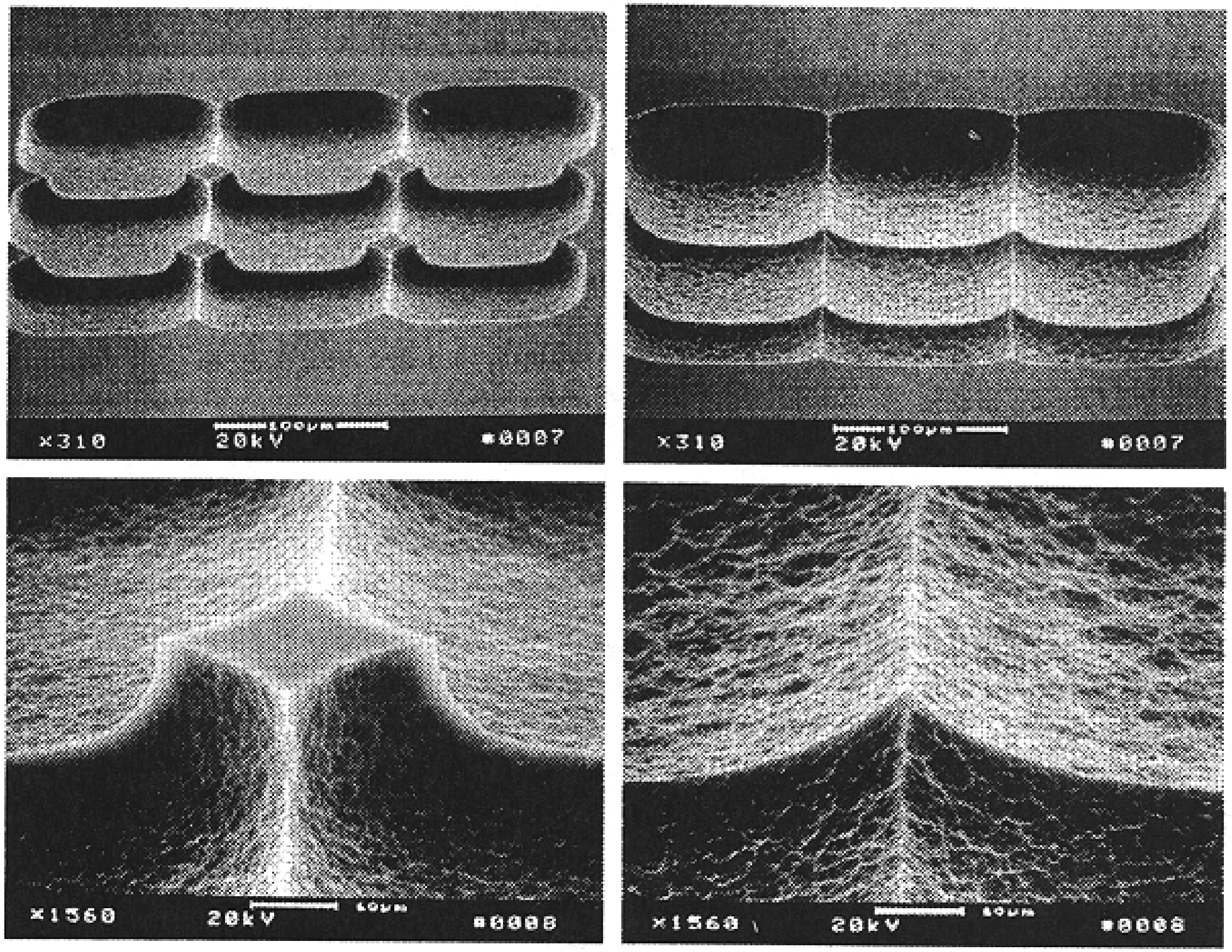
1분 주기로 반복적으로 식각. 이 경우, 식각율이 5-10 μm/pulse.

