What are the key elements of this ‘new’ fabrication technology?

- Making a pattern (template)
- Transferring that template into your material

1. Lithography
2. Metalization and making contact to the outside world
3. Defining local electronic behavior: doping
4. Isolating electronic regions: oxidation
5. Carving out different regions of the material: etching

Wet Chemical Etches: provide different etched profiles

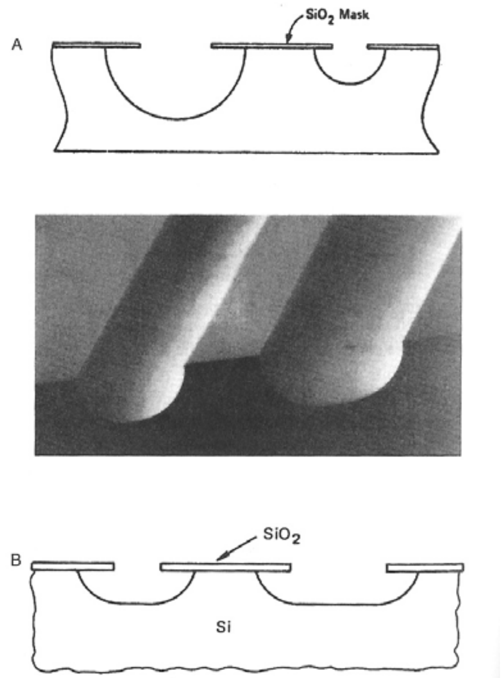


Figure 4.32 Isotropic etching of Si with (A) and without (B) etchant solution agitation.

Isotropic etch

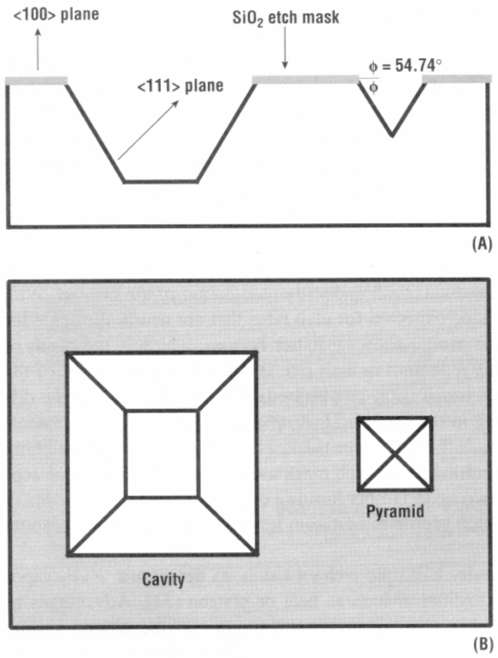


Figure 19.10 Cross section (A) and top view (B) of pyramidal holes and cavities formed in a (100) silicon wafer with an anisotropic etchant.

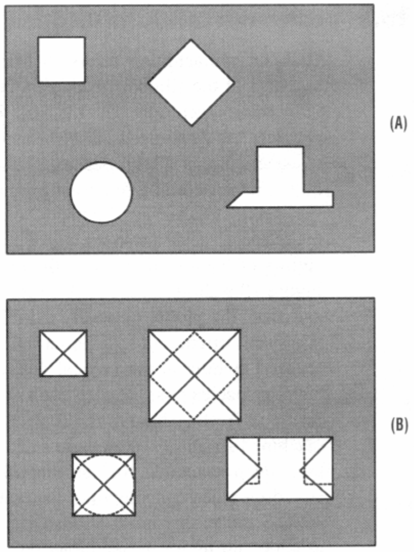


Figure 19.11 Effect of mask opening orientation on the etch profile. (A) Top view of mask openings as oriented to the <110> direction. (B) Etched structures resulting for an anisotropic etchant on (100) silicon.

Crystallographic etch

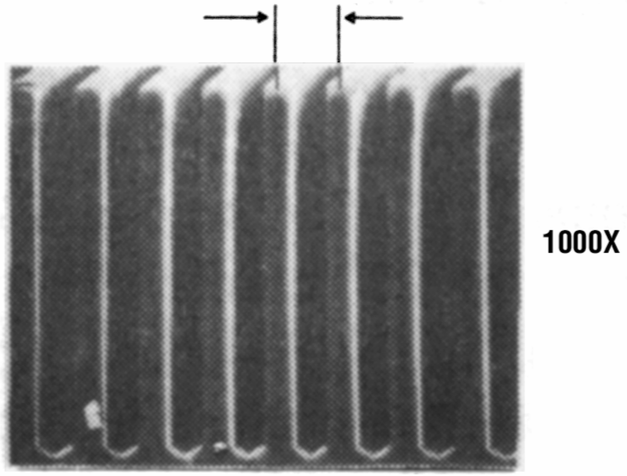
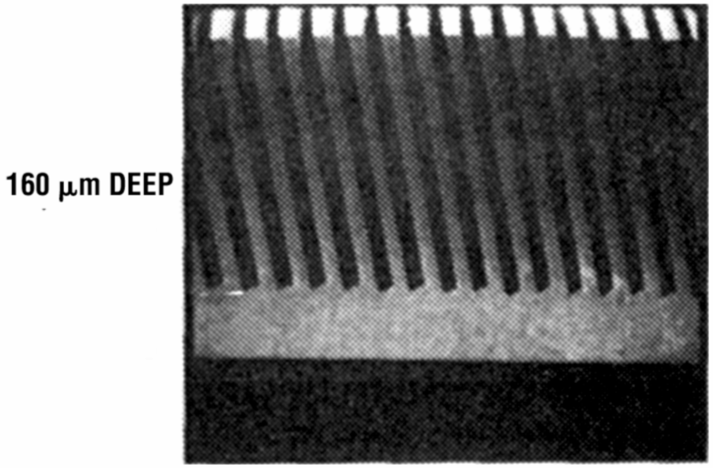


Figure 11.6 (100) silicon wafers after directional etching in KOH, isopropyl alcohol, and water. The upper photo shows a 50-mm-deep etch. The lower photographs are of 80-mm-deep trenches etched at 10 mm pitch on (110) and 107off (110) *(after Bean, ©1978 IEEE).*



Deep etches with high aspect ratios possible: with careful understanding of crystal orientations

3-component Etch of Silicon

Etching generally a combination of *oxidation* (breaking bonds) and making the oxidized form *soluble in solution*

$Si + 2\ h+ \rightarrow Si^{2+}$

Where do we get the holes?

→ $HNO_3 + HNO_2 \rightarrow N_2O_4 + H_2O$

$N_2O_4 = 2\ NO_2$

$2NO_2 = 2\ NO_2^- \boxed{+\ 2h^+}$

$2\ NO_2^- + \boxed{2H^+} = \boxed{2HNO_2}$

Where do we get H^+?

→ $H_2O = OH^- + H^+$

Total: $Si^{2+} + 2\ (OH)^- \rightarrow Si\ (OH)_2$

$Si(OH)_2 \rightarrow SiO_2 + H_2$

How do we make the oxide soluble?

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

↑

Etch Rate of Silicon in HF/HNO$_3$/dilutent

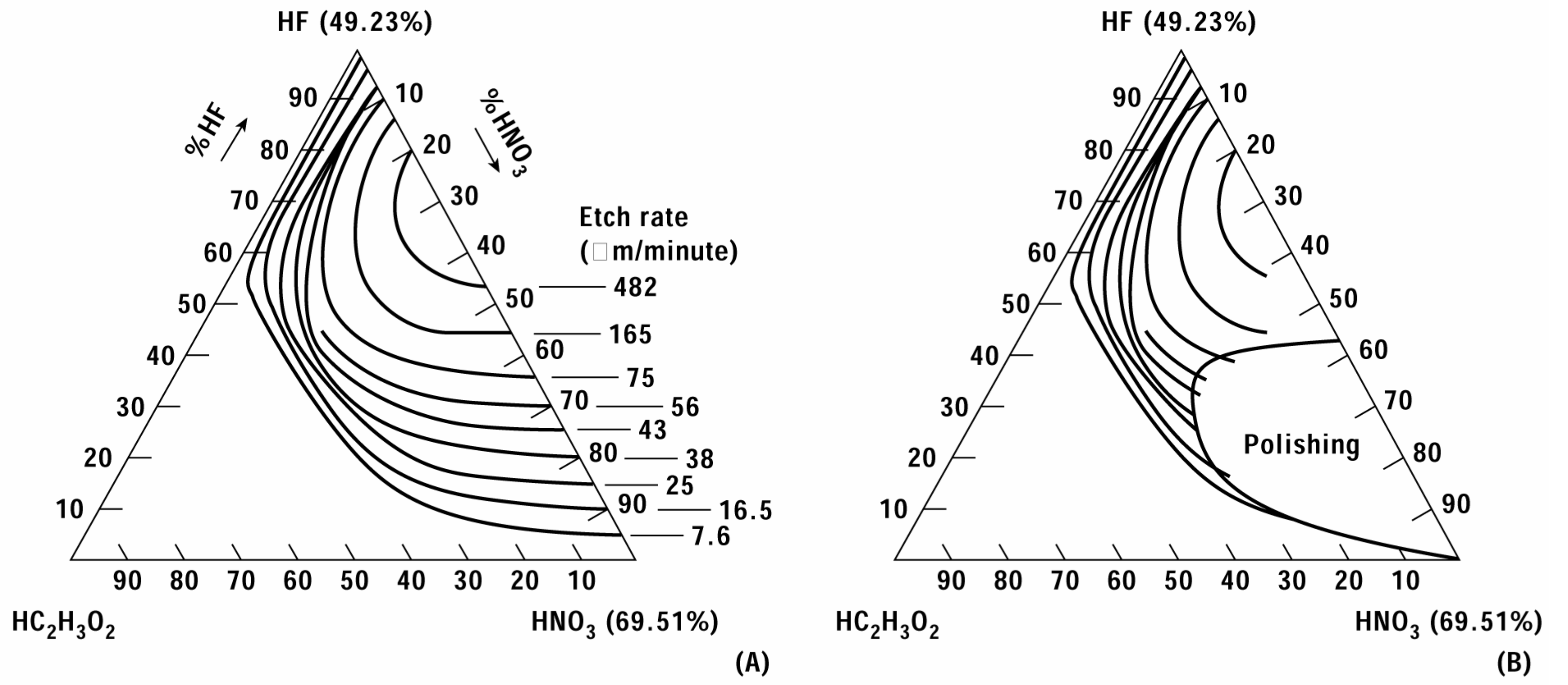


Figure 11.4 The etch rate of silicon in HF and HFO$_3$ *(after Schwarz and Robbins, reprinted by permission of the publisher, The Electrochemical Society Inc.).*

