Lecture 4-1 Bulk Micromachining

● Silicon as A Mechanical Material:

Material property comparison:

TABLE I

	Yield Strength (10^{10} dyne/cm^2)	Knoop Hardness (kg/mm^2)	Young's Modulus (10^{12} dyne/cm^2)	Density (gr/cm^3)	Thermal Conductivity (W/cm°C)	Thermal Expansion (10^{-6}/°C)
•Diamond	53	7000	10.35	3.5	20	1.0
•SiC	21	2480	7.0	3.2	3.5	3.3
•TiC	20	2470	4.97	4.9	3.3	6.4
•Al_2O_3	15.4	2100	5.3	4.0	0.5	5.4
•Si_3N_4	14	3486	3.85	3.1	0.19	0.8
•Iron	12.6	400	1.96	7.8	0.803	12
SiO_2 (fibers)	8.4	820	0.73	2.5	0.014	0.55
•Si	7.0	850	1.9	2.3	1.57	2.33
Steel (max. strength)	4.2	1500	2.1	7.9	0.97	12
W	4.0	485	4.1	19.3	1.78	4.5
Stainless Steel	2.1	660	2.0	7.9	0.329	17.3
Mo	2.1	275	3.43	10.3	1.38	5.0
A[illegible]	0.17	130	0.70	2.7	2.36	25

•Single crystal. See Refs. 8, 9, 10, 11, 141, 163, 166.

K. E. Petersen

Major difference:

Silicon yields by fracturing (at room temp) while metals usually yield by deforming inelastically—chipping, cleave along crystallographic planes.

- **Definition of Bulk Micromachining:**
  Based on the device shaping by etching a bulk substrate.
- **Materials used for bulk micromachining: single crystal silicon, gallium arsenide, quartz, etc…**
- **Silicon bulk micromachining:**

  1. Isotropic silicon wet etching

  HNA system (*HNO_3+HF*), etching rate can be 50 μm/min:

  a. Holes injection

$$HNO_3 + H_2O + HNO_2 \rightarrow 2HNO_2 + 2OH^- + 2h^+$$

  b. Oxide formation

$$Si^{4+} + 4OH^- \rightarrow SiO_2 + H_2$$

  c. Oxide etched

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

  Total reaction:

$$Si + HNO_3 + 6HF \rightarrow H_2SiF_6 + HNO_2 + H_2O + H_2(bubbles)$$

  Iso-Etch Curve:

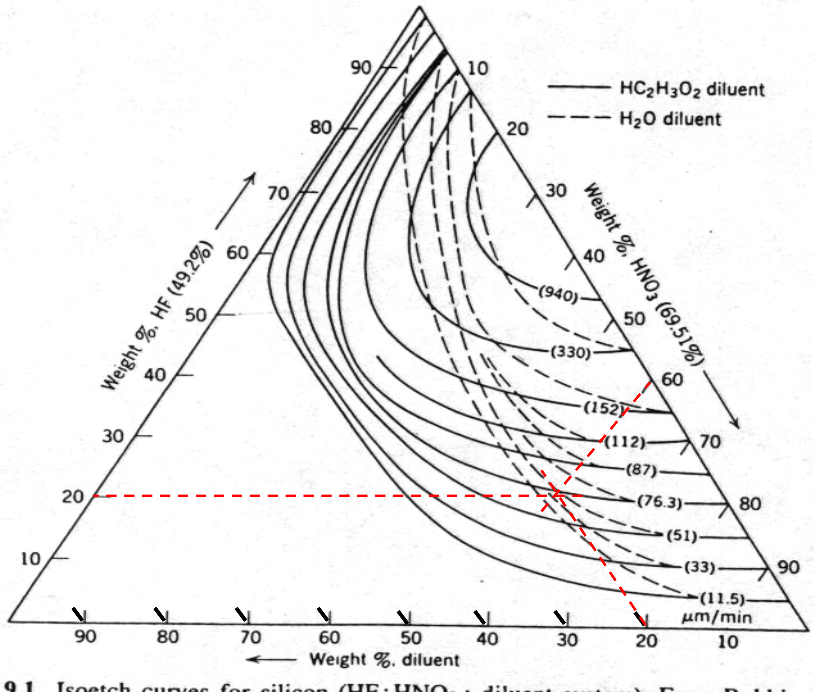
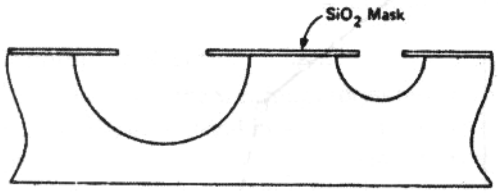
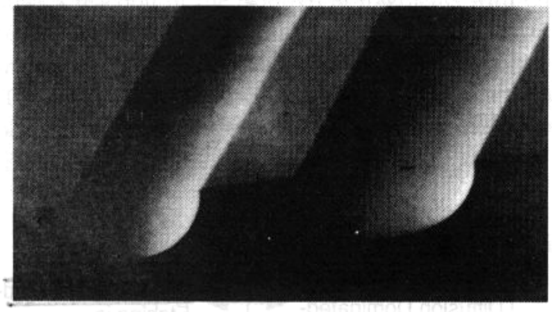


Fig. 9.1 Isoetch curves for silicon (HF : HNO3 : diluent system). From Robbins and Schwartz [5]. Reprinted with permission of the publisher, The Electrochemical Society, Inc.

Effects:
High HF Low HNO_3: oxidation limit, rough surface
High HNO_3 Low HF: etching limit, smooth surface

Examples of isotropic etching:





Masking materials:

TABLE 4.6 Masking Materials for Acidic Etchants[a]

Masking	Etchants: Piranha (4:1, H_2O_2:H_2SO_4)	Buffered HF (5:1 NH_4F:conc. HF)	HNA
Thermal SiO_2		0.1 μm/min	300–800 Å/min; limited etch time, thick layers often are used due to ease of patterning
CVD (450°C) SiO_2		0.48 μm/min	0.44 μm/min
Corning 7740 glass		0.063 μ/min	1.9 μ/min
Photoresist	Attacks most organic films	Okay for short while	Resists do not stand up to strong oxidizing agents like HNO_3 and are not used
Undoped Si, polysilicon	Forms 30 Å of SiO_2	0.23 to 0.45 Å/min	Si 0.7 to 40 μm/min at room temperature; at a dopant concentration $<10^{17}$ cm^{-3} (n or p)
Black wax			Usable at room temperature
Au/Cr	Okay	Okay	Okay
LPCVD Si_3N_4		1 Å/min	Etch rate is 10–100 Å/min; preferred masking material

[a] The many variables involved necessarily means that the given numbers are approximate only.