계속 식각하는 경우는 식각율 : 3-5 μm/min at 2.5 Torr.

3인치 웨이퍼 상에서의 식각 균일성은 좋지 않음.

	Constant pressure etching (10 min)	Pulse etching (10 pulses)
최저식각율	5.84 μm	8.43 μm
최고식각율	20.74 μm	21.69 μm

Etch Profiles



SEMs of etch pits resulting from arrays of 50μm square openings with 50 μm spacing after six and ten 3T, 60s pulses. The oxide mask has been removed with HF.

Vapor Phase Etching of Silicon Oxides

- J. Lee : IEEE MEMS Proc.97, pp.448-453, 1997. or
JMEMS Vol.6, No.3, pp.226-233, 1997.

• HF와 methanol 사용, vapor phase etching.

• Dotted line : gas-liquid interface.

- 종래의 방법 A

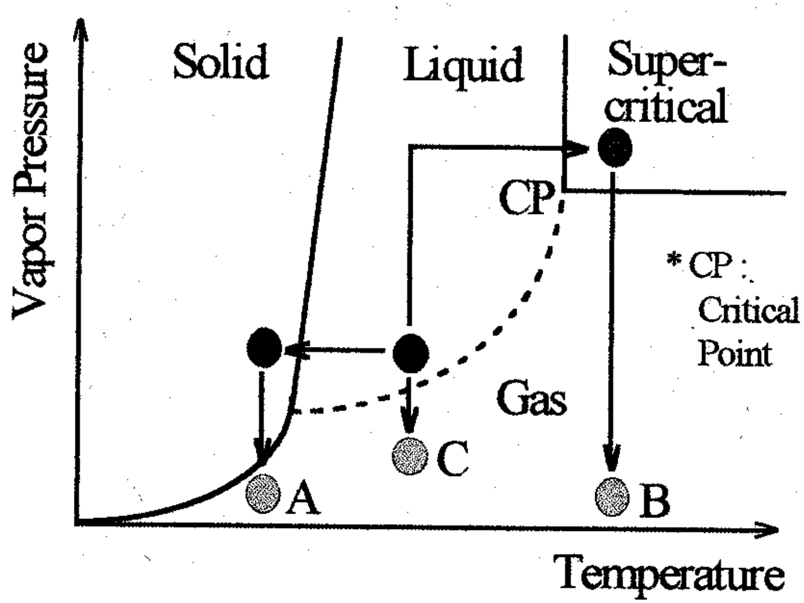
• Rinse liquid를 low temperature melting point material로 교체. 예를 들면, p-dichlorobenzene.

• 낮은 압력에서 승화시킴.

- 종래의 방법 B

• Rinse liquid를 low pressure supercritical state material로 교체. 예를 들면, CO_2.

• 낮은 압력에서 승화시킴.



Phase diagram of dry release processes

- A, B 모두 고 압력기기이므로 다루는 데 주의해야 함.

Chemical Reaction Mechanism

- 식각시 HF and CH_3OH gas molecules이 silicon dioxide 표면에 흡착.

HF (g) $\leftrightarrow$ HF (ads)

M (g) $\leftrightarrow$ M (ads), M = CH_3OH.

흡착된 HF와 CH_3OH가 HF_2^-를 생성.

$$2HF(ads) + M(ads) \rightarrow HF_2^-(ads) + MH^+(ads)$$

HF가 SiO_2와 반응해서 HF의 F가 SiO_2의 O를 대체한다.

$$SiO_2(s) + 2HF_2^-(ads) + 2MH^+(ads) \rightarrow SiF_4(ads) + 2H_2O(ads) + 2M(ads)$$

생성물 SiF_4, H_2O, CH_3OH는 oxide표면에서 분리된다.