A Schematic View of the Etch Process

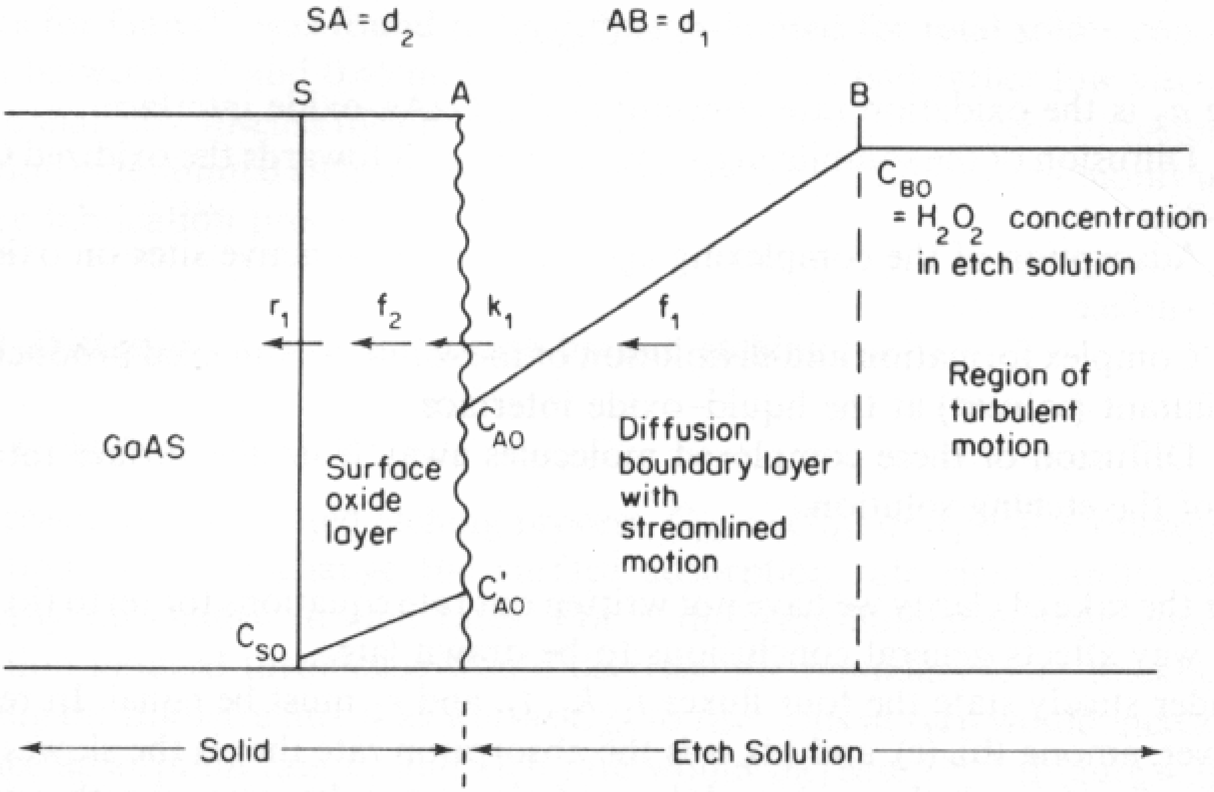


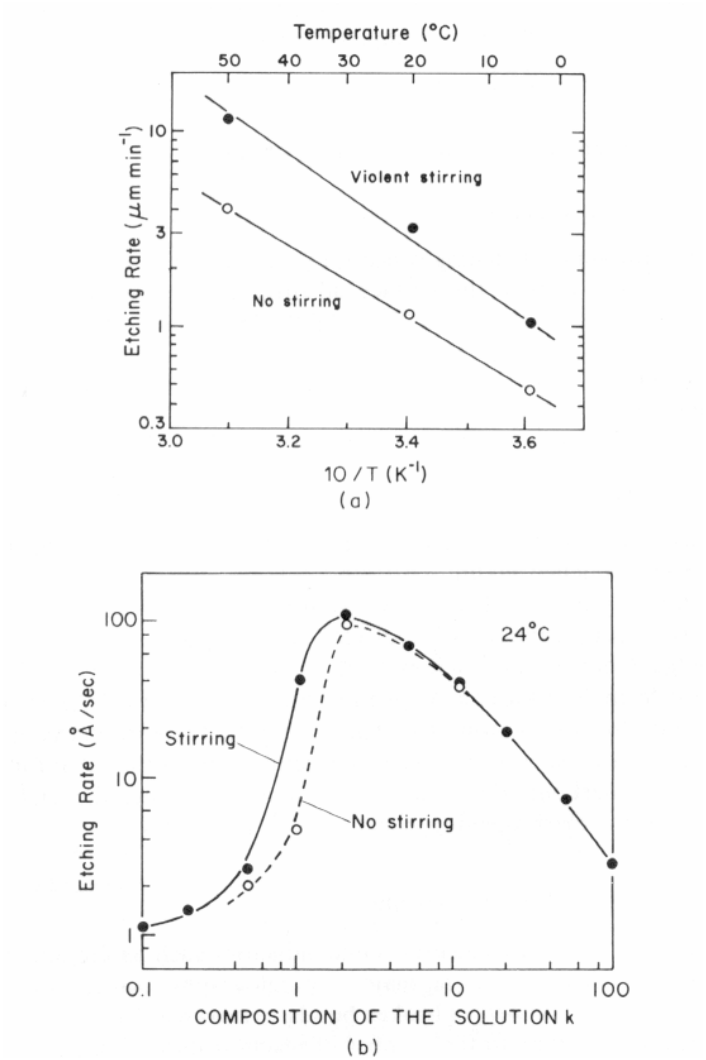
Figure 4.2 Schematic generalized representations of the concentration of the oxidizing component, H_2O_2, in the etch solution close to the surface and inside the thin surface oxide, during a wet chemical etching process

Etch behavior with *diffusion characteristics*

Etch behavior with a *reaction characteristics*

Howes & Morgan

Diffusion-limited etching



Material-transport limited

Can provide mirror-like surfaces

Howes & Morgan

Gallium Atsenide: Material, Devices and Circuits

Diffusion-limited, effects of mass transport seen in etch profiles

Now to gas-phase etching

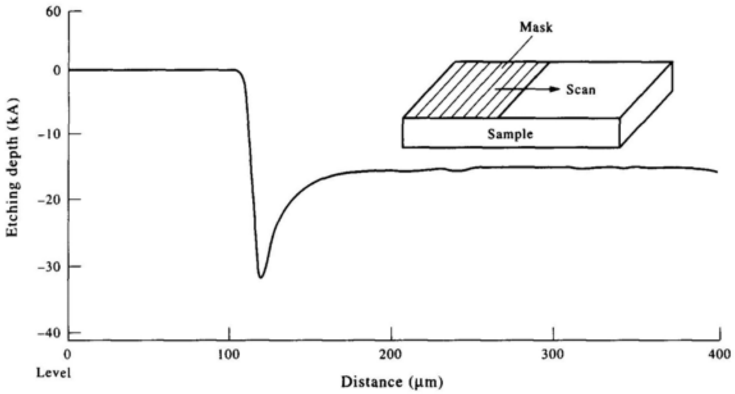


Fig. 1. The etching profile across the mask edge measured by Tencor Instrument model 200. *n*-type (100) GaSb in 2% Br_2 solution at room temperature for 1 min.

Etching of GaSb in 2% Br solution

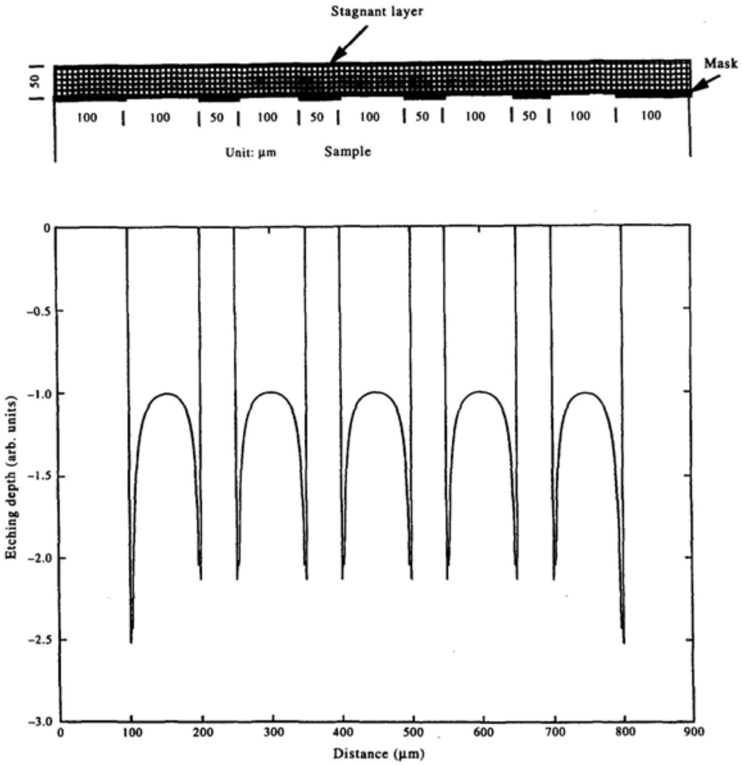


Fig. 8. The simulation etching profile in Shaw's experiment[1].

Simulated etched profile

Tan et al., Diffusion Limited Chemical Etching Effects in Semiconductors,
Solid State Electronics, 38, p 17 (1995)

Etch rate of GaAs in H_2SO_4:H_2O_2:H_2O

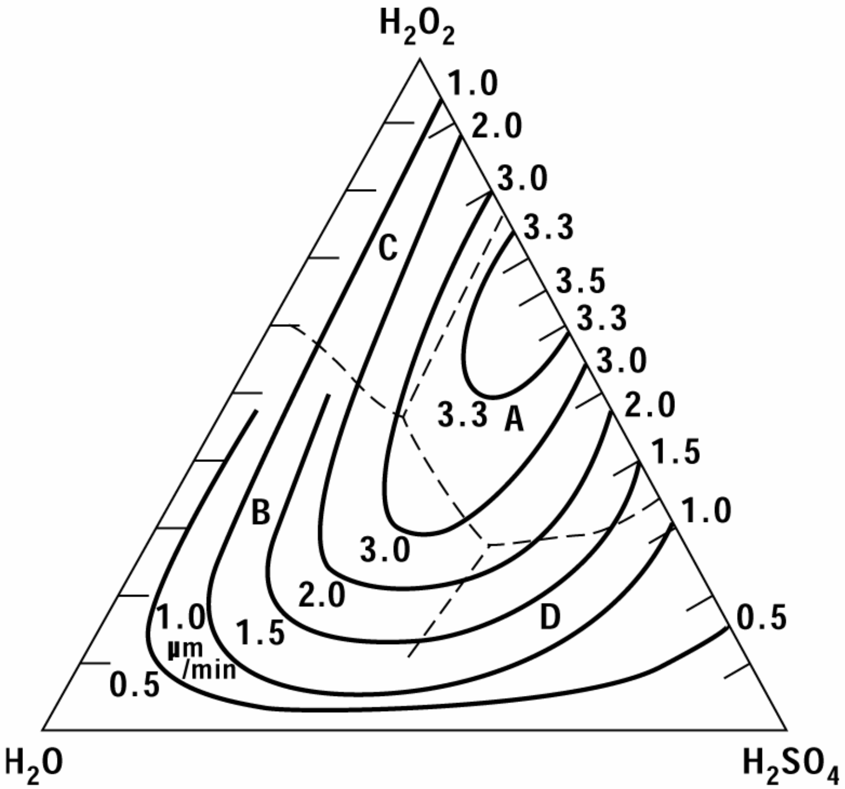
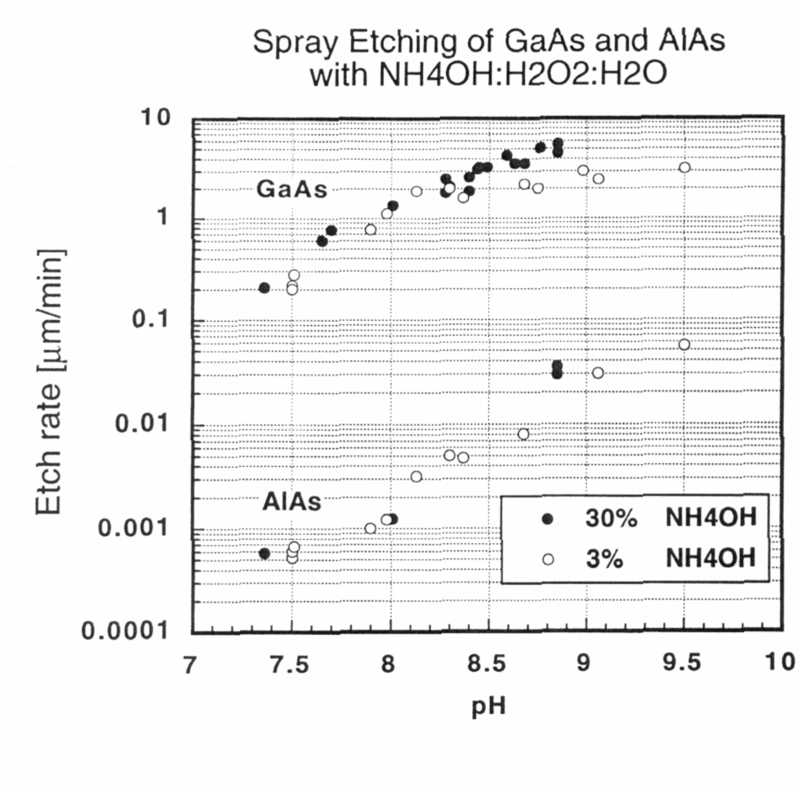