2. Anisotropic silicon wet etching:

A process of preferential directional etching of material using liquid source etchants (a crystal orientation-dependent etching).

a. Classification of solids based on atomic order:

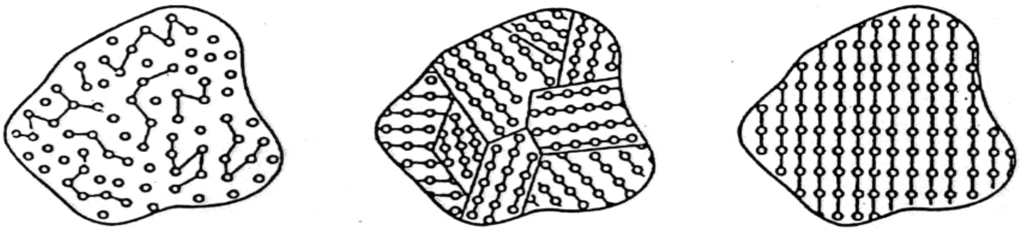


Fig. 1.1 General classification of solids based on the degree of atomic order: (a) amorphous, (b) polycrystalline, and (c) crystalline.

b. Silicon crystal structure:

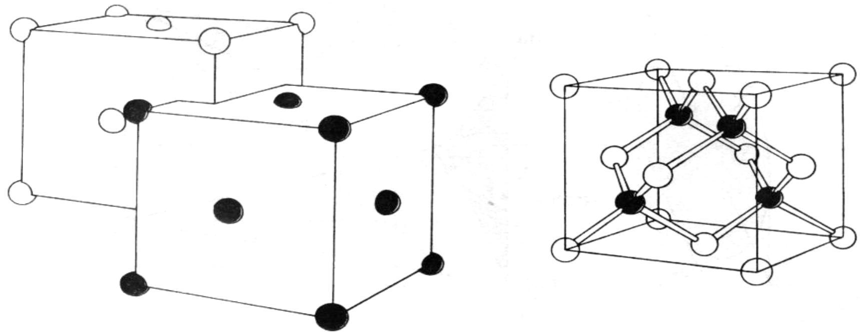
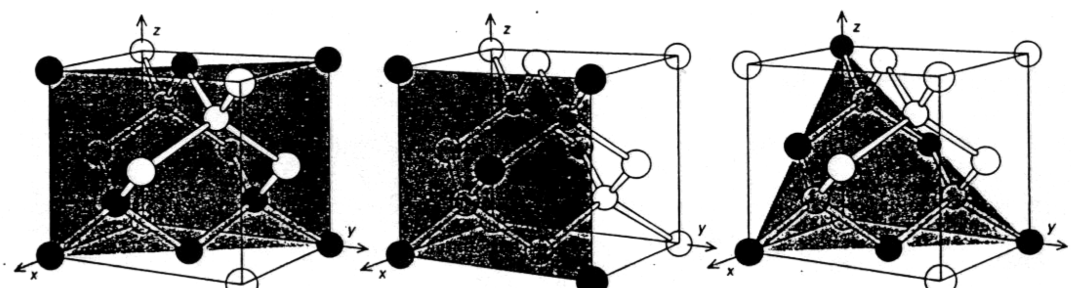
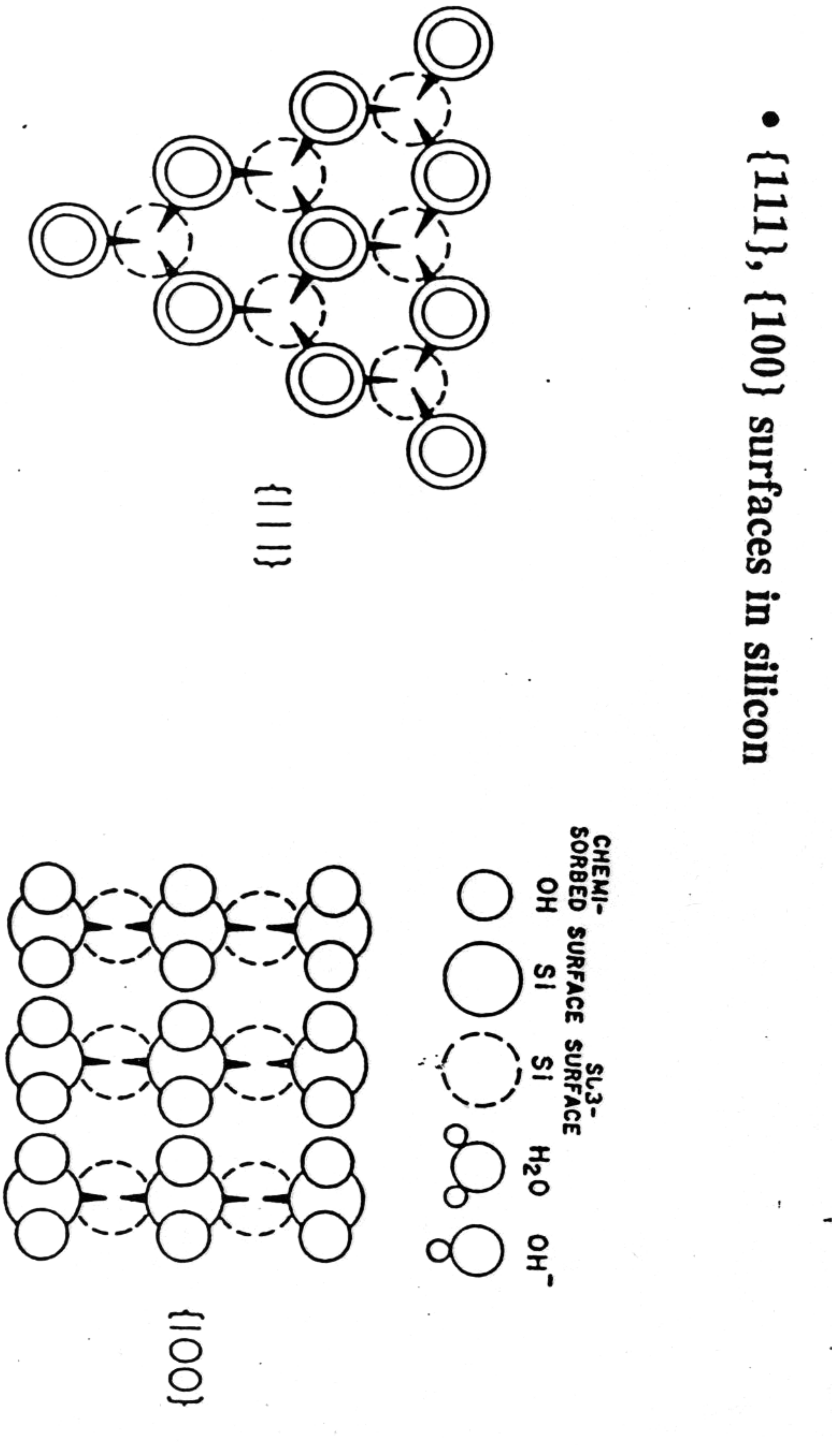


FIGURE 4.4 The diamond-type lattice can be constructed from two interpenetrating face-centered cubic unit cells. Si forms four covalent bonds, making tetrahedrons.