SiF_4 (ads) $\leftrightarrow$ SiF_4 (g)

M (ads) $\leftrightarrow$ M (g)

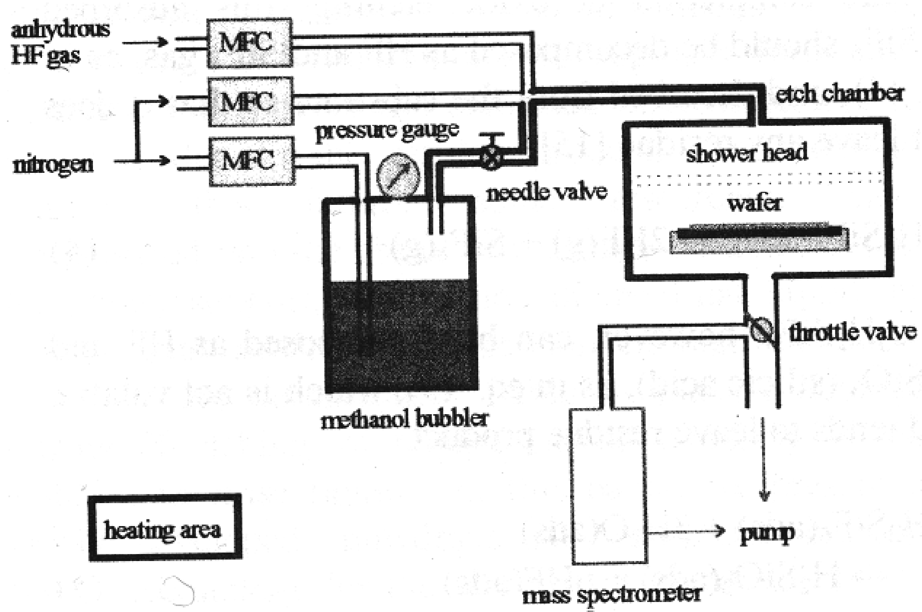
H_2O (ads) $\leftrightarrow$ H_2O (g)

VPE System

- Etch chamber, gas delivery system, exhaust system, mass spectrometer, controller.
- Etch chamber : Aluminum coated with Teflon film to prevent corrosion from HF and CH_3OH.
- Wafer와 chamber wall은 80 °C로 유지. Vapor의 응축방지.
- HF와 CH_3OH의 flow rate는 식각 성능에 매우 중요함.
- CH_3OH flow rate :

  N_2 carrier gas의 flow rate,

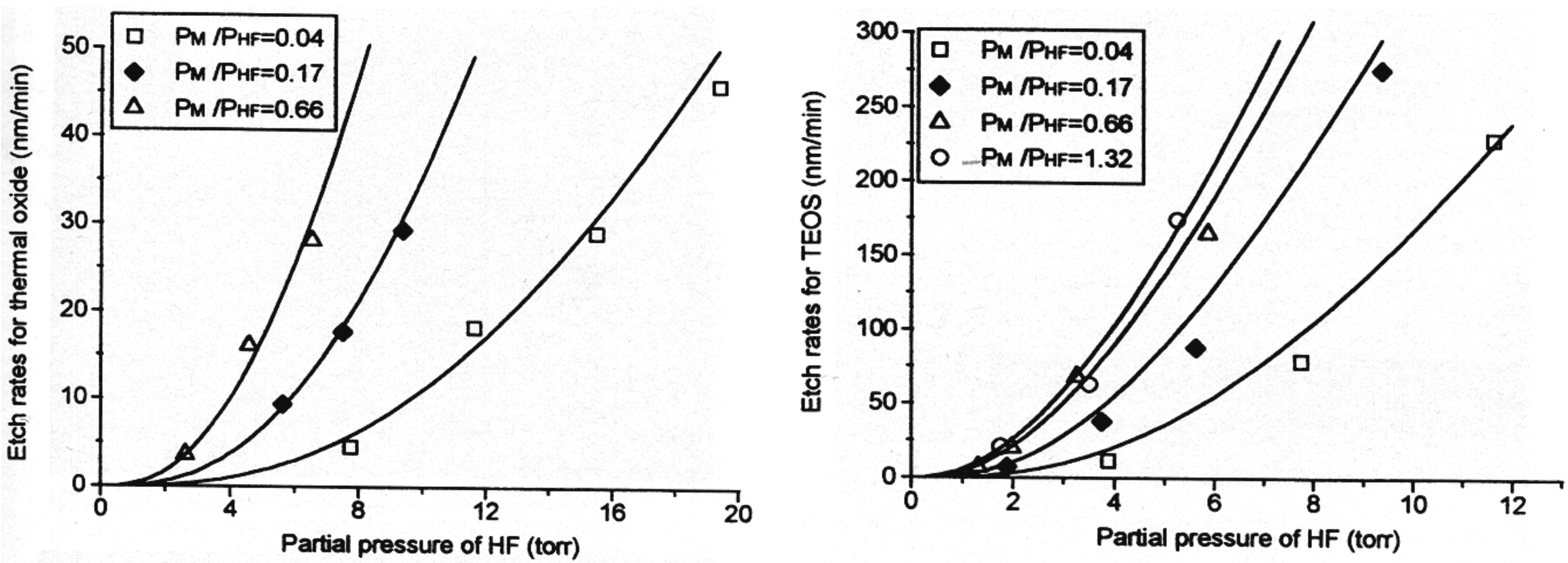
  bubbler temperature, bubbler pressure
- HF : MFC로 조정.



A schematic of the VPE(vapor-phase etch) system using anhydrous HF gas and CH_3OH vapor

Etch Rates of Oxide

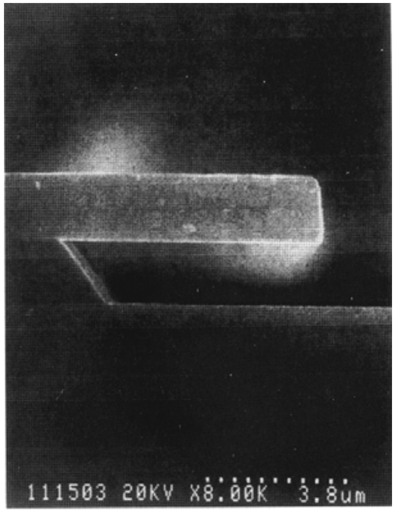
- Thermal oxide : 450 nm thick, wet oxidation at 950 °C.
- TEOS (tetraethylorthosilicate) : 800 nm thick, LPCVD at 710 °C.
- Partial pressure가 높을 수록 etch rate이 증가.

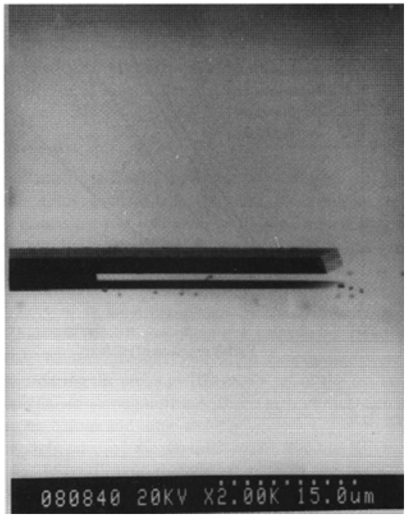


Etch rates for thermal oxide and TEOS: (a) for thermal oxide and (b) TEOS [22].

Cantilever Release

- 구조물 : 2 µm thick polysilicon cantilever.
- 희생층 : TEOS 와 LTO.
- 식각조건 : HF 15 Torr, CH_3OH 4.5 Torr at 25 °C.
- 식각율 : TEOS 10 µm /h, LTO 3 µm /h.
- 폭 40 µm 식각시 7.5 시간 걸림.
- 폭 80 µm 식각시 buffered oxide etchant로 4시간 + VPE로 7.5시간 걸림.





SEM photograph of partially etched sacrificial layers: (a) cross-sectional view with sacrificial TEOS and (b) perspective view with sacrificial LTO.

Plasma-Assisted Etching

- A low-pressure glow-discharge plasma produces ionized species sufficiently.
- When directed to the surface of the wafer,
- (1) these ions can produce both sputtering effects,
- (2) removing material by direct ion-beam bombardment,
- (3) and chemical-reaction effects,
- (4) converting surface atoms to volatile species that can be removed by the vacuum pump.

Dry Etching

- Dry etching : 고체 표면을 gas phase로 식각한다.

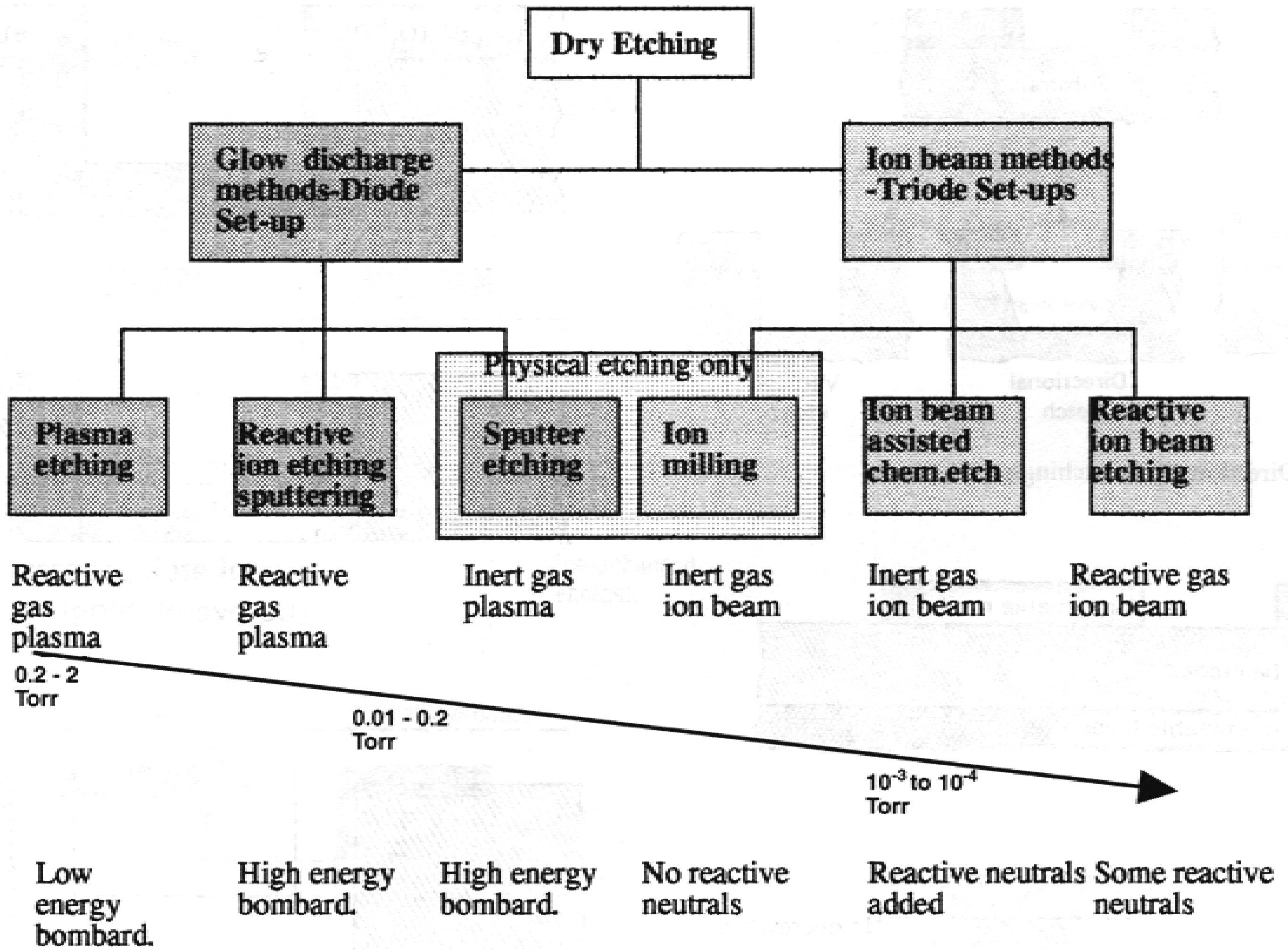
  이용 (1) 물리적인 이온 충격.

  (2) 표면에서의 반응제와의 화학반응.

  (3) 물리와 화학적인 방법의 혼합.

- Glow discharge techniques (diode set-up) : 플라즈마가 시료가 놓인 chamber에서 발생.
- Ion-beam techniques (triode set-up) :플라즈마는 별도의 chamber에서 발생하고 이온이 grid에 의해 시료가 놓은 곳으로 이동.
- Sputter/ion etching과 ion-beam milling 또는 ion-beam etching에서는 식각은 물리적인 효과에 의해서 일어난다. 즉, 에너지를 갖고 있는 Ar^+이온과 기판표면과의 모멘트의 변환.
- 물리/화학적 식각에서는 충돌하는 이온, 전자, photon이 화학 반응을 유도하거나, sidewall-protected ion assisted etching에서는 보호막이 바닥면에 충돌하는 입자에 의해 제거된다. 결과적으로 식각은 거의 깨끗한 바닥면에서만 일어나게 된다.
- 10^{-3} ~ 10^{-4} Torr 영역에서는 이방성은 얻기 쉽지만 선택비는 좋지 않다.
- 1 Torr 영역 (plasma etching)에서는 화학적인 효과가 지배적이어서 선택비는 좋으나 등방성이다.

Various Dry Etching Techniques



Relationship between the various dry etching techniques. (Adapted from Lehmann, H.W., in Thin Film Processes II, J.L. and Kern, W., Eds. Academic Press, Boston, 1991.

Ion Milling

- The least selective use of ions produced in a plasma is for the sputtering away of material.
- This can be done with a blanket exposure to a plasma, for example argon plasma, removing material from all parts of the wafer.
- Selectivity is achieved by the relative rate of sputtering of different materials.
- Focused ion beam milling, using an argon ion source in combination with focusing electrodes so that ions from the plasma only strike the surface within a small region.
- Direct-write patterning can be accomplished by scanning the ion-beam location across the wafer surface.
- Masking of ion-beam removal is difficult because the physical process of sputtering has no chemical specificity.

Ashing

- The ions have some chemical reactivity, such as the ions produced in an oxygen plasma.
- The result of reaction of the ionic species with the wafer surface can be a volatile species.
- The volatile species are removed by the vacuum pump.
- The use of blanket oxygen-plasma exposure to remove photoresist from wafers after completion of lithography processes,
- It converts the polymer to carbon dioxide and water.

Plasma Chemistries

- Plasma chemistries can be used for etching all of the microelectronic thin films: oxides, nitrides, metals and silicon.
- Most etch chemistries involve either flourinated or chlorinated species.
- Recipes are developed to achieve the desired chemical selectivity, for example, etching oxide and stopping on nitride, or etching silicon and stopping on oxide.
- Generally, the selectivity that can be achieved with plasma etching is not as great as with wet etching.
- As a result, RF power levels, gas mixtures and flow rates, and pressure can be critical to achieve the desired result.

Examples of etch gases for plasma etching of selected materials.

Material to be etched	Etch gas
Silicon or polysilicon	CF_4, SF_6
Silicon dioxide	CF_4/H_2
Silicon nitride	CF_4/O_2
Organics	O_2, O_2/CF_4, O2 /SF_6
Aluminum	BCl_3

Reactive Ion Etching

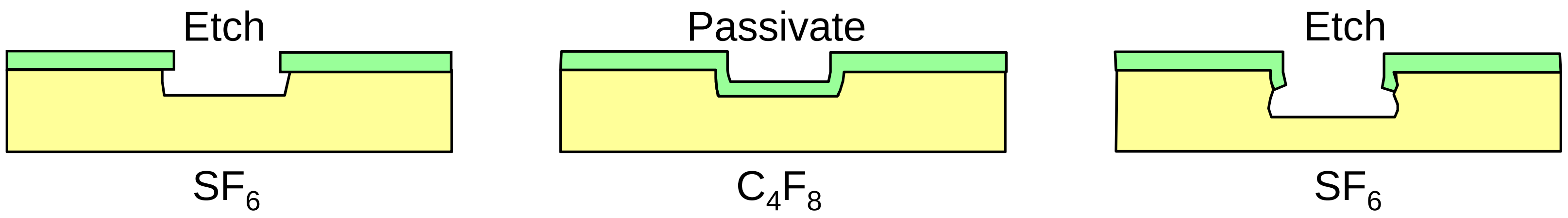
- The shape of plasma-etched feature is a strong function of the etching conditions.
- The higher the base pressure in the plasma, the more isotropic the etch profile.
- As the pressure is reduced in a plasma etcher, the etch rate generally reduces, and the etch becomes more directional because the ions that are accelerated through the dark space at the edge of the plasma strike the surface with a definite orientation.
- At higher pressure, the trajectories of these atoms are randomized by collisions, producing a less directional ion flux at the wafer surface.
- At the limit of low pressures and a correspondingly high degree of directionality, the process is called reactive ion etching, essentially directing a flux of reactive ions normal to the surface.
- Sidewalls are not significantly etched because the ions do not strike them.
- As a result, nearly vertical sidewall features can be produced.

Deep Reactive Ion Etching

- This process takes advantage of a side-effect of a glow discharge, the tendency to create polymeric species by chemical crosslinking.
- In fact, most plasma processes are a critical race between deposition of polymeric material from the plasma and the removal of material from the surface.
- In well-designed plasma chemistries, removal dominates.
- However, in a new process developed by workers at Bosch, the deposition of polymer from the etchant is used to great advantage.

Deep RIE Process

- A photoresist mask can be used.
- For very deep etches, a combination of phtoresist and oxide may be required.
- The etch proceeds in alternating steps of reactive-ion etching in an SF_6 plasma and polymer deposition from a C_4F_8 plasma.
- During the etch process, the polymer is rapidly removed from the bottom of the feature but lingers on the sidewall, protecting it from the SF_6 etchant.
- As a result, the silicon beneath the first cut is removed during the second etch cycle, but the top of the feature does not become wider.
- Eventually the polymer protecting on the sidewalls is eroded.
- At that point, another polymer deposition step is used, and the cycle is repeated.



Scalloping

- At low magnification, the structures appear perfectly smooth and the sidewalls are perfectly vertical.
- At higher magnification, a slight scalloping of the walls corresponding to the alternation between etching and passivation is observed.
- It is now possible to cut features all the way through the wafer thickness with a precision of a few microns.

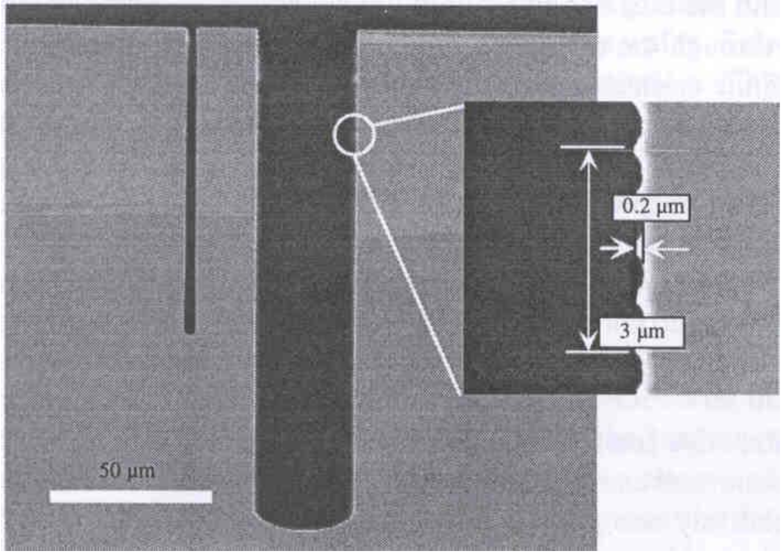


Photo of features etched in silicon with DRIE. Note that the slender trench etches at a slower rate than the wider trench.

Microloading and Footing Effects

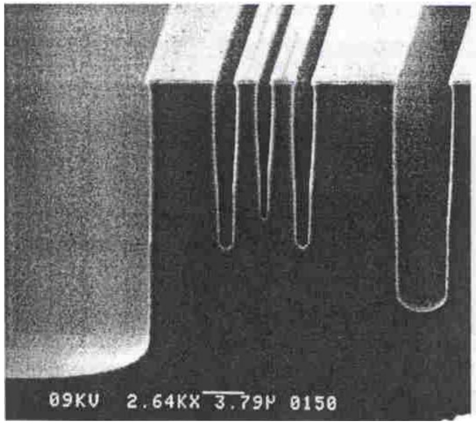


Fig. Microloading effect

- Microloading effects

- Interdependency between the etch rate and the aspect ratio
- Wide trenches are etched more fastly than narrow trenches
- Footing or bowing phenomenon occurs.
  → Structure shape deformation occurs.

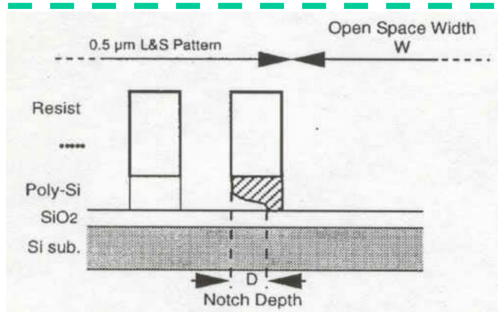


Fig. Footing effect

- Footing effects

- Rapid lateral etching at the silicon / oxide or polysilicon / oxide interface
- Evident in DRIE systems because of high-density plasma

• Footing in comb actuator

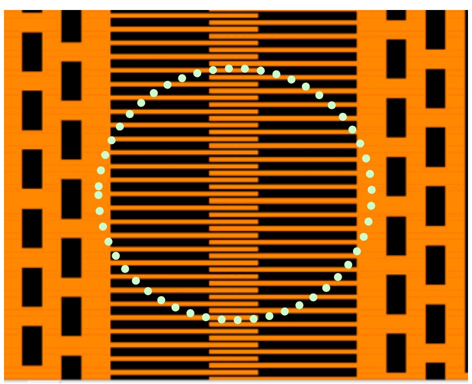


Fig. Comb actuator layout

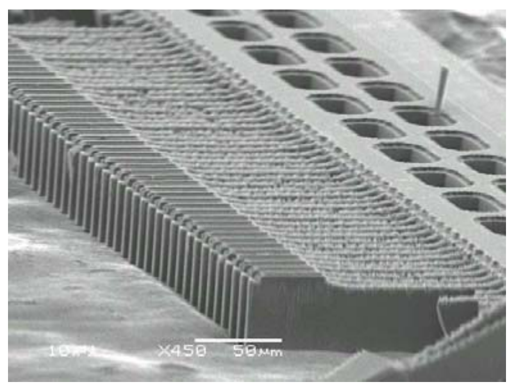


Fig. Footing phenomena (bottom side of the structure)

- Footing occurs because of etch rate difference between trenches
  → 'L' shape comb electrodes
  → Electric spring exists in differential driving mode
  → Nonlinear differential driving characteristics