Silicon Basics -- General Overview.

Semiconductor Electronics: Review.

hydrogen **1** H 1.00794(7)							helium **2** He 4.002602(2)
lithium **3** Li 6.941(2)	beryllium **4** Be 9.012182(3)	boron **5** B 10.811(7)	carbon **6** C 12.0107(8)	nitrogen **7** N 14.00674(7)	oxygen **8** O 15.9994(3)	fluorine **9** F 18.9984032(5)	neon **10** Ne 20.1797(6)
sodium **11** Na 22.989770(2)	magnesium **12** Mg 24.3050(6)	aluminium **13** Al 26.981538(2)	silicon **14** Si 28.0855(3)	phosphorus **15** P 30.973761(2)	sulfur **16** S 32.066(6)	chlorine **17** Cl 35.4527(9)	argon **18** Ar 39.948(1)
potassium **19** K 39.0983(1)	calcium **20** Ca 40.078(4)	gallium **31** Ga 69.723(1)	germanium **32** Ge 72.61(2)	arsenic **33** As 74.92160(2)	selenium **34** Se 78.96(3)	bromine **35** Br 79.904(1)	krypton **36** Kr 83.80(1)

Semiconductor Electronics: Review.

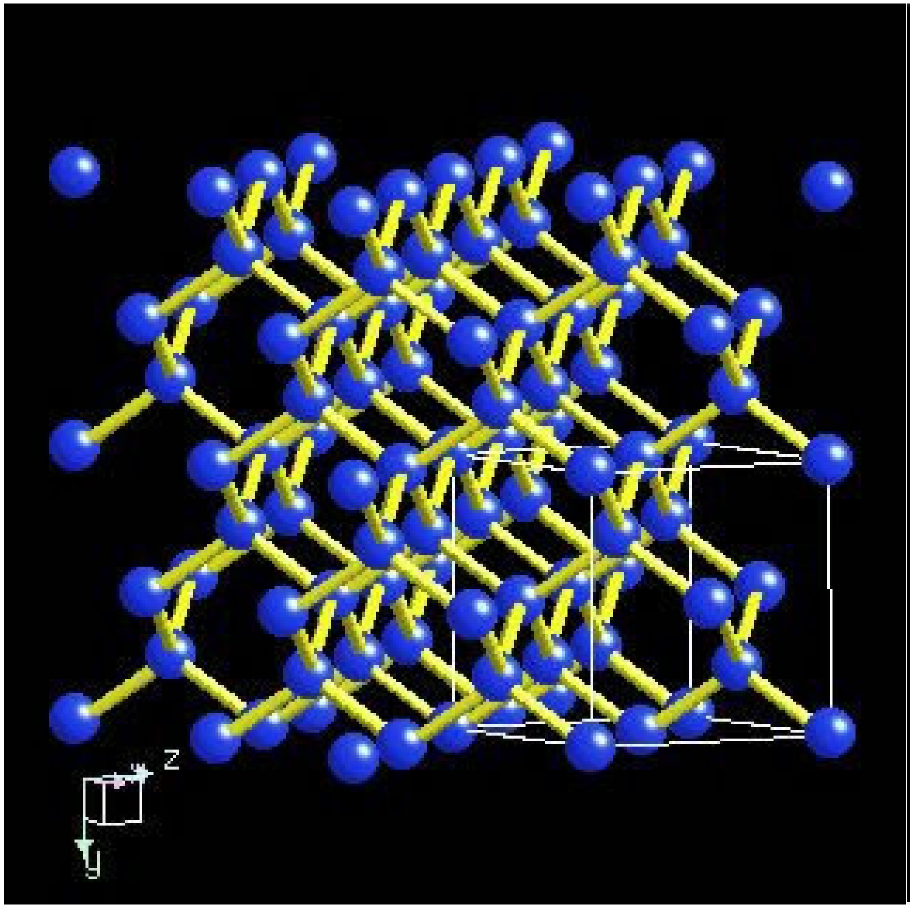
Silicon: basic information and properties.

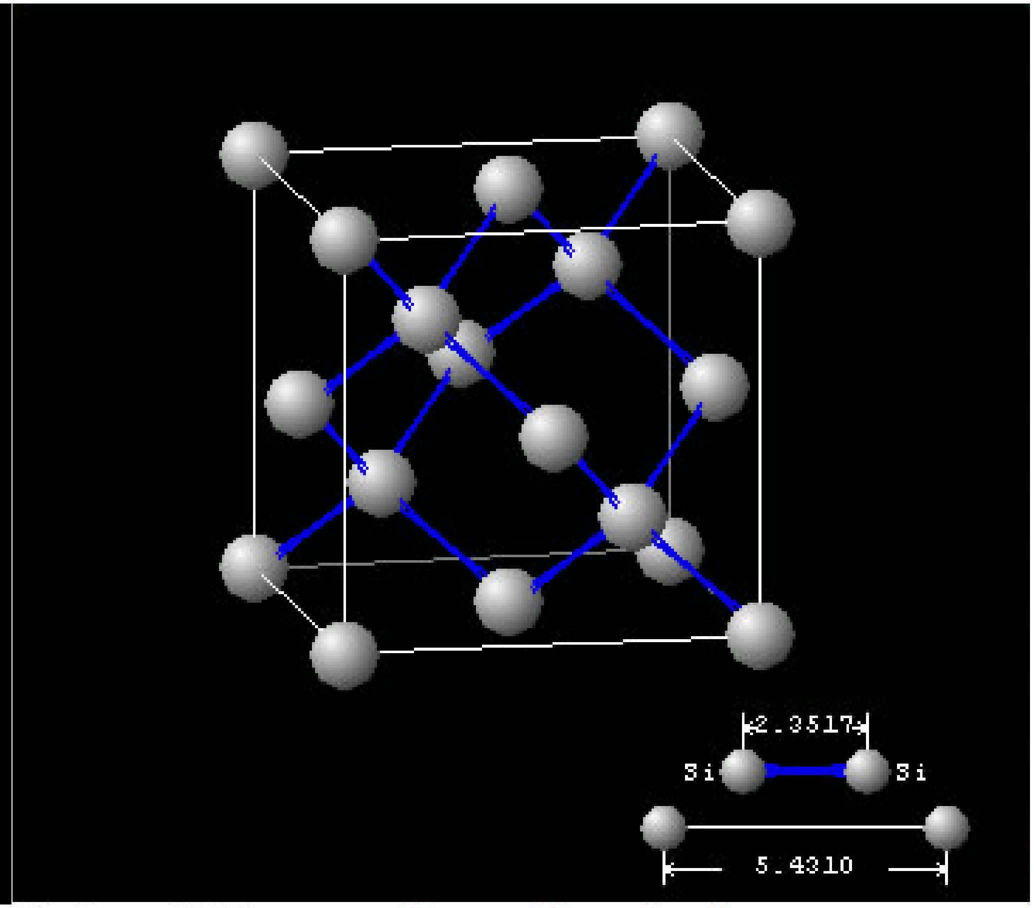
Atomic Weight	28.09
Electron configuration	[Ne] $3s^2 3p^2$
Crystal structure	Diamond
Lattice constant (Angstrom)	5.43095
Density: atoms/cm^3	4.995E+22
Density (g/cm^3)	2.328
Dielectic Constant	11.9
Density of states in conduction band, N_C (cm^{-3})	3.22E+19
Density of states in valence band, N_V (cm^{-3})	1.83E19
Effective Mass, m*/m0	
Electrons	
m*l	0.98
m*t	0.19
Holes	
m*l	0.16
m*h	0.49
Electron affinity, x(V)	4.05
Energy gap (eV) at 300K	1.12

Silicon: basic information and properties.

Intrinisic carrier conc. (cm^{-3})	1.0E10
Intrinsic Debye Length (micron)	24
Intrinsic resistivity (ohm cm)	2.3 E+05
Linear coefficient of thermal expansion ($1/^{o}C$)	2.6 E-06
Melting point (C)	1415
Minority carrier lifetime (s)	2.5 E-03
Mobility (cm^2 / V sec)	
μ(electrons)	1500
μ(holes)	450
Optical-phonon energy (eV)	0.063
Phonon mean free path (Angstrom)	76(electron) 55(hole)
Specific heat (J/g ^{o}C)	0.7
Thermal conductivity (W/cm ^{o}C)	1.5
Thermal diffusivity (cm^2/s)	0.9
Vapor pressure (Pa)	1 at 1650C 1E-6 at 900 C
Index of refraction	3.42
Breakdown field (V/cm)	~3 E+05

Crystal structure of silicon (diamond structure).





To view in 3D: mouse drag on the unit cell.

hyperlinks\silicon\@silicon java\cell.html

Source of applet is Semiconductor Applet Service, SUNY, Buffalo:
http://jas2.eng.buffalo.edu/applets/education/solid/unitCell/home.html

Consistency check:

Unit cell: 8 atoms at corners at 1/8 each in cell
6 atoms in faces at ½ each in cell
4 atoms within cell.

Thus total of 8 Si atoms per unit cell.

Each Si atom weighs 28 atomic mass units (1.66 E-24 grams).
Dimension of unit cell is 5.43 angstroms or 5.43 E-08 cm.

Thus density should be:

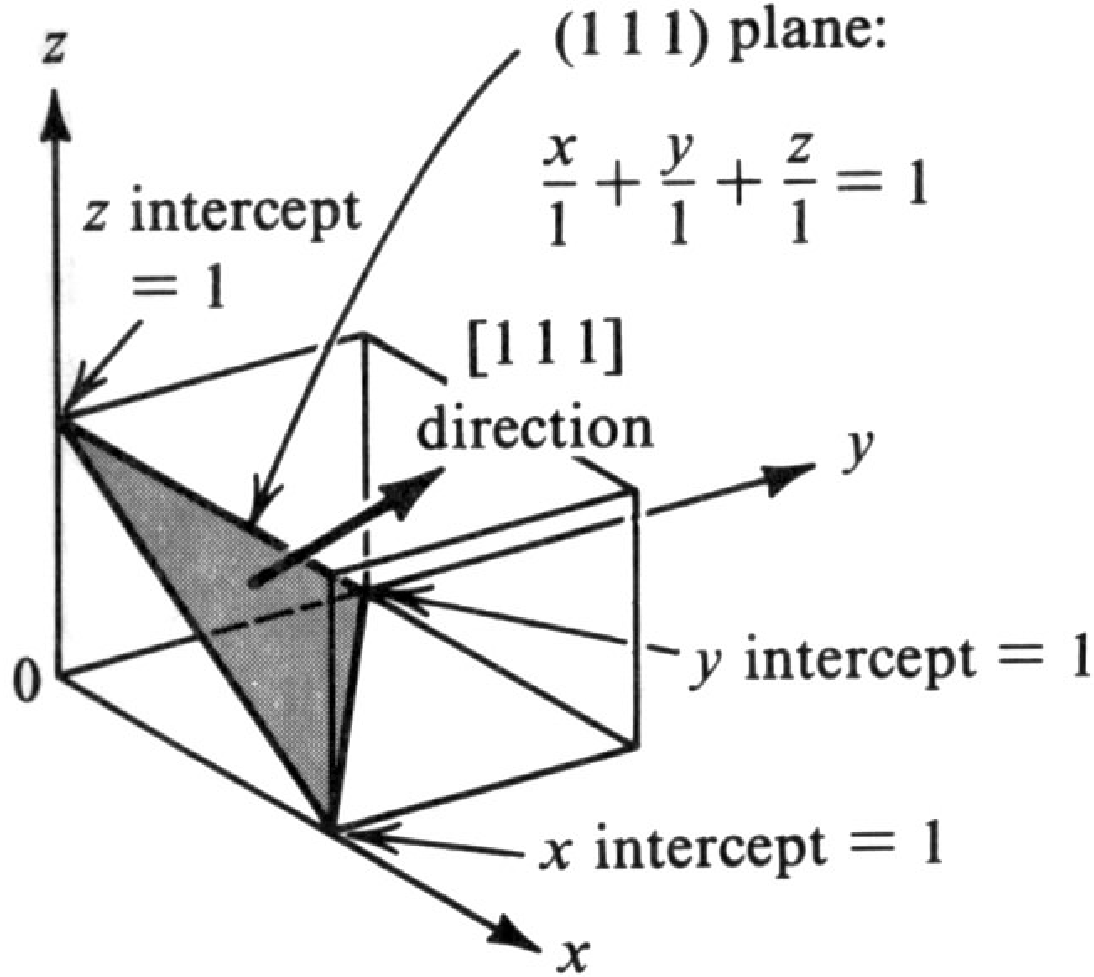
$$\frac{8 atoms \times 28 amu / atom \times (1.66e-24) g / amu}{([5.43e-08] cm)^3} = 2.32 g / cm^3$$

Agrees with measured density of 2.33 g/cm^3

Crystal planes of Silicon and Miller Indexes.

Start with unit cell with unit dimension along all axes.
Plane can be defined in terms of intercepts along 3 unit cell axes.

$$\frac{x}{\sim}+\frac{y}{}+\frac{z}{¥}=1$$

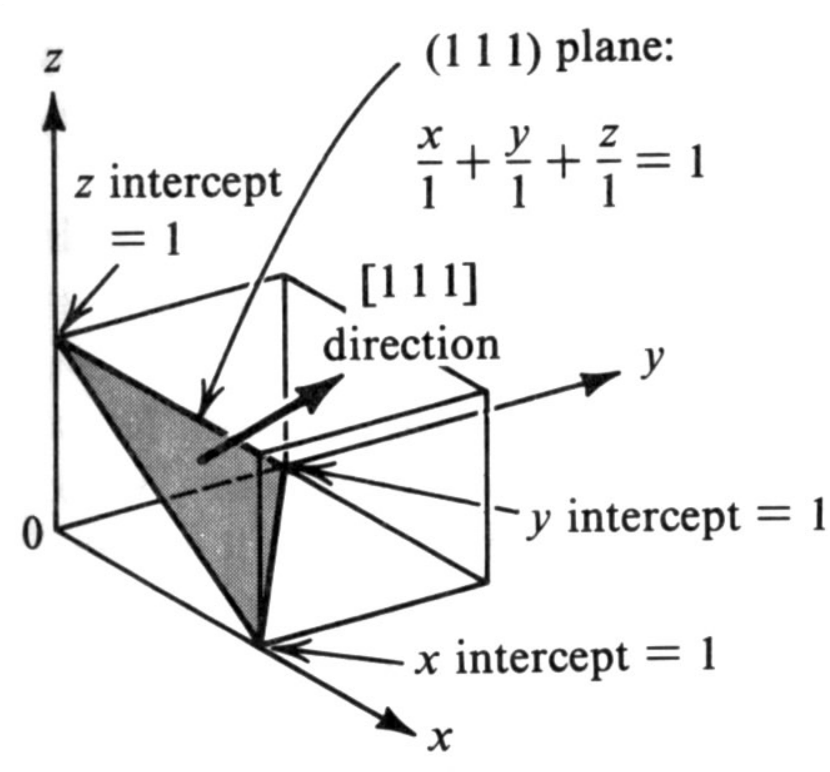


Miller Indexes.

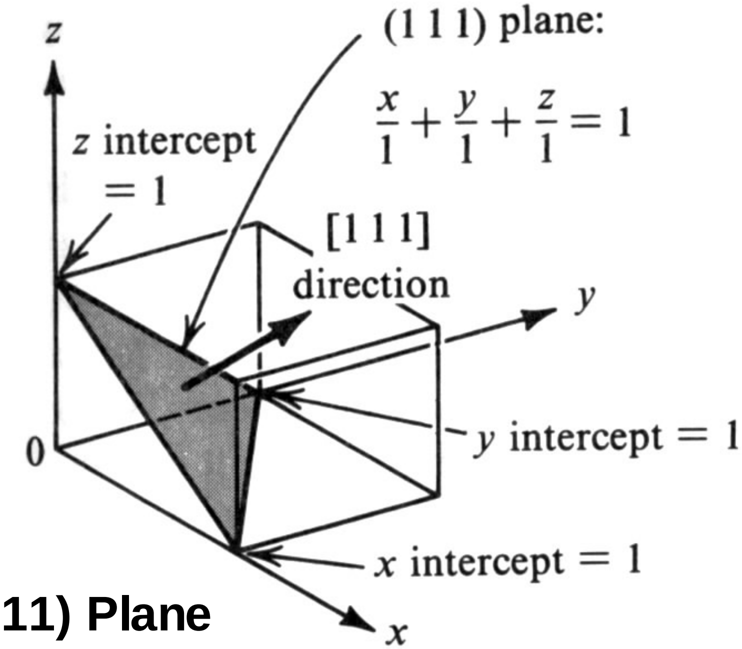
Miller indexes that define plane are inverse of α, β, γ : h, k, l .

The plane is then designated (hkl).
The set of symmetrically equivalent planes is designated {hkl}.
The direction normal to the plane is often designated [hkl].
The set of equivalent directions is <hkl>.
Planes can involve multiple cells:

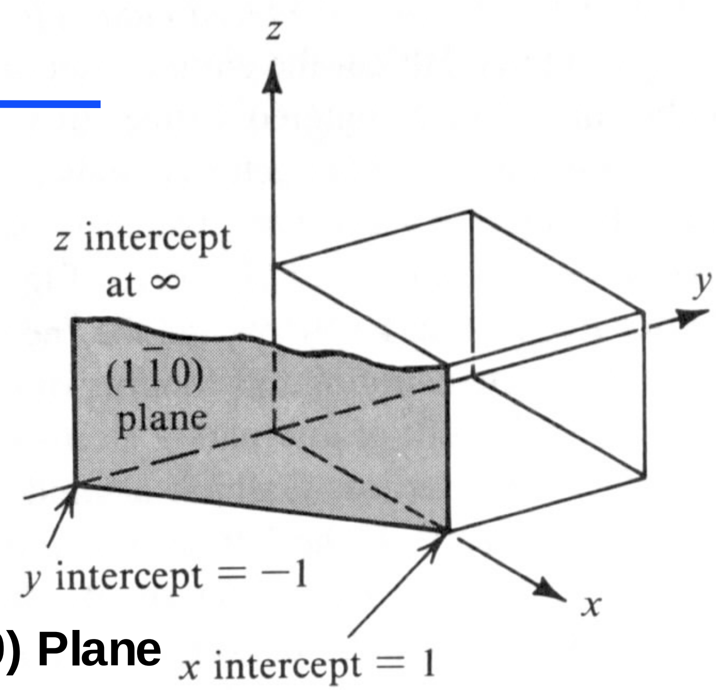
- Negative direction denoted by line above miller index: $(0\bar{1}1)$
- Fractions are usually rationalized.



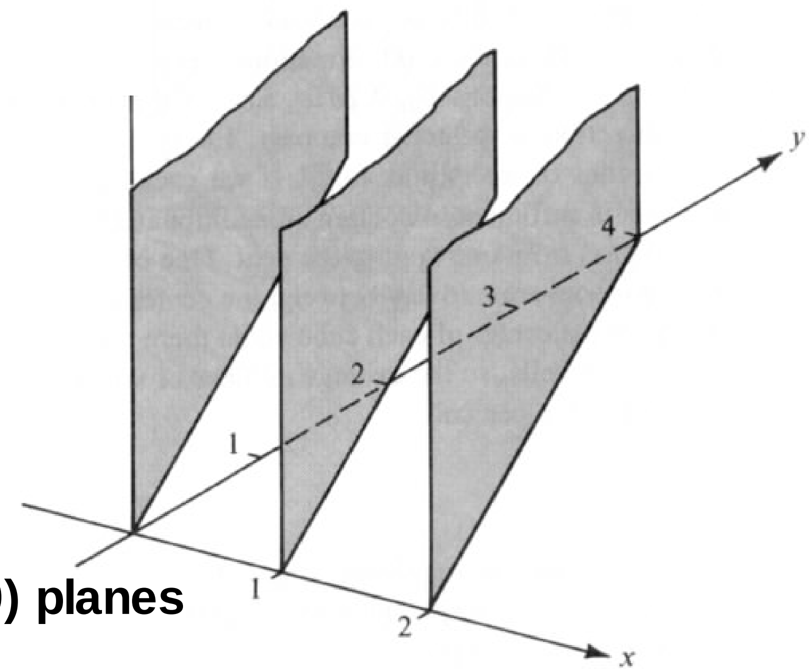
Miller indexes for silicon: examples.



(111) Plane

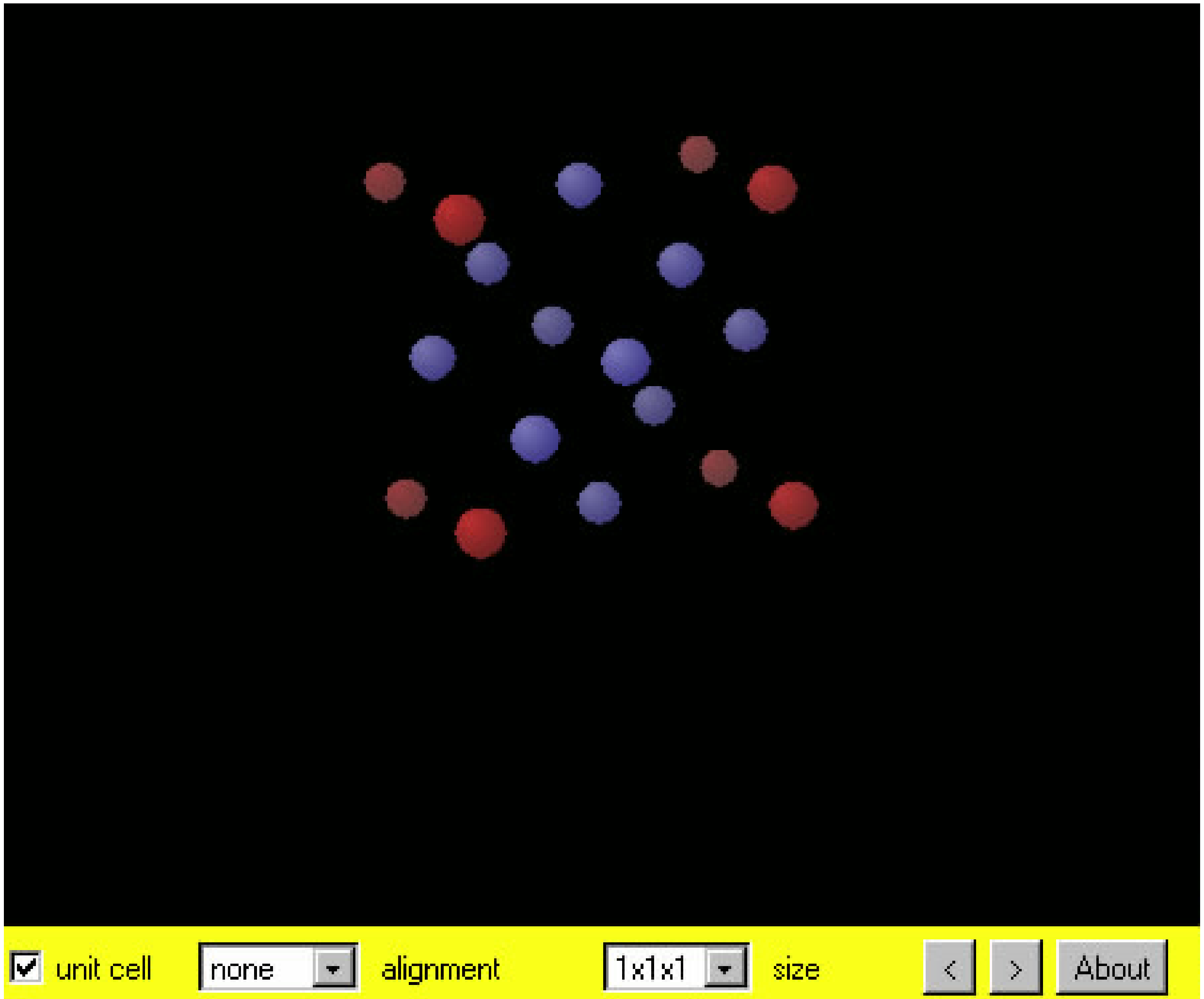


(1$\bar{1}$0) Plane



Set of (120) planes

Crystal structure of Silicon: Graphical representation.



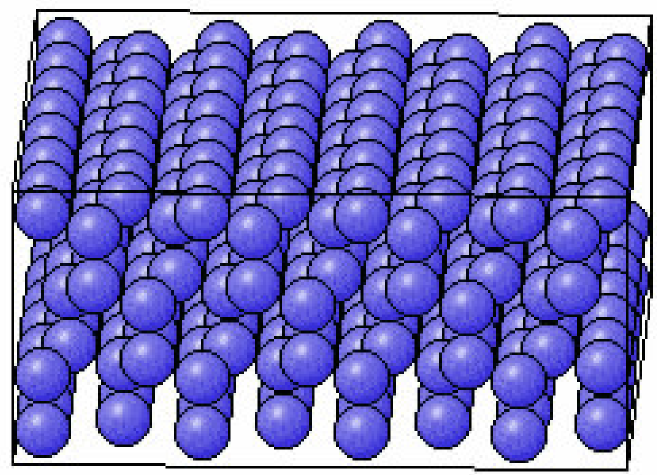
Diamond structure: hyperlinks\diamond xtal\diamond.htm

Source of applet: Unversity of Iowa, Physics.
http://ostc.physics.uiowa.edu/~wkchan/SOLIDSTATE/CRYSTAL/

Crystal geometries … continued.

Miller indices	1 1 1
Size	8 8 7 1
View	75 2 Parallel
Color	blue
Design	Glossy balls
Magnification	1.20

View



http://www.fhi-berlin.mpg.de/grz/pub/surfexp/SXinput.html

Standard designations for Silicon wafers.

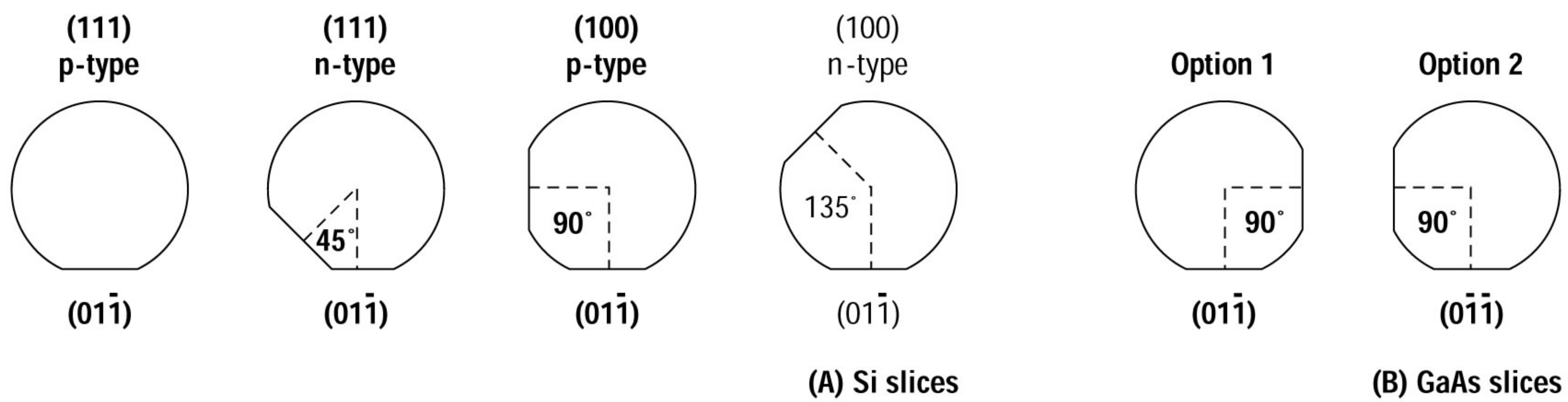


Figure 2.23 Standard flat orientations for different semiconductor wafers.

Source: Campbell

Production cycles for silicon wafers.

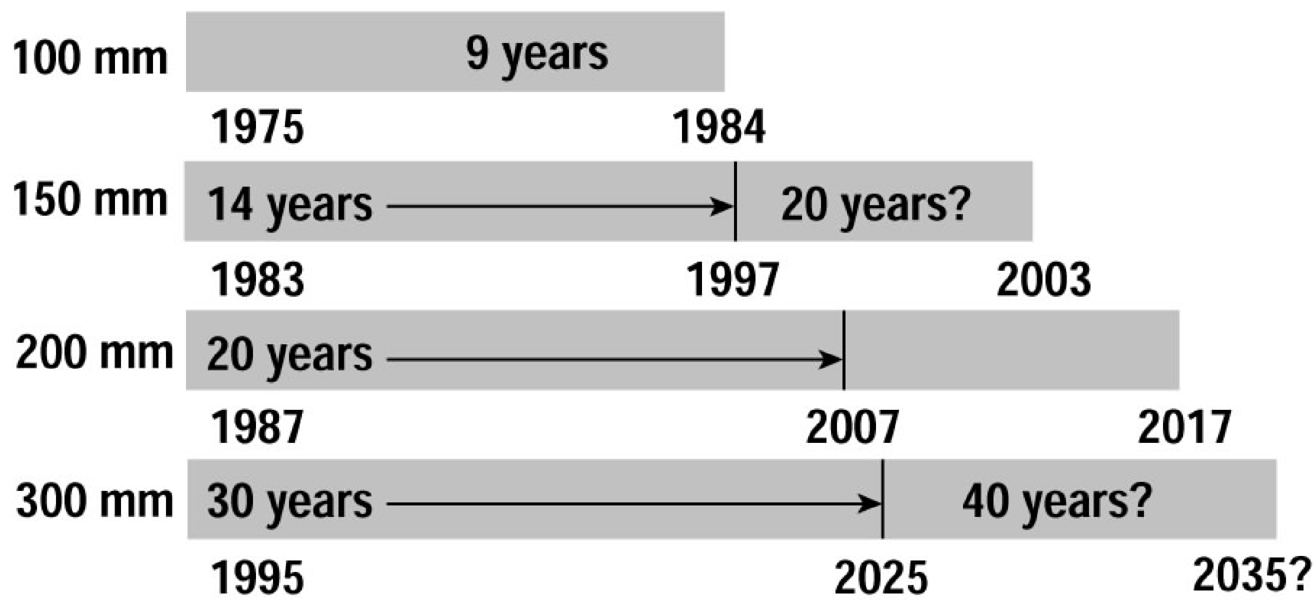