Figure 11.5 The etch rate of GaAs in H_2SO_4, H_2O_2, and H_2O. The bottom leg is the concentration of H_2SO_4, the left leg is H_2O, and the right leg is H_2O_2. All scales increase in the clockwise direction *(after Iida and Ito, reprinted by permission of the publisher, The Electrochemical Society Inc.).*

Selectivities possible with chemical etchants

According to material



Dubrovko Babic

According to Doping

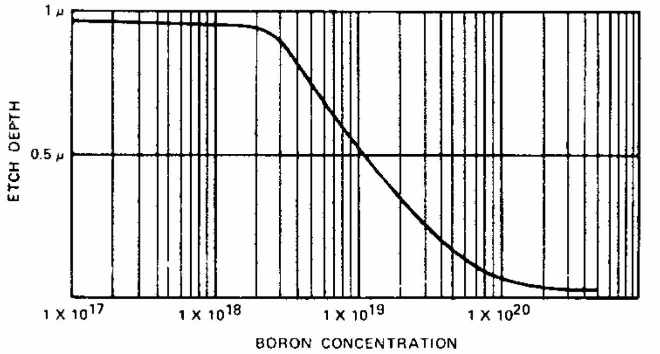
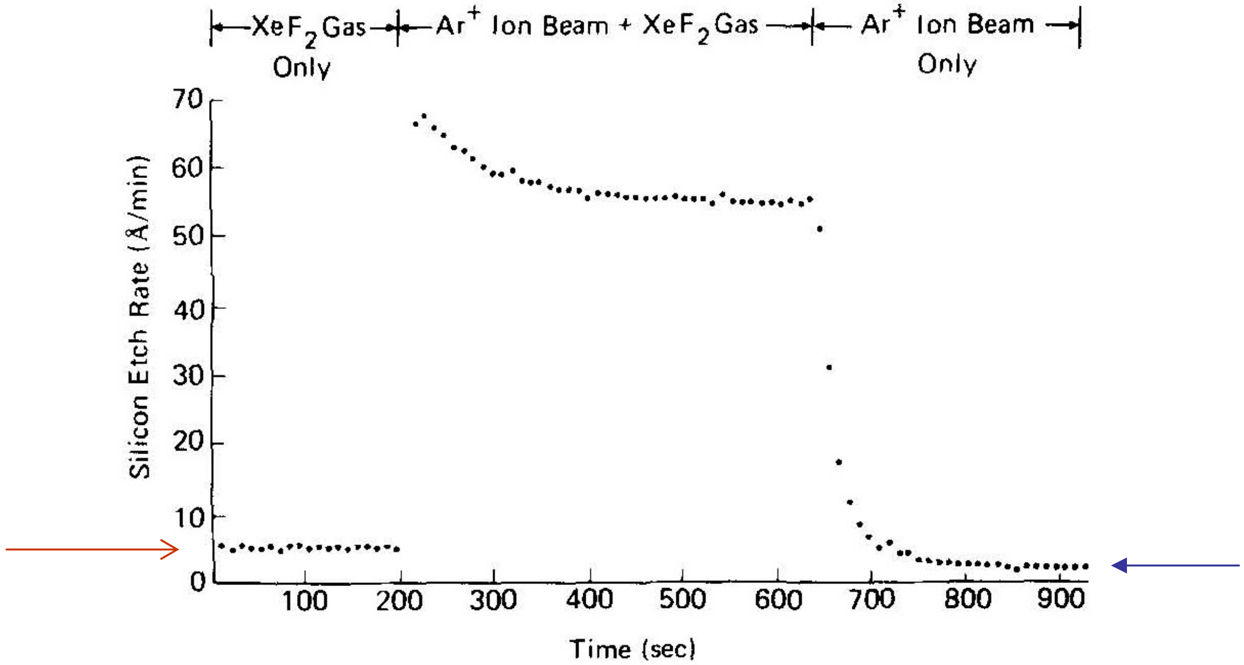


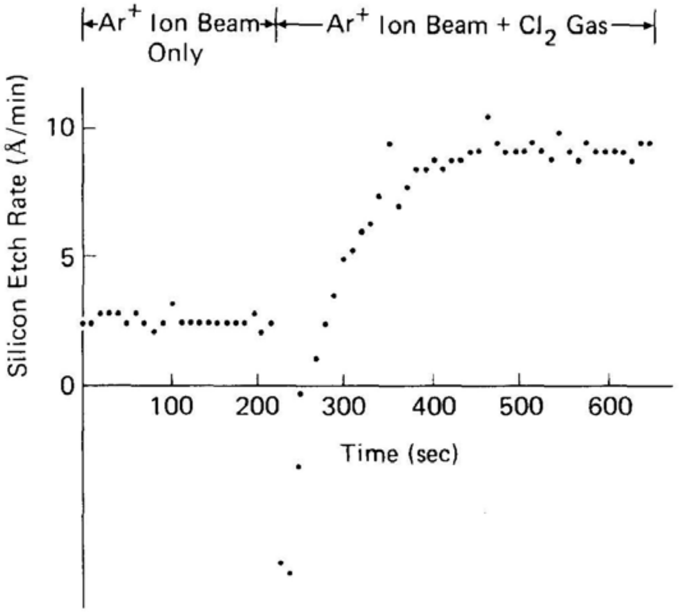
Fig. 11. Selective etching of silicon: Si ⟨100⟩ etch rate per minute versus boron concentration. Etchant system is $KOH-H_2O$–isopropyl alcohol at 80°C (from Kuhn and Rhee [348], reprinted by permission of the publisher, The Electrochemical Society, Inc.).

Runyan & Bean,
Semiconductor Integrated
Circuit Processing

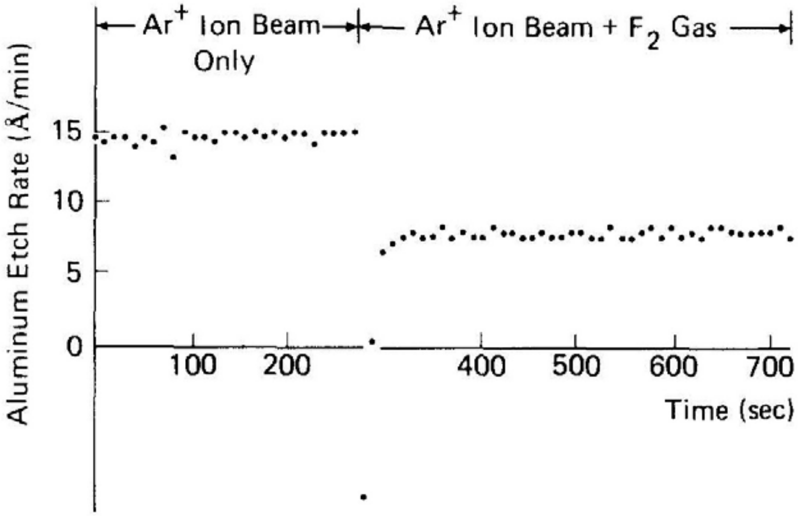
Etch rate of Si, using Ar^+ AND XeF_2 MUCH GREATER than sum of etch rates using either Ar^+ or XeF_2 alone.



Coburn & Winters, J. Appl. Phys. **50**, 3189 (1979)



Chlorine greatly enhances etch rate of Silicon in Ar$^+$



Fluorine RETARDS etch rate of Al in Ar$^+$

What Can an Ion Do to a Substrate?

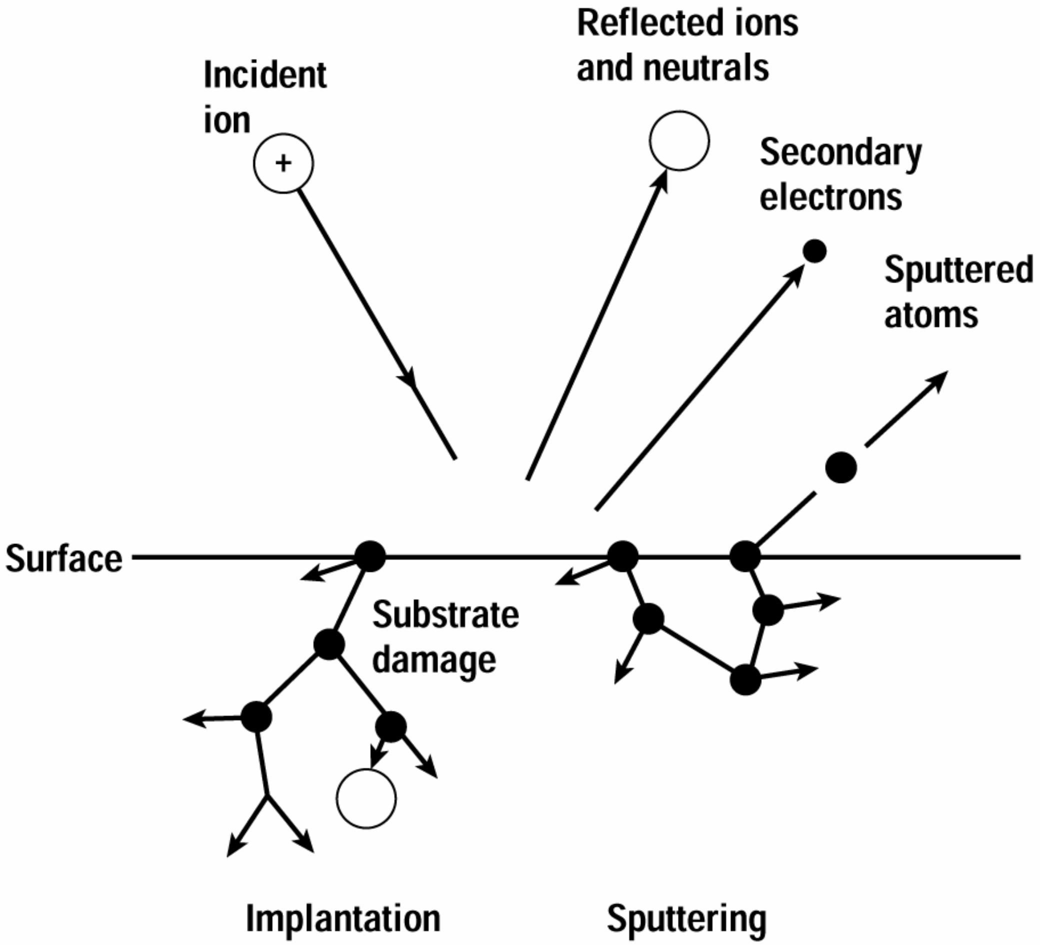
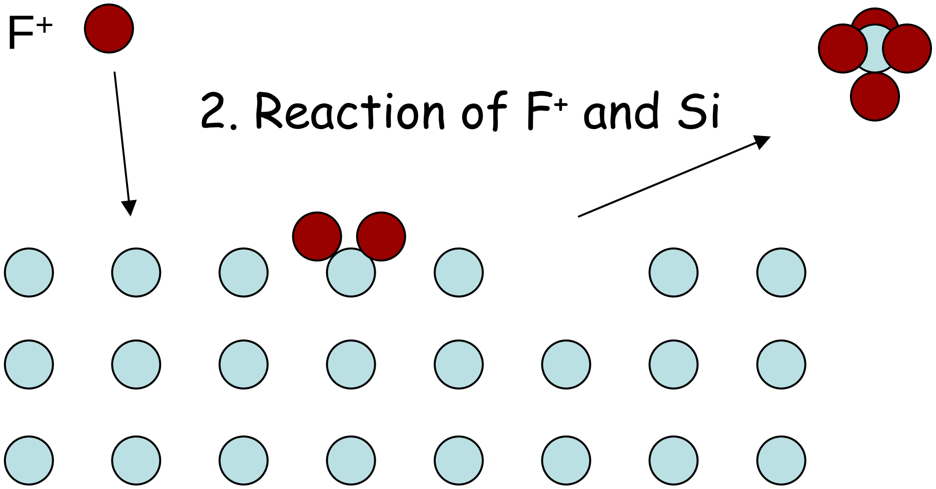


Figure 12.12 Possible outcomes for an ion incident on the surface of a wafer.

Mechanism of Etching



1. Adsorption or chemisorption

2. Reaction of F^+ and Si

3. Desorption of SiF_4 (volatile)

How do ions enhance the chemical etch rate?

An Etch Mechanism

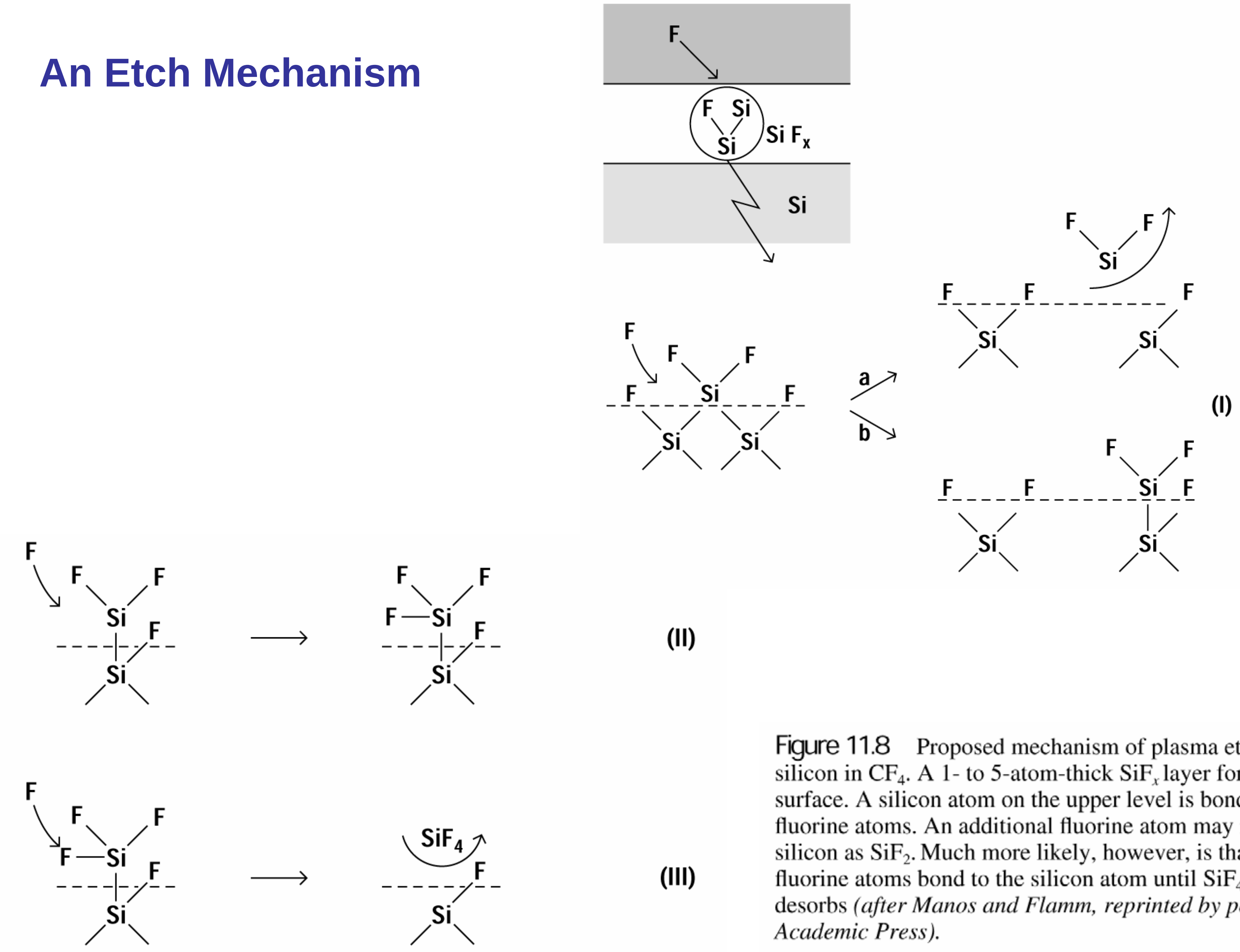


Figure 11.8 Proposed mechanism of plasma etching of silicon in CF_4. A 1- to 5-atom-thick SiF_x layer forms on the surface. A silicon atom on the upper level is bonded to two fluorine atoms. An additional fluorine atom may remove the silicon as SiF_2. Much more likely, however, is that additional fluorine atoms bond to the silicon atom until SiF_4 forms and desorbs *(after Manos and Flamm, reprinted by permission, Academic Press).*

Physical Etch

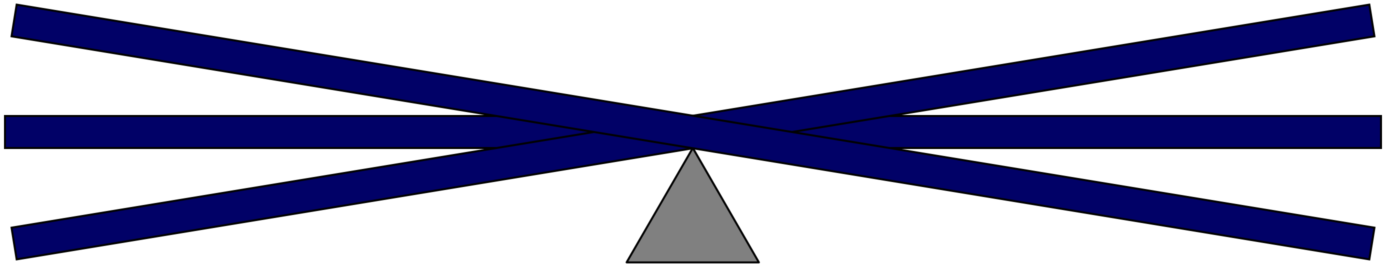
Ions, electrons, photons

- anisotropy control
- insensitivity to surface, crystal orientation

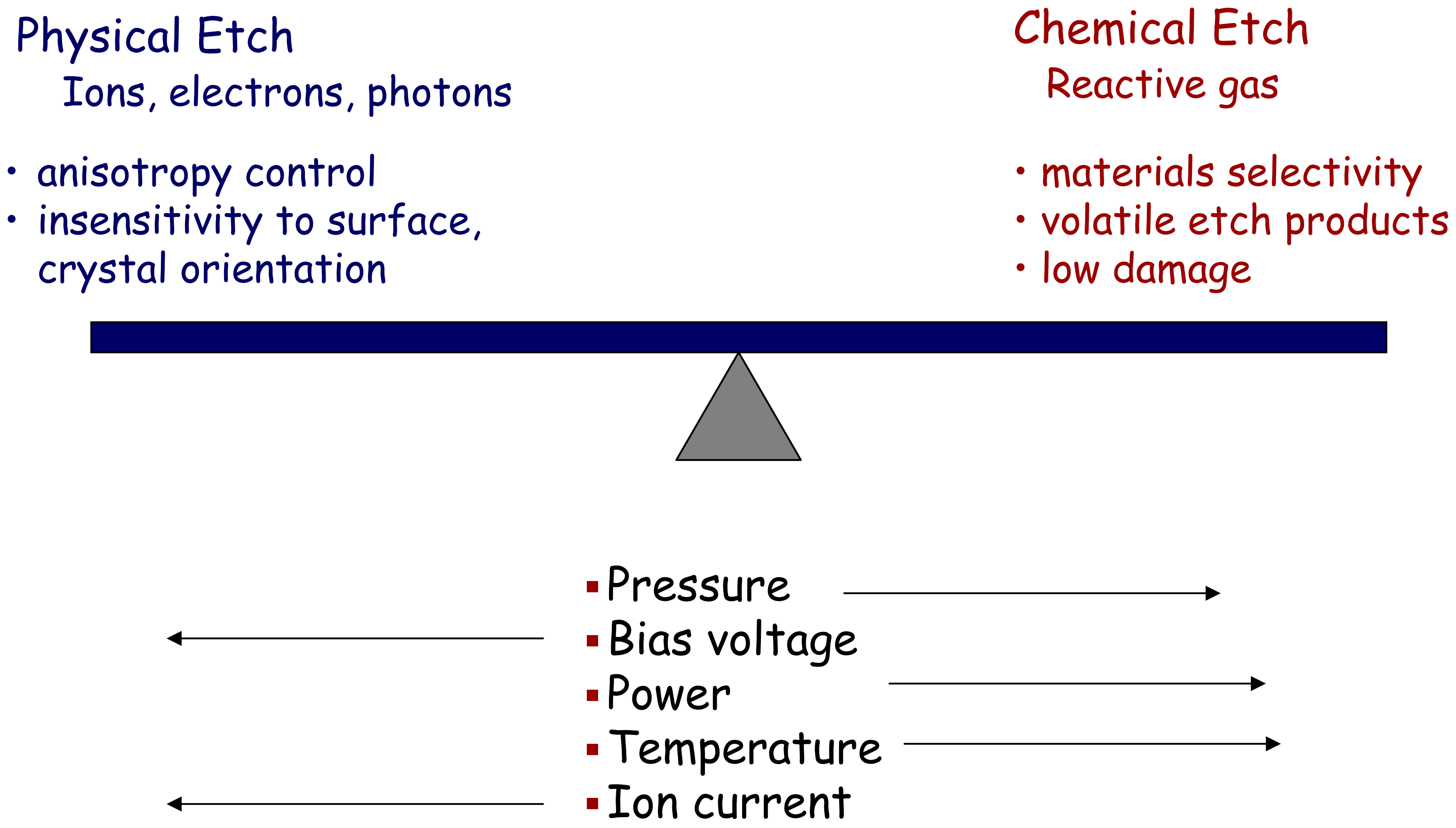
Chemical Etch

Reactive gas

- materials selectivity
- volatile etch products
- low damage



Need to achieve the right balance between physical and chemical etching



Physical Etch

Ions, electrons, photons

- anisotropy control
- insensitivity to surface, crystal orientation

Chemical Etch

Reactive gas

- materials selectivity
- volatile etch products
- low damage

- Pressure →
- ← Bias voltage
- Power →
- Temperature →
- ← Ion current

Ion Milling: Purely Physical Etching

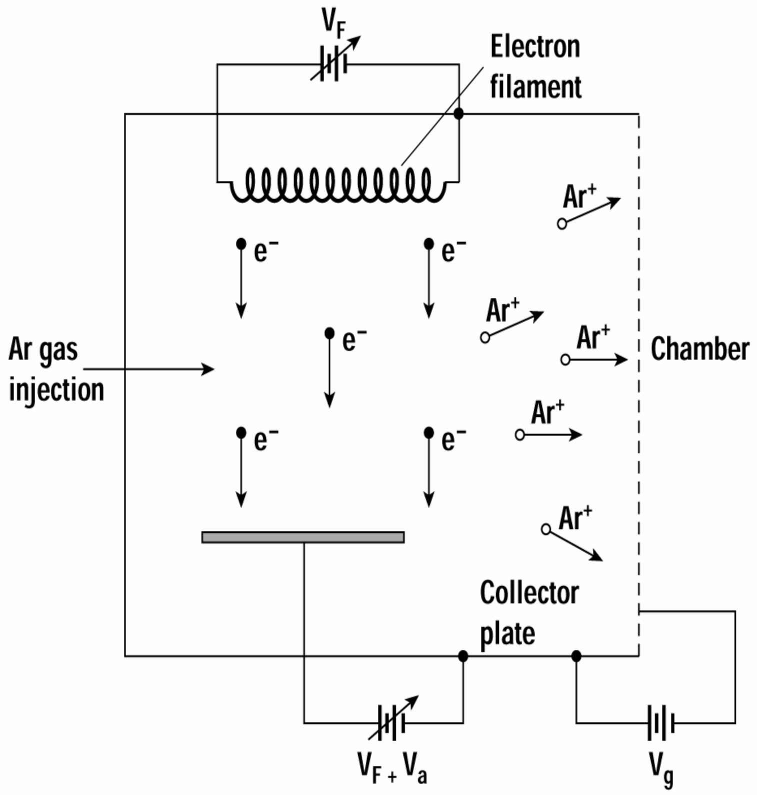


Figure 11.14 Cross section schematic of a Kaufman ion source.

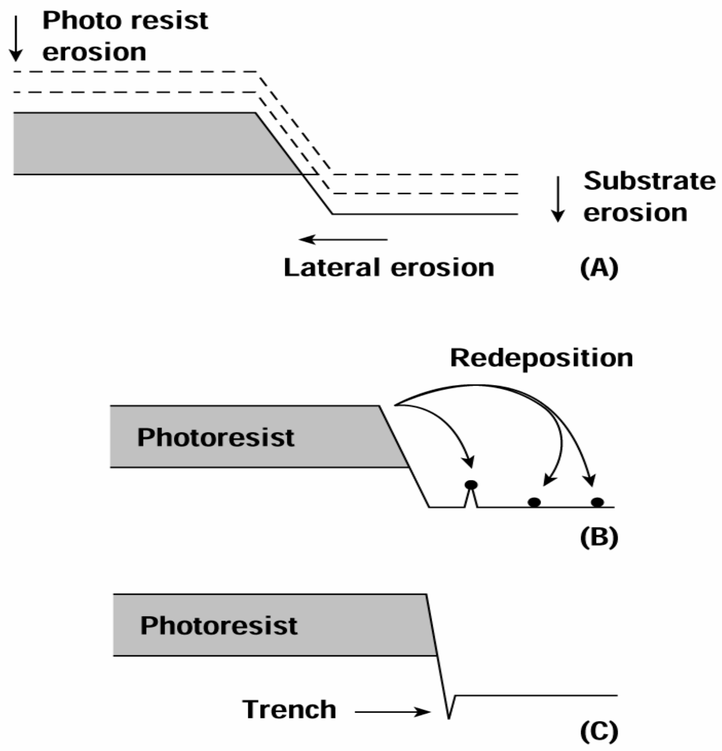


Figure 11.15 Problems that may occur during ion milling: (A) mask taper transfer, (B) redeposition from the mask, and (C) trenching.

Reactive Ion Etching: parallel plate reactor

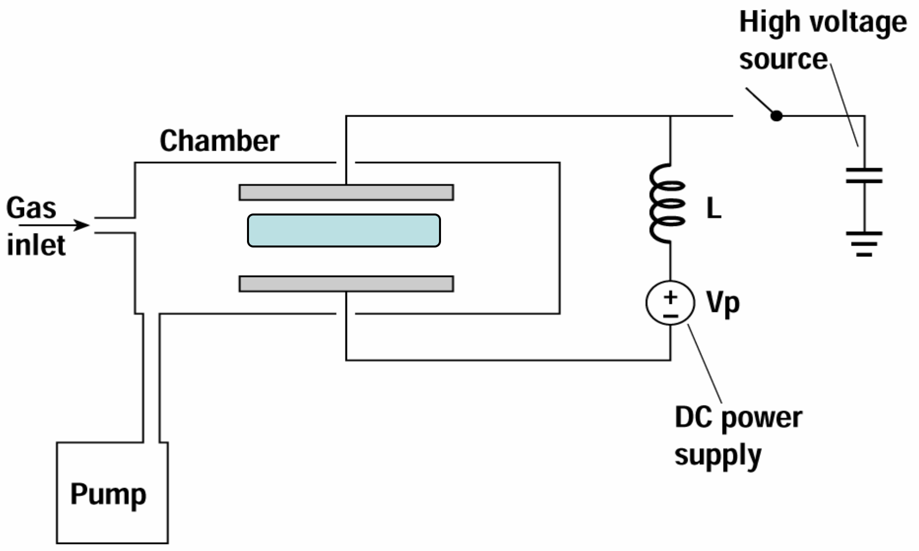


Figure 10.14 A simple parallel plate plasma reactor.

Figure 10.18 Typical plot of dc voltage as a function of position in an RF plasma.

Fine-tuning Etch Parameters to Achieve Desired Outcomes

Controllable Parameters	
• Choice of gases	
– Flow rates	
• Plasma pressure	• Generally few – 100 mTorr
• Power into plasma	• Several hundred watts
• Voltage between plasma and substrate	• ~ 100 – 500 V
• Temperature of substrate	• Generally room temperature

Fine-tuning Etch Parameters to Achieve Desired Outcomes

Controllable Parameters

- Choice of gases
  - Flow rates
- Plasma pressure
- Power into plasma
- Voltage between plasma and substrate
- Temperature of substrate

Desired Process Features

- Fidelity of the etch
  - No mask erosion
  - No undercut
  - No 'overcut'
- Rapid etch rate
- High etch selectivity: controlled etch depth
- Low damage

Predicting ‘Etchability’ in F-containing and Cl-containing gases

Element	F compound	T_b (°C)	Cl compound	T_b (°C)
Al	AlF_3	1291 T_s	$AlCl_3$	177 T_s
Si	SiF_4	-86	$SiCl_4$	58
Ga	GaF_3	~1000	$GaCl_3$	201
As	AsF_3	-63	$AsCl_3$	63
Ni	NiF_2	1000Ts	$NiCl_2$	973 Ts
In	InF_3	>1200	$InCl_3$	300 T_s

- Fluorine gases: can etch Si , poorly etch GaAs, WON'T etch AlGaAs
- Ni would be a good masking material
- InP difficult to etch in fluorine or chlorine-containing gases

Common chlorine-containing gases

Cl_2
BCl_3
CCl_4
$SiCl_4$
HCl

C-containing gases can polymerize in the plasma, forming a polymer that deposits on the wafer

Common fluorine-containing gases

CF_4
SF_6
NF_3
CHF_3

O_2 removes polymers and organic materials (CO_2)

H_2: etches oxides
Ar, He (inert gases) : can enhance physical etch mechanisms

For InP: a 'reverse deposition process': $H_2 + PH_3 + In(CH_3)_3 \rightarrow InP + \boxed{CH_4 + H_2}$

Selective etching of Si and SiO_2

Oxygen initially increases etch rate:
Reduces CF_x polymerization

CF_4 and O_2

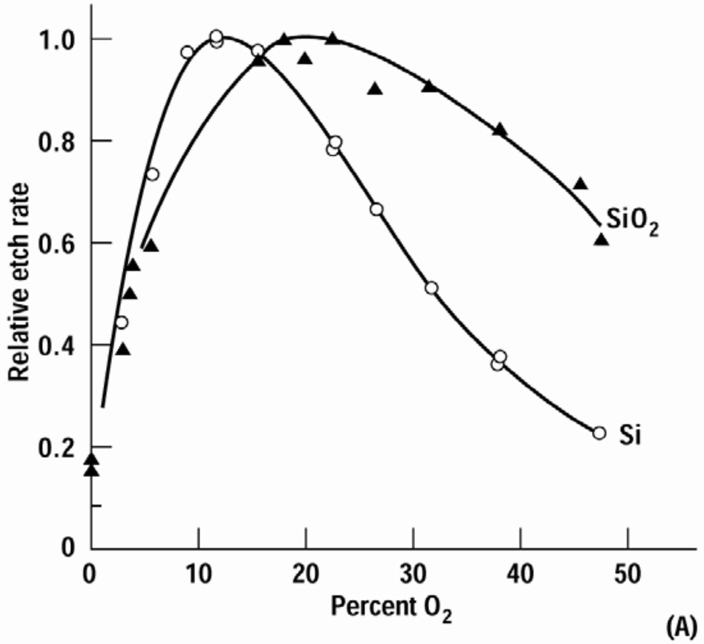
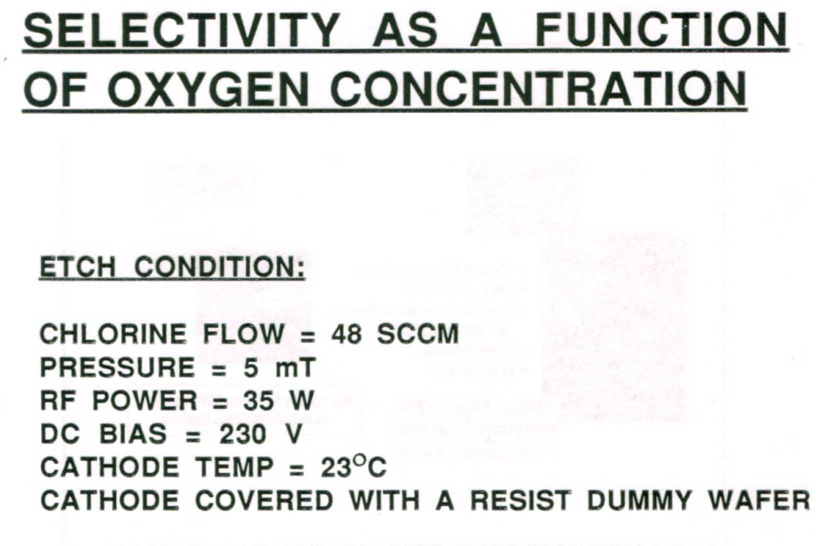


Figure 11.11 Etch rate of Si and SiO_2 in (A) CF_4/O_2 plasma *(after Mogab et al., reprinted by permission, AIP)*, and (B) CF_4/H_2 plasma *(after Ephrath and Petrillo, reprinted by pe*

Hydrogen enhances CF_x polymerization,
Slows etch rates, unless oxygen present

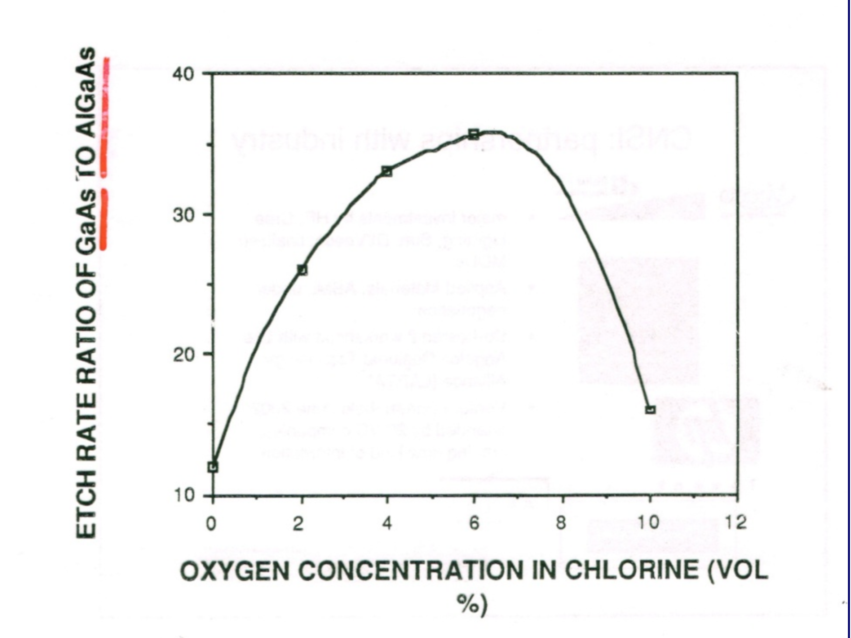
Using oxygen to achieve selective etching of GaAs and AlGaAs



SELECTIVITY AS A FUNCTION OF OXYGEN CONCENTRATION

ETCH CONDITION:

CHLORINE FLOW = 48 SCCM
PRESSURE = 5 mT
RF POWER = 35 W
DC BIAS = 230 V
CATHODE TEMP = 23°C
CATHODE COVERED WITH A RESIST DUMMY WAFER



Al reacts much more readily with OXYGEN, forming an oxide

Fine-tuning Etch Parameters to Achieve Desired Outcomes

Controllable Parameters

- Choice of gases
  - Flow rates
- Plasma pressure
- Power into plasma
- Voltage between plasma and substrate
- Temperature of substrate

Desired Process Features

- Fidelity of the etch
  - No mask erosion
  - No undercut
  - No 'overcut'
- Rapid etch rate
- High etch selectivity: controlled etch depth
- Low damage

Fine-tuning Etch Parameters to Achieve Desired Outcomes

Controllable Parameters

- Choice of gases
  - Flow rates
- Plasma pressure
- Power into plasma
- Voltage between plasma and substrate
- Temperature of substrate

Mixing and matching gases to get

- Straight walls, sloped walls
- Faster etch rates
- Etch material faster than mask (selectivity)
- Etch polymers

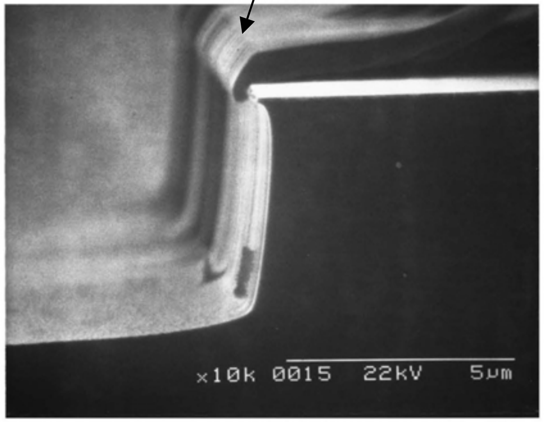
What is the difference between

- Plasma etching (barrel etcher/asher)
- RIE
- ICP?

Forming polymers in $CH_4/H_2/Ar$ etching of InP

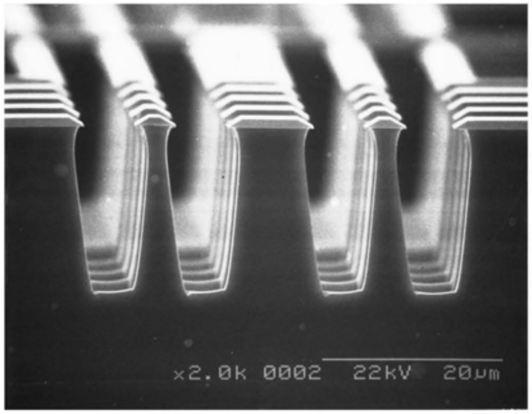
No O_2

polymer

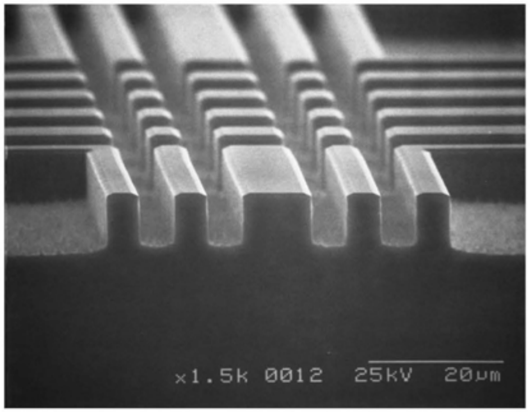


(a)

4 sccm O_2



(b)



(c)

6 sccm O_2

Etch gas composition:
$CH_4/H_2/Ar = 4/20/10$
75 mTorr, 500 V

Schramm et al., JVSTB **15**, [1997]

Different pressures for etch processes

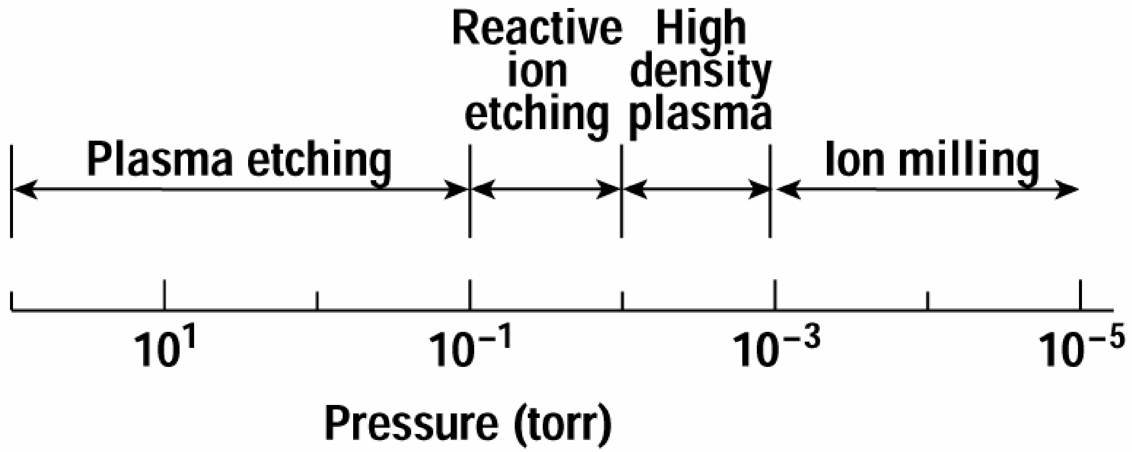


Figure 11.2 Types of etch processes on a chamber pressure scale.

High Pressure ->
- higher plasma density, higher etch rates
- Lower bias voltages -> more chemical etching (less directionality?)
- Higher ion scattering -> less directionality

Reactive Ion Etcher (RIE)

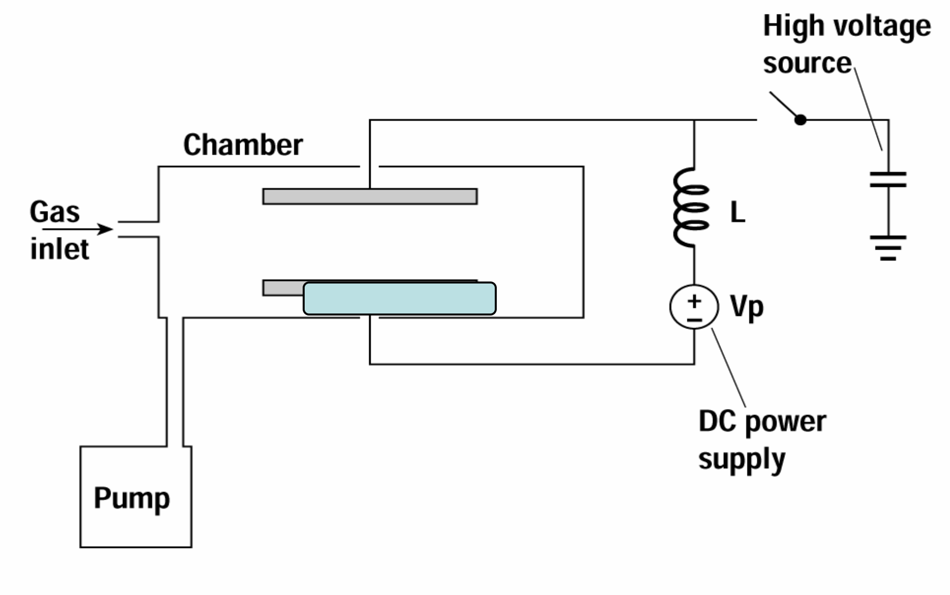


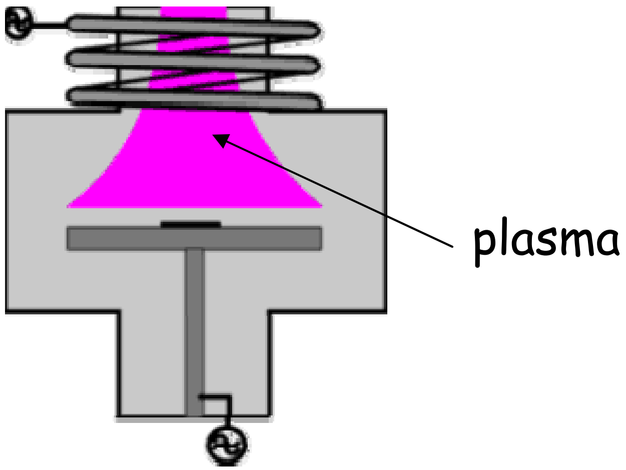
Figure 10.14 A simple parallel plate plasma reactor.

- Few mTorr – 100 mTorr pressure
- Few hundred volts bias

POWER TO PLASMA AND BIAS TO SUBSTRATE ARE COUPLED

Does choice of etcher make a difference?

Inductively Couple Plasma (ICP) Etcher



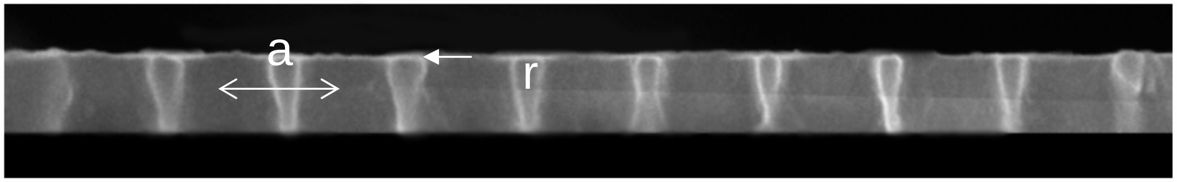
- High Density Plasma

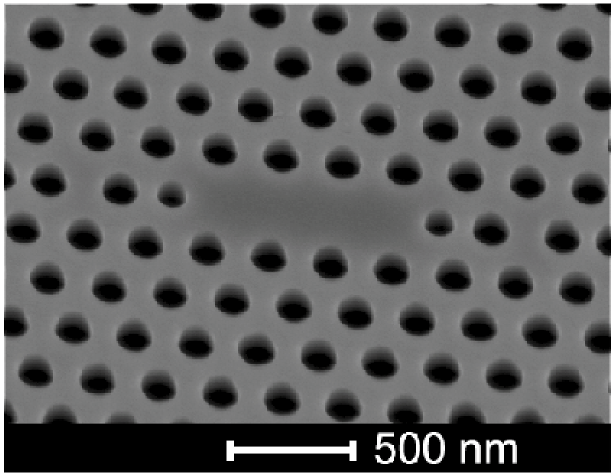
Separate control of plasma power and substrate bias

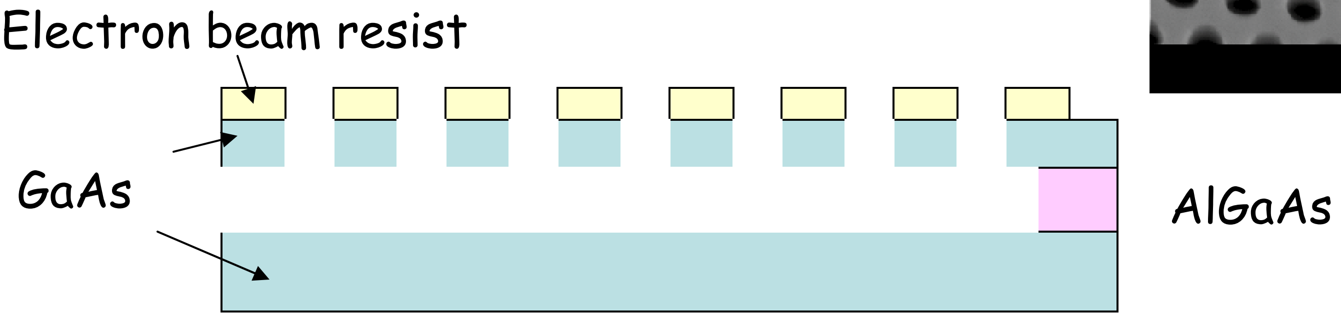
HIGH etch rates with LOW damage, at low pressure

Etching Holes in Photonic Crystal Cavities

RIE $\Delta r / a = 12\%$ $Q = 4000$






Electron beam resist

GaAs

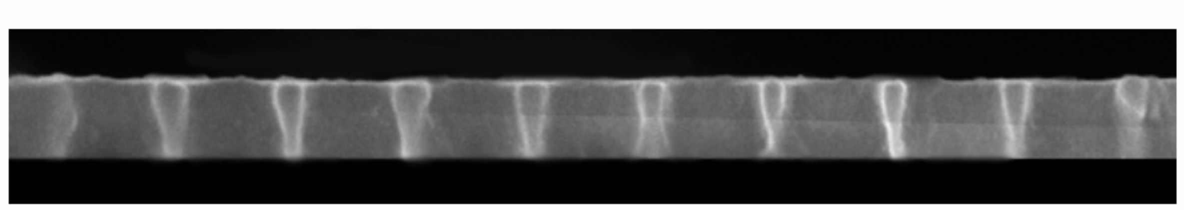
AlGaAs

Use RIE to etch into GaAs

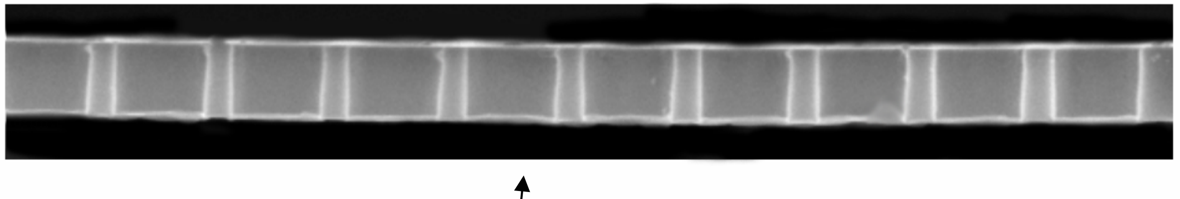
Selectively wet etch AlGaAs

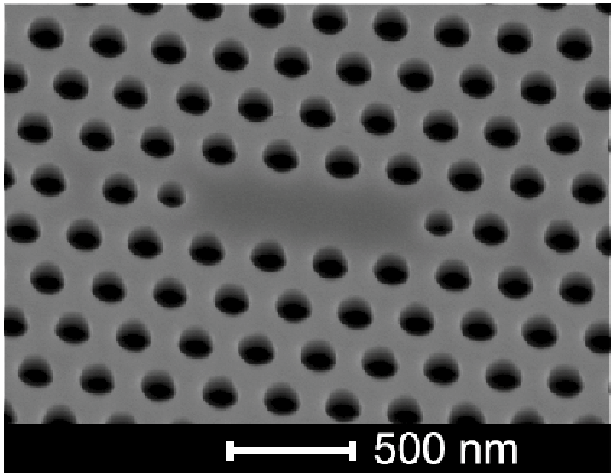
Etching Holes in Photonic Crystal Cavities

RIE $\Delta r / a = 12\%$ *Q* = 4000



ICP $\Delta r / a = 2\%$ ***Q* = 8500**

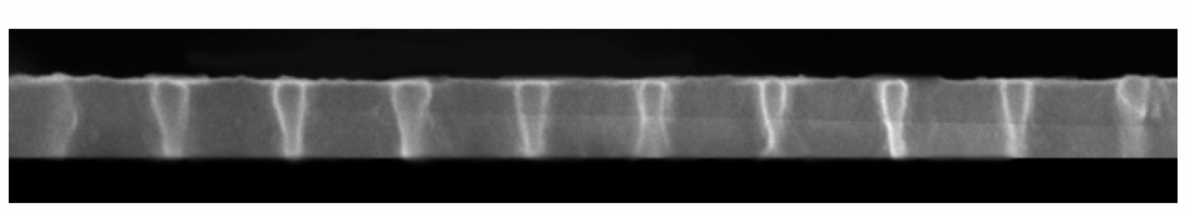


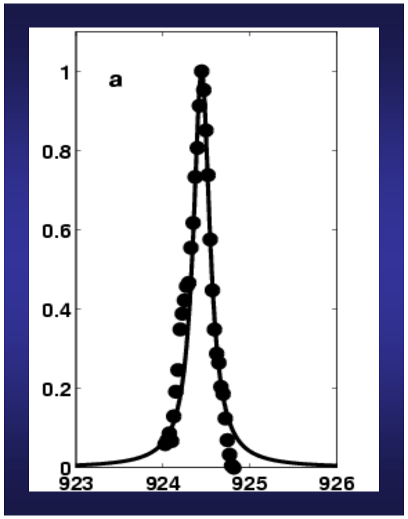


Redesigning the etch process to use ICP etching

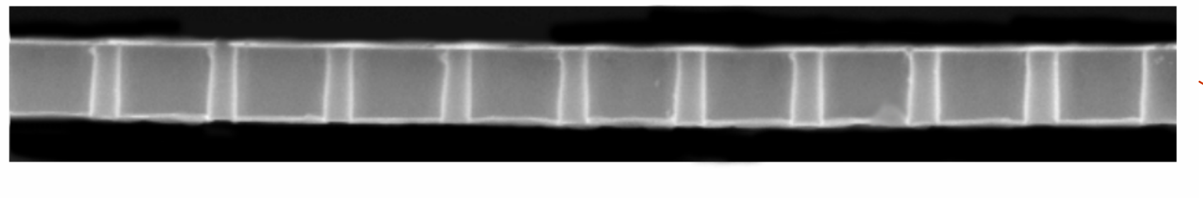
Sensitivity to fabrication

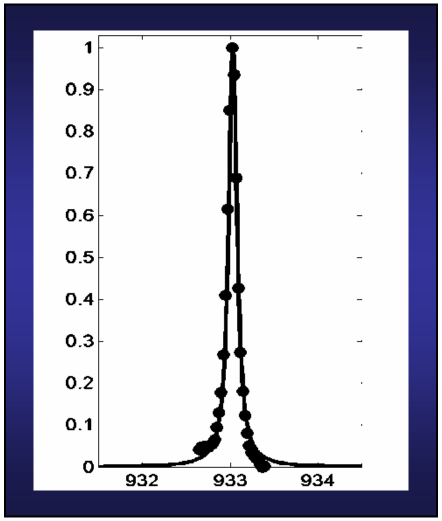
RIE $\Delta r / a = 12\%$ $Q = 4000$





ICP $\Delta r / a = 2\%$ **$Q = 8500$**

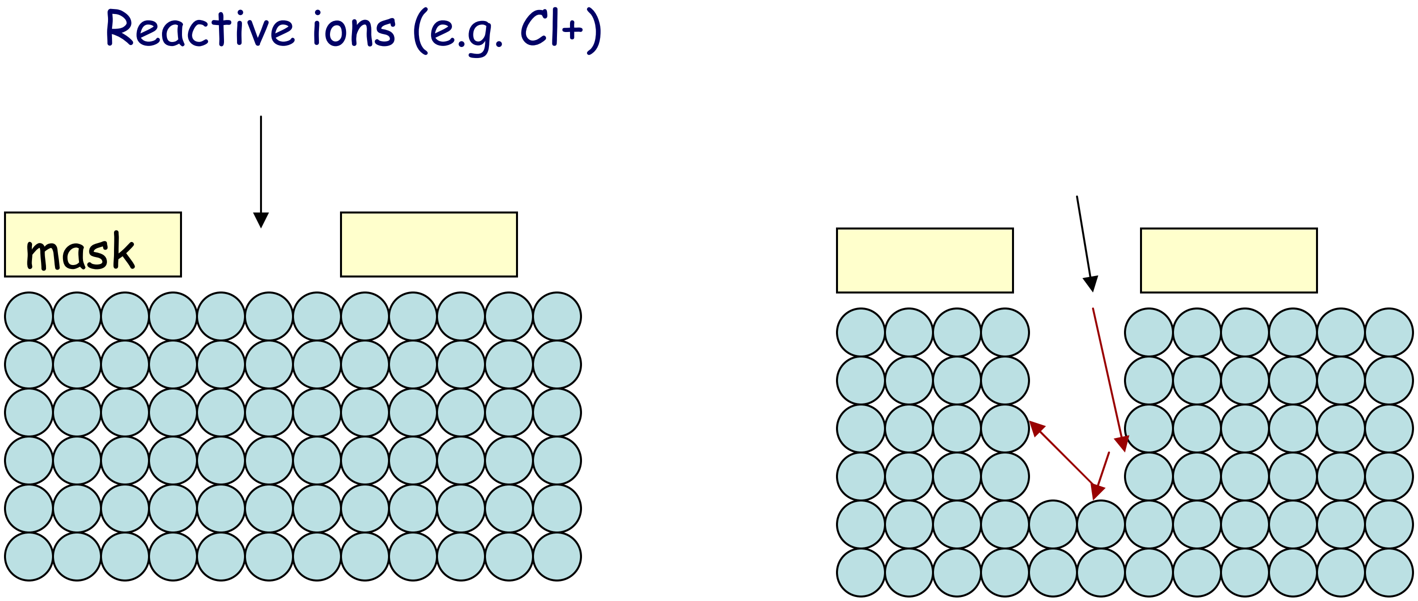




Dry etching conditions

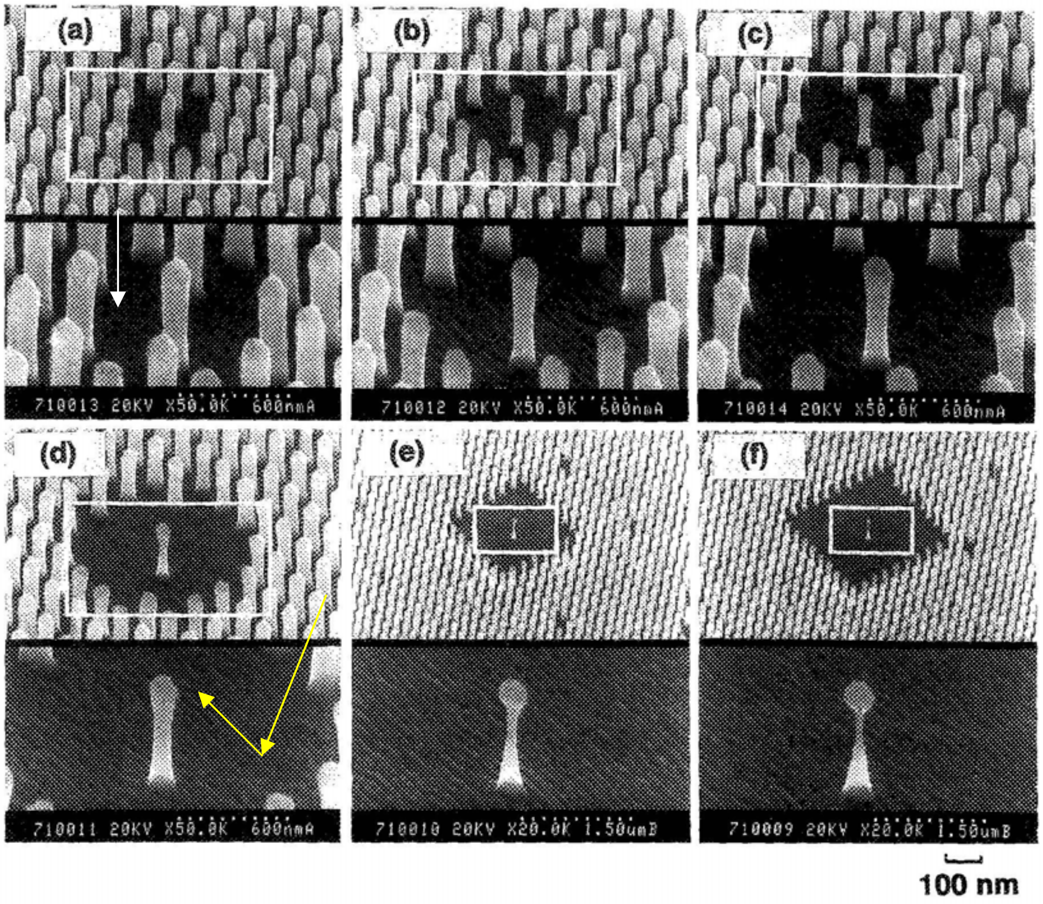
	gas	flow (sccm)	pressure (mTorr)	bias power (W)	ICP power (W)
RIE	$SiCl_4$	10	3	250	NA
ICP	$Ar/Cl_2/BCl_3$	12/4/3	2.4	80	700

Why such a difference in etched profile?



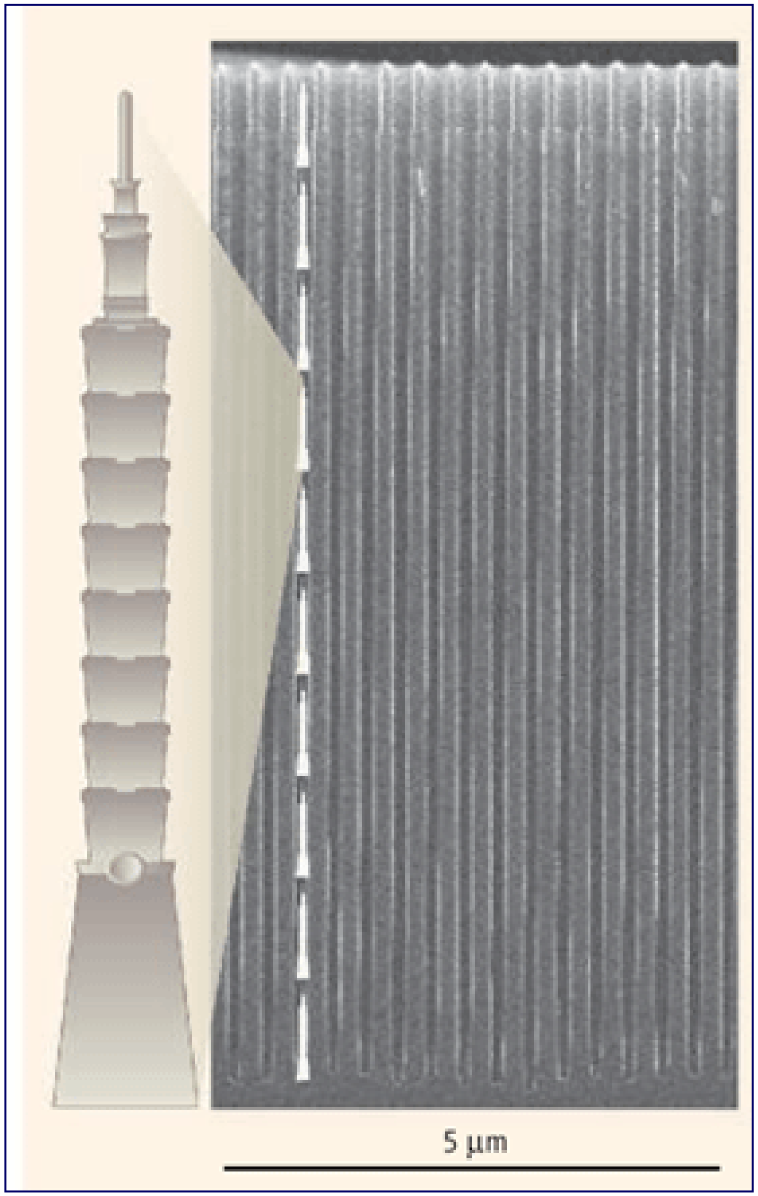
When the etched features are very narrow (high aspect ratio = depth/width)…small changes in ion angles can produce big changes in the etched features

Ion Scattering in Dense Geometries



- ZnTe, patterned with 60 nm Ti dots
- Etched in CH4/H2 = 5/40 sccm, 150W, 1000V
- Shape of etched profile changes depending on the density of the local environment: all etch conditions the same

Tsutsui et al., JVSTB **11** [1993]



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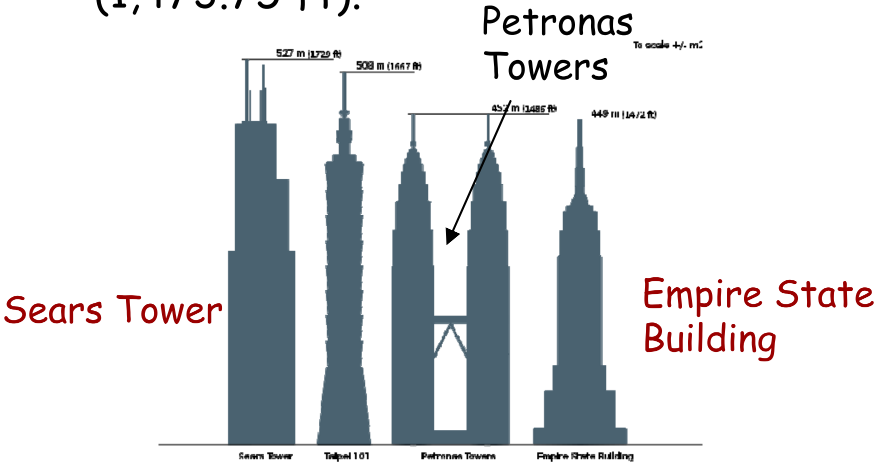
Ultimate etching?

- Etched trenches in silicon: aspect ratio of 80:1
- 7 x 10 ^{11} trenches on a wafer: combined length of 4000 km
- If Taipei 101 were scaled so that its width would fit the trench, it could stack up <u>10 times</u> within a trench
  - *Ground to highest architectural structure (spire):* 509.2 metres (1,670.60 ft).
  - *Ground to roof:* 449.2 m (1,473.75 ft).



http://en.wikipedia.org/wiki/Taipei_101

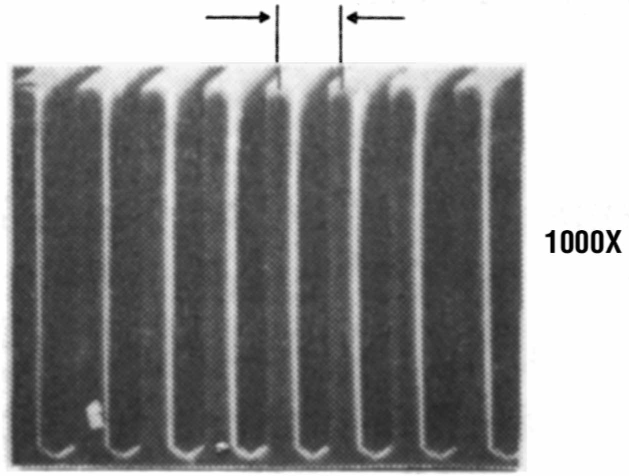
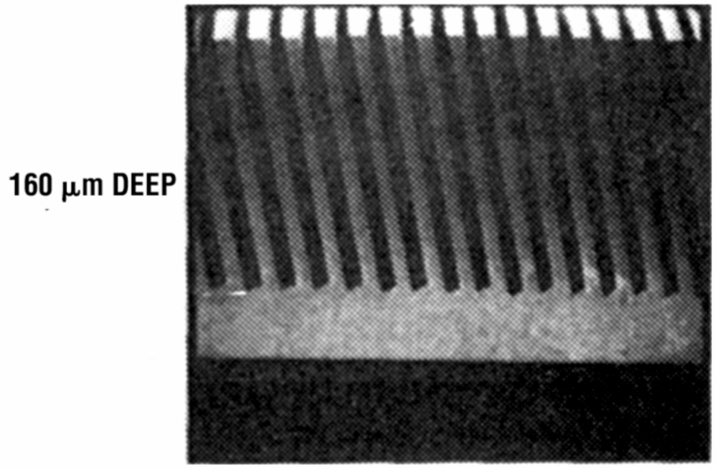


Figure 11.6 (100) silicon wafers after directional etching in KOH, isopropyl alcohol, and water. The upper photo shows a 50-mm-deep etch. The lower photographs are of 80-mm-deep trenches etched at 10 mm pitch on (110) and 107off (110) *(after Bean, ©1978 IEEE).*



Deep etches with high aspect ratios possible: with careful understanding of crystal orientations