CRYSTALLINE SILICON shares with diamond the crystal structure called interlocking face-centered cubic. An atom lies at each corner and in the center of each face of the unit cube, and the cubes interlock in such a way that several atoms from neighboring cubes lie within each unit cube. The axes of the unit cube provide a rectilinear coordinate system that makes it possible to specify directions and planes within the crystal. A crystalline direction is designated by three coordinates called the Miller indexes, which are integer multiples of the length of one edge of a unit cube. The same set of indexes designates the planes perpendicular to the direction. Crystalline orientation is important in the fabrication of micromechanical devices because some of the etchants employed attack different directions in the crystal at different rates. Most such anisotropic etchants progress rapidly in the crystal direction perpendicular to the (110) plane and less rapidly in the direction perpendicular to the (100) plane. The direction perpendicular to the (111) plane etches very slowly, if at all.

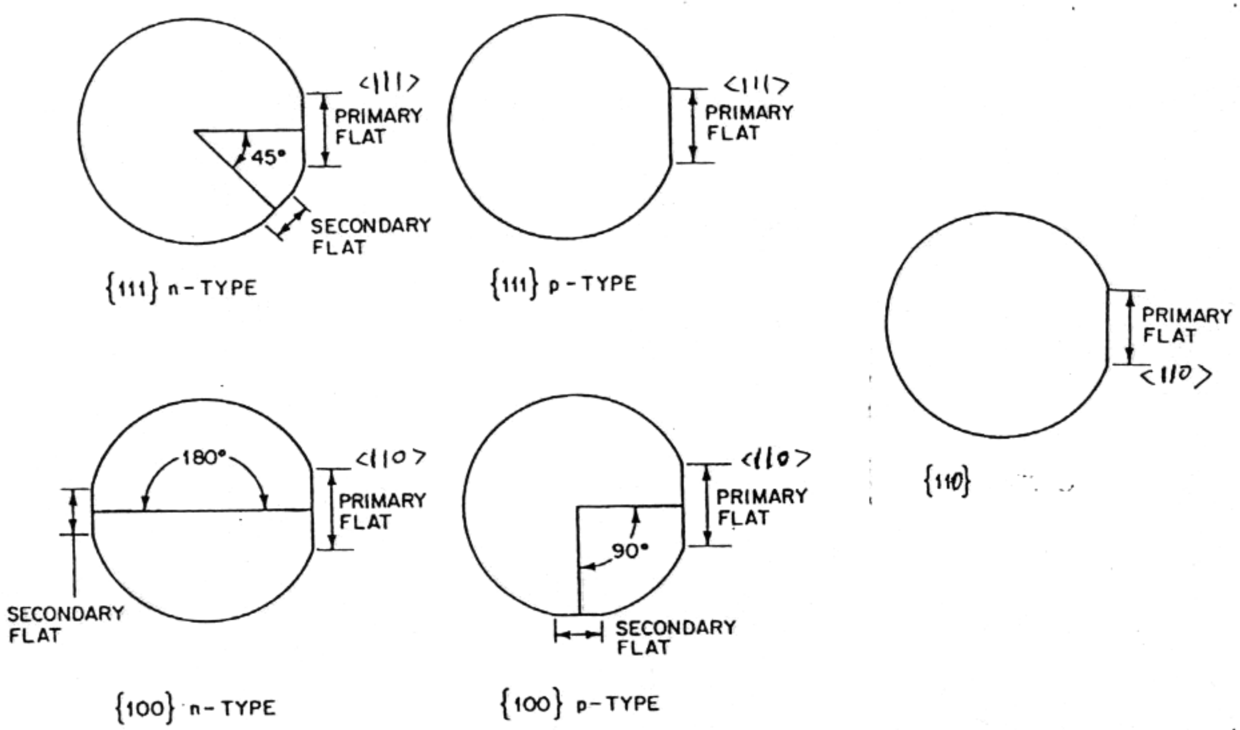


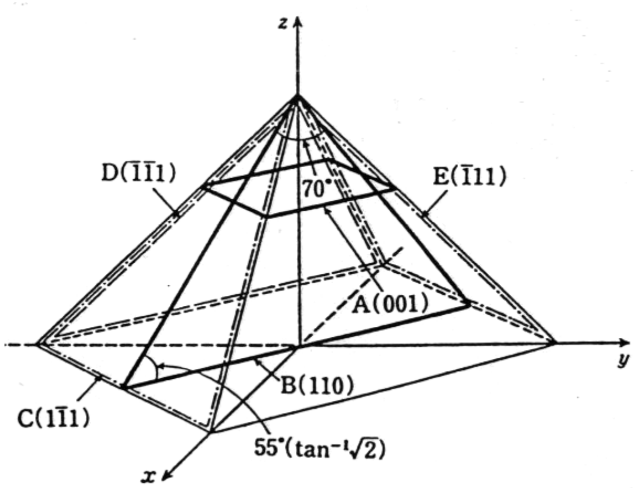
c. Miller indices (integer form of surface direction vector):

1. Take the intercepts with three axes, say a, b, c

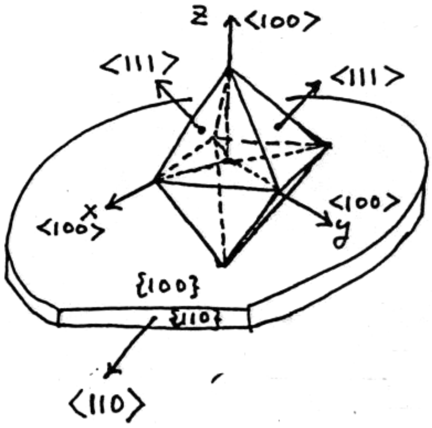
2. Take the reciprocal of these three integers, multiplied by smallest common denominator, get miller indices (d,e,f)

d. Silicon wafer flats and the relationship to crystal orientation:





Relation between crystal planes



Crystal direction of <100> wafer

e. Etching rate and selectivity among different crystal surface:

Concentration ↑: etching rate↓ selectivity ↑ surface roughness↓
Temperature ↑: etching rate ↑ selectivity ↓ surface roughness↑

Have

○ Etching characteristics

Etchant	Temperature	Etch Rates (μm hour^{-1}) {100}	{110}	{111}	SiO_2#
KOH 42% wt.	75°C	42	66	0.5*	0.34
KOH 57% wt.	75°C	25	39	0.5*	0.62
EDP Type S	110°C	51	57	1.25	0.004
NH_2:H_2O	118°C	176	99	11	0.01
NH_4OH 3.7% wt.	75°C	24	8	1	0.003
TMAH 22% wt.	80°C	32	-	1.4	0.00054

 # thermally grown in steam at 1000°C

TABLE 2 Experimentally Determined Activation Energies (E_a) and Pre-exponential Factors (R_0) for Etch Rate Calculation with the Arrhenius Equation: $R = R_0 \exp(-E_a/kT)$

Etchants	⟨100⟩ Si E_a(eV)	⟨100⟩ Si R_0 (μm h)	⟨110⟩ Si E_a(eV)	⟨110⟩ Si R_0 (μm h)	SiO_2 E_a(eV)	SiO_2 R_0 (μm h)
Type-S EDP	0.40	9.33×10^6	0.33	1.16×10^6	0.80	1.36×10^8
KOH, 20%	0.57	1.23×10^{10}	0.59	3.17×10^{10}	0.85	3.52×10^{11}
a-KOH, 20%	0.62	4.08×10^{10}	0.58	4.28×10^9	0.90	1.72×10^{12}
KOH, 34%	0.61	3.10×10^{10}	0.60	3.66×10^{10}	0.89	2.34×10^{12}
NaOH, 24%	0.65	1.59×10^{11}	0.68	7.00×10^{11}	0.90	3.20×10^{12}
LiOH, 10%	0.60	3.12×10^{10}	0.62	8.03×10^{10}	0.86	2.34×10^{11}

a-KOH contains isopropyl alcohol at 250 ml/l

S.M. Sze

f. Silicon anisotropic etching on <100> wafers

Along <110> direction:

Concave and convex corner:

The surface revealed in concave corner is the slowest one, however, it is the fastest one in convex cases.

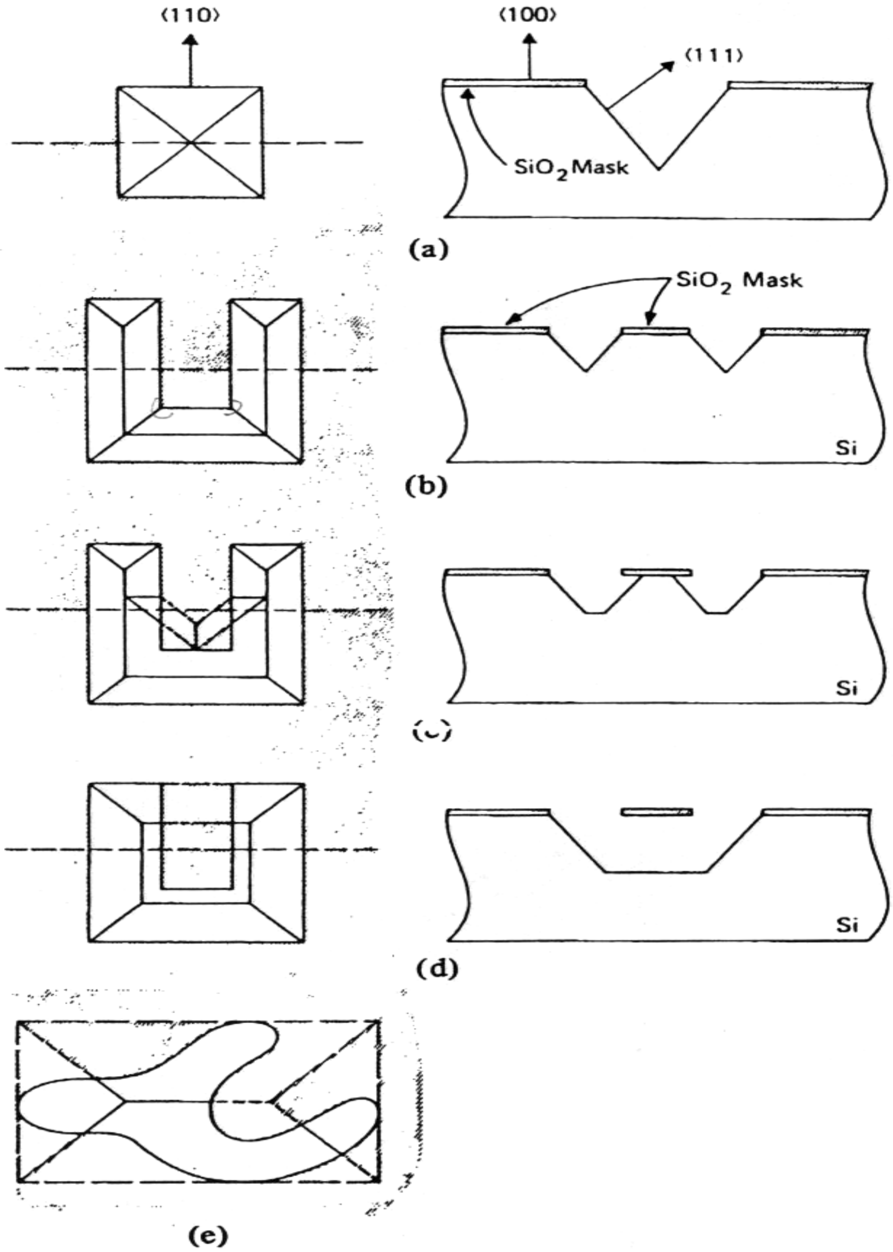
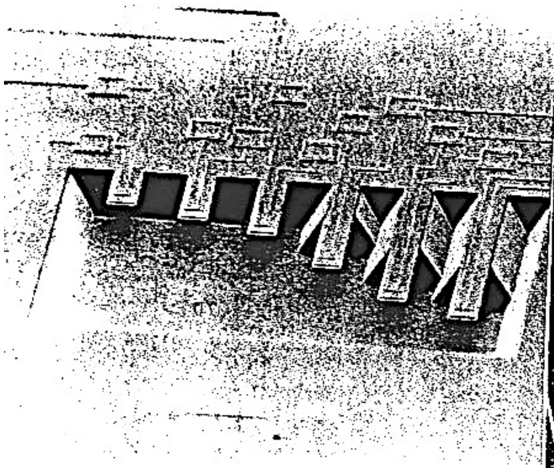
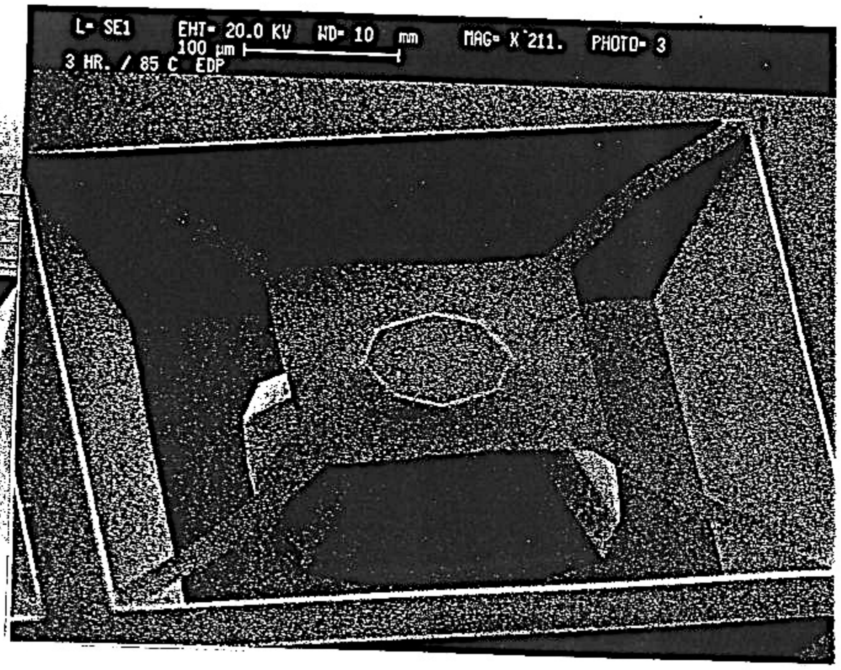


Fig. 5. (a) Typical pyramidal pit, bounded by the (111) planes, etched into (100) silicon with an anisotropic etch through a square hole in an oxide mask. (b) Type of pit which is expected from an anisotropic etch with a slow convex undercut rate. (c) The same mask pattern can result in a substantial degree of undercutting using an etchant with a fast convex undercut rate such as EDP. (d) Further etching of (c) produces a cantilever beam suspended over the pit. (e) Illustration of the general rule for anisotropic etch undercutting assuming a "sufficiently long" etching time.

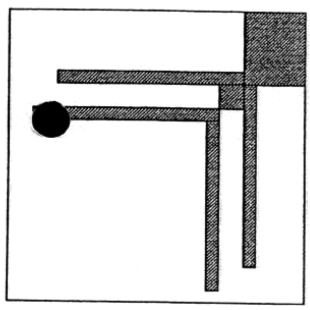
Examples:





Conner compensation:

A



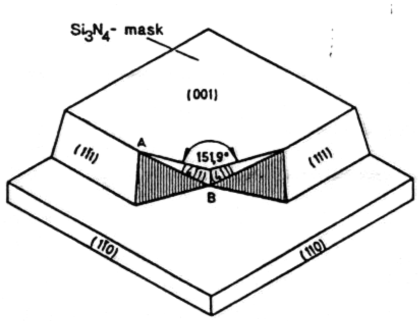


FIGURE 4.62 Planes occurring at convex corners during KOH etching. (From Mayer, G.K. et al., *J. Electrochem. Soc.*, 137, 3947–3951, 1990. With permission.)

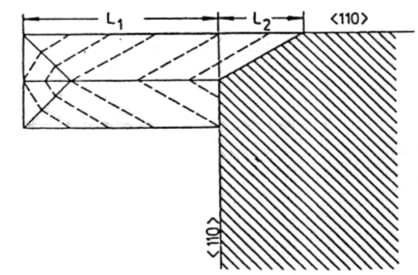
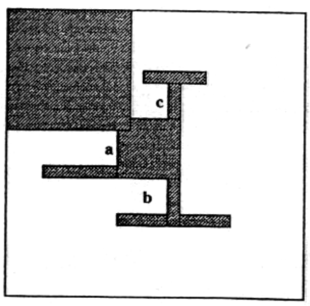
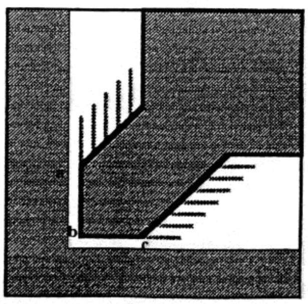


FIGURE 4.63 Dimensioning of the corner compensation structur with a <110>-oriented beam. (From Sandmaier, H. et al., Corner Com pensation Techniques in Anisotropic-Etching of (100) Silicon Usin Aqueous KOH, presented at Transducers '91, San Francisco, CA, 1991 With permission.)

B



C



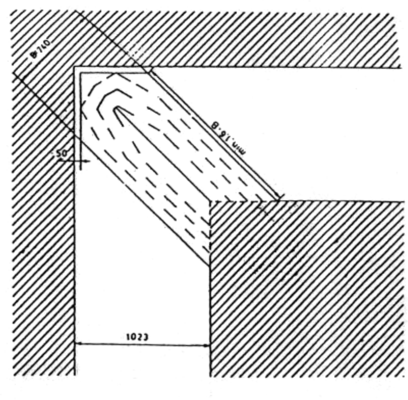


FIGURE 4.64 Beam structure open on one side. The beam is oriented in the <010> direction. Dimensions in microns. B is the width of the beam.

Along <100> direction:

HH'88, Chang&Hicks

KOH<110>><100> vs EDP<100>><110>

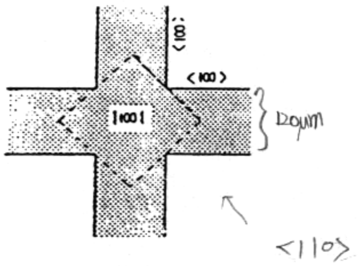


Fig. 1 Mask layout. The compensation streets are aligned in the <100> directions. The width of the street is 120 µm.

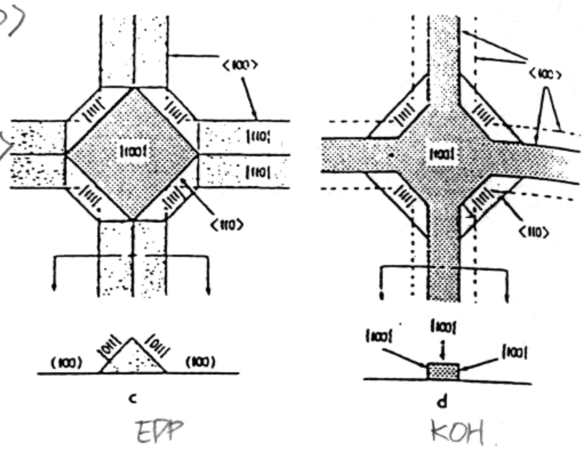
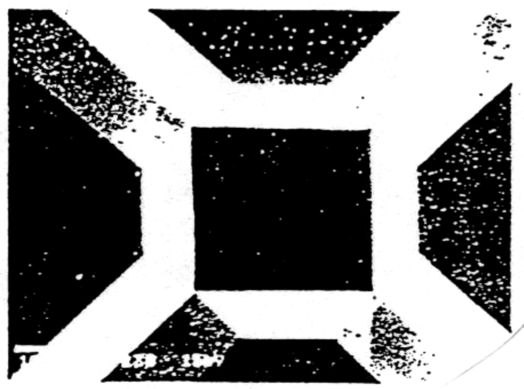
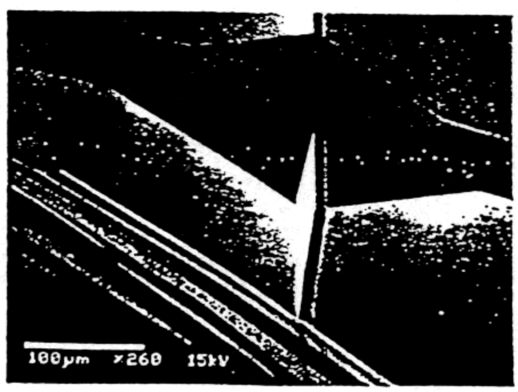


Fig. 2 (a) An SEM photograph of a silicon feature etched in EDP for 45 minutes. Note the triangular cross section of the street; (b) The same feature etched in KOH for 30 minutes. Note the rectangular cross section of the street; (c) and (d) are illustrations of the different etching characteristics between EDP and KOH respectively.

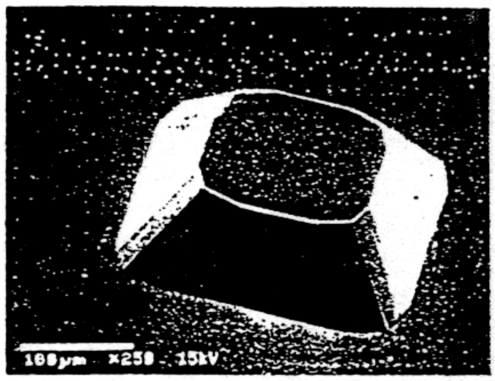


a

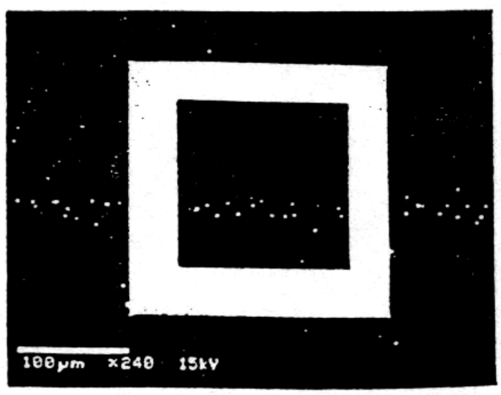
<110>



b



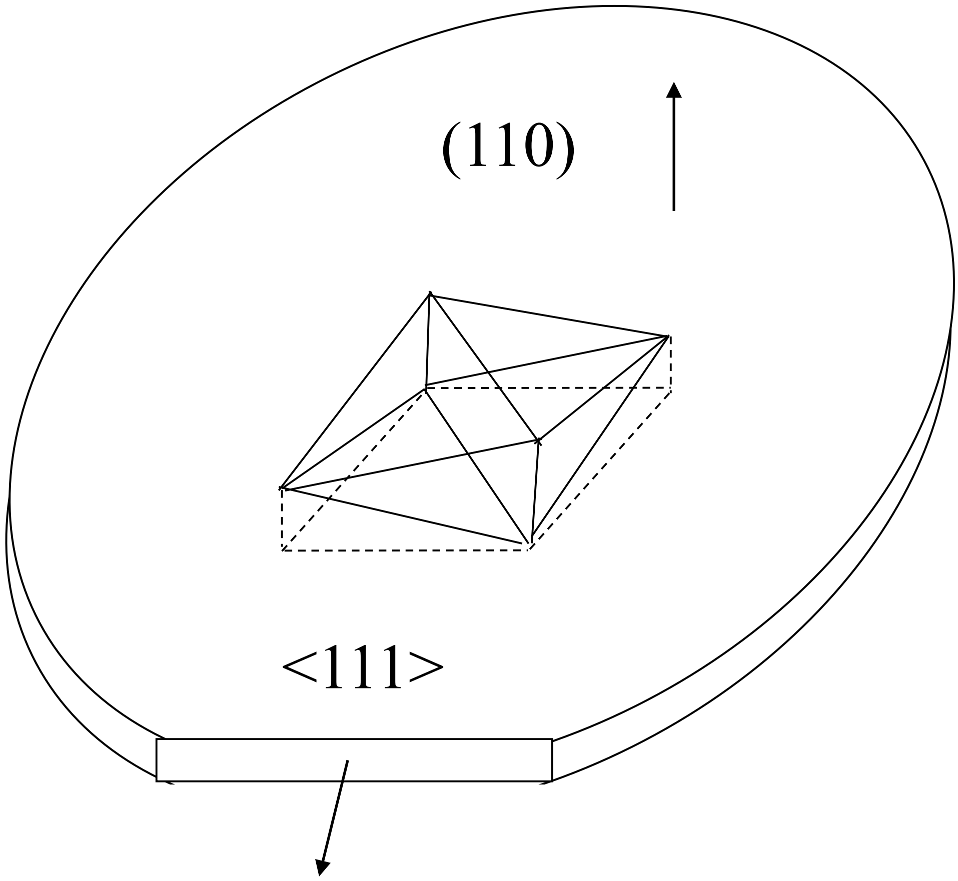
a



b

Fig. 3 SEM photographs of silicon mesa structures generated by (a) EDP and (b) KOH.

g. Silicon anisotropic etching on <110> wafers



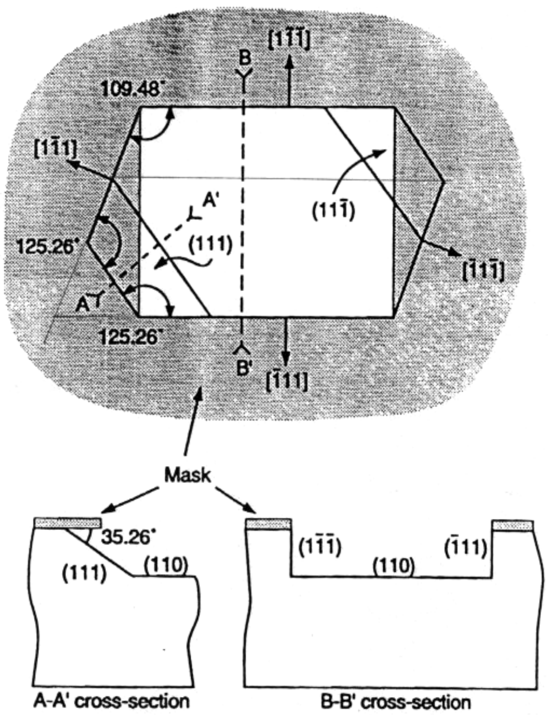


Fig. 24 Top view and cross-sectional views of an etched cavity in a (110) silicon wafer, showing angular relationships between adjacent sidewalls

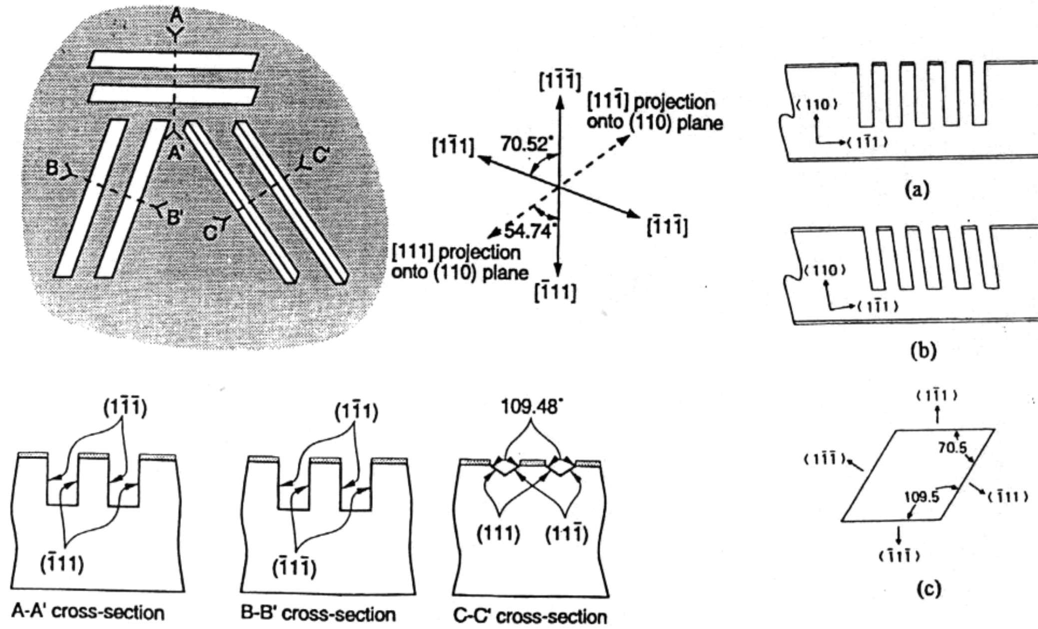
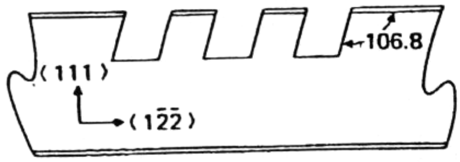
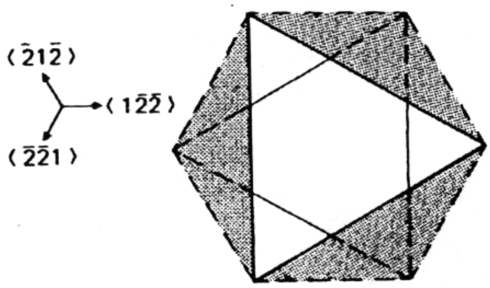


Fig. 25 Parallel trenches with vertical sidewalls are created from surface line patterns parallel to the $(1\bar{1}\bar{1})$ or $(\bar{1}1\bar{1})$ planes. The line patterns parallel to the $(\overline{111})$ and $(11\bar{1})$ planes result in shallow V-grooves with sidewalls at angles of 35.26° with the surface.

h. Silicon anisotropic etching on <111> wafers



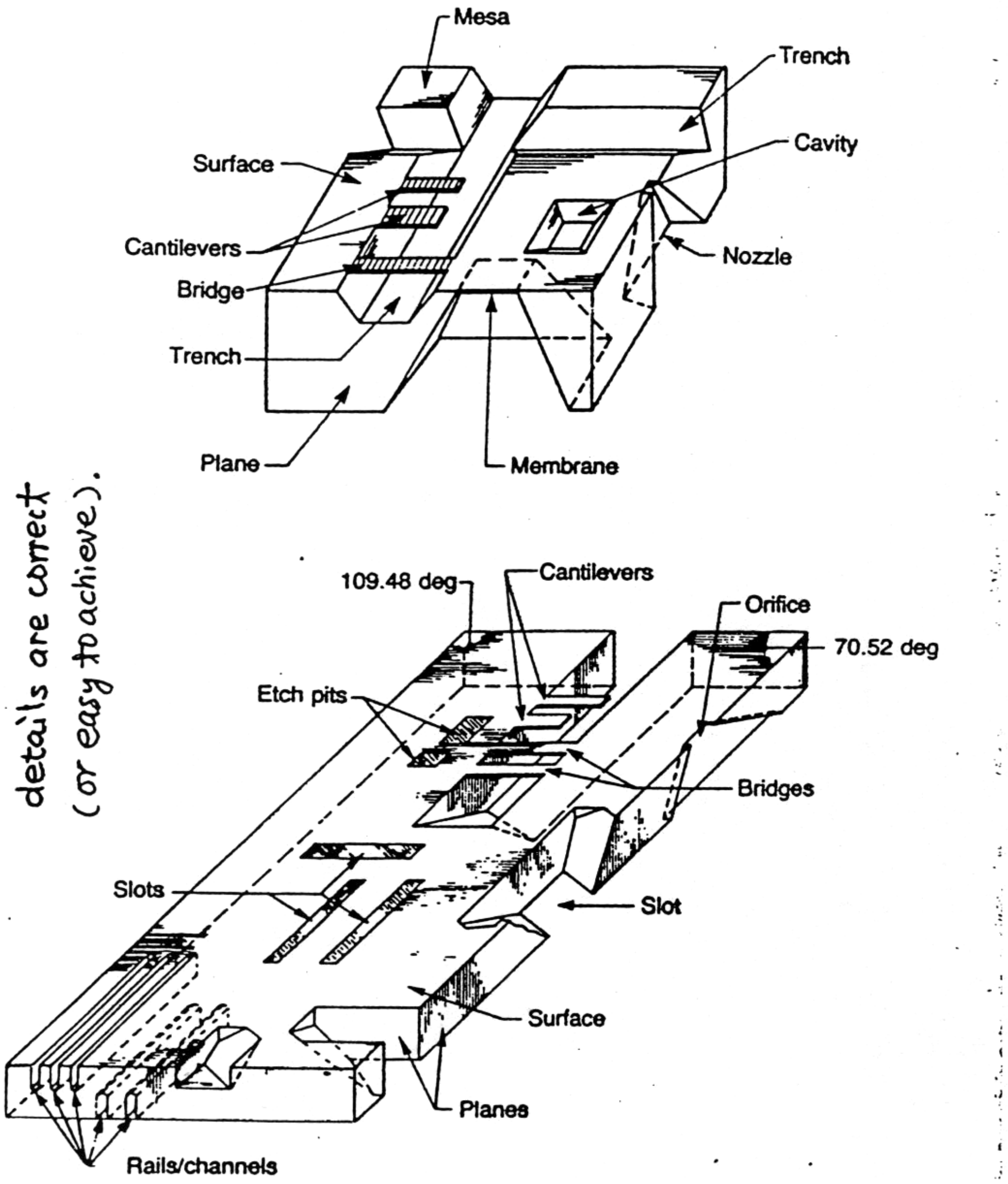
(a)



(b)

Fig. 7. Anisotropic etching of (111) silicon surfaces. (a) Wafer cross section with the steep sidewalls which would be found from grooves aligned along the (122) direction. (b) Top view of a hole etched in the (111) surface with three inward sloping and three undercut sidewalls, all (111) crystallographic planes.

Summary of possible shape by bulk etching <100> or <110> wafers:



Note: Not all the details are correct (or easy to achieve).

Typical three-dimensional structures formed by anisotropic etching of single-crystal silicon (monosilicon). Crystal planes normal to the surface (in the top drawing) produce perpendicularly intersecting sidewalls. Sloping sidewalls (in the lower drawing) are formed by self-limiting etch planes.

i. Etch stop:

High Boron Concentration:

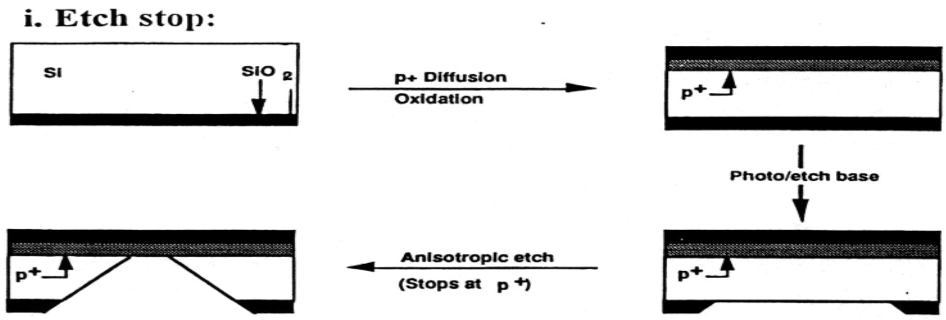


Figure 3.14 The p^+ region used as an etch-stop in anisotropic etching. The thickness of the diaphragm is determined by the thickness of the p^+ region.

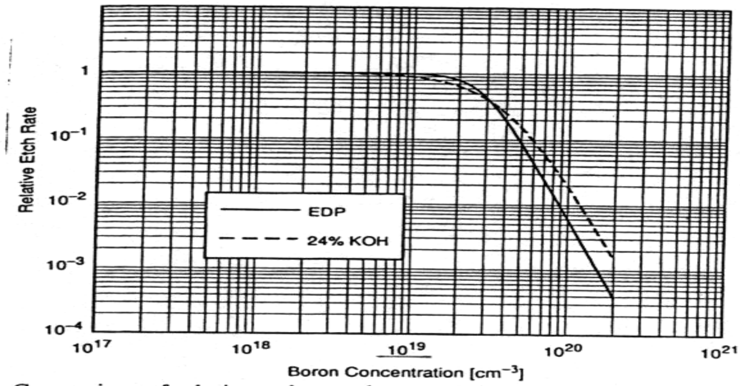


Fig. 26 Comparison of relative etch rates between EDP and KOH solutions of silicon in the ⟨100⟩ direction as a function of boron-doping level.

Electrochemical etch stop

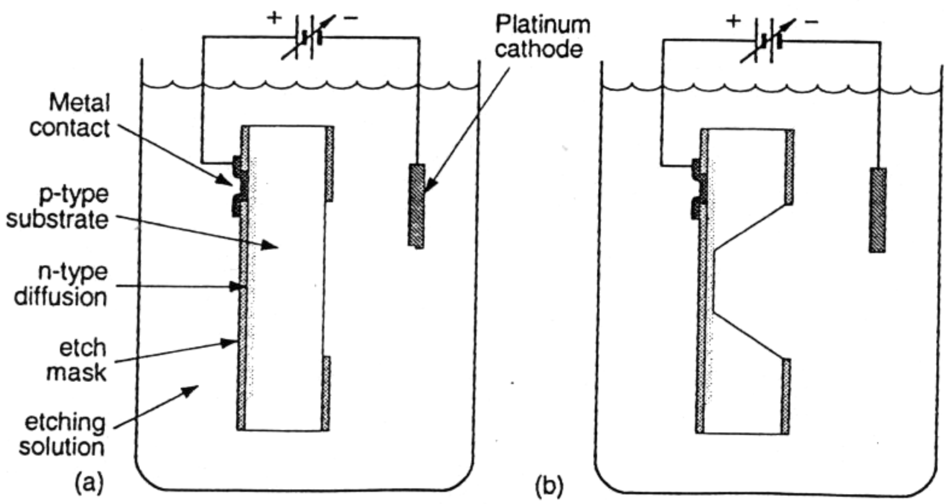


Fig. 27 The electrochemical etch-stop technique used to form a diaphragm.

2. Silicon dry etching:
Deep silicon RIE:

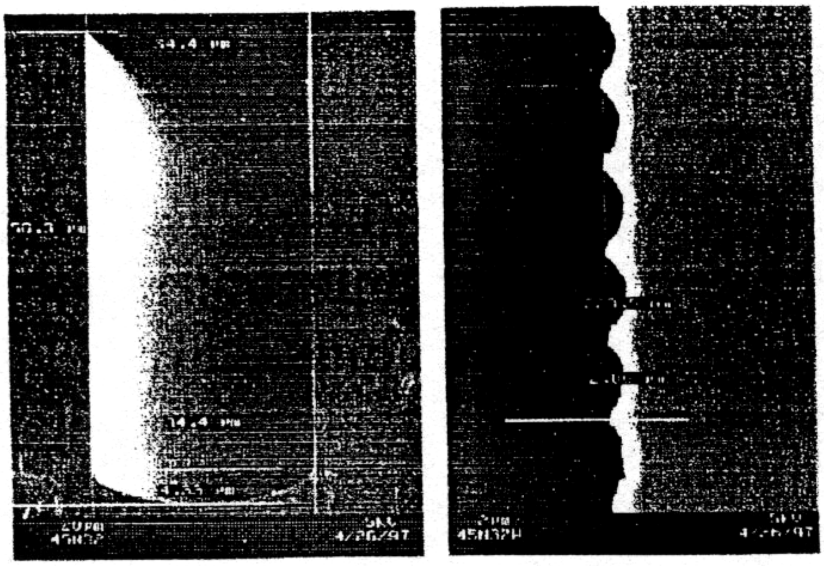


Figure 2. Micrograph view of an anisotropic etch (left) and the scalloping observed on the walls due to the periodic etch/deposition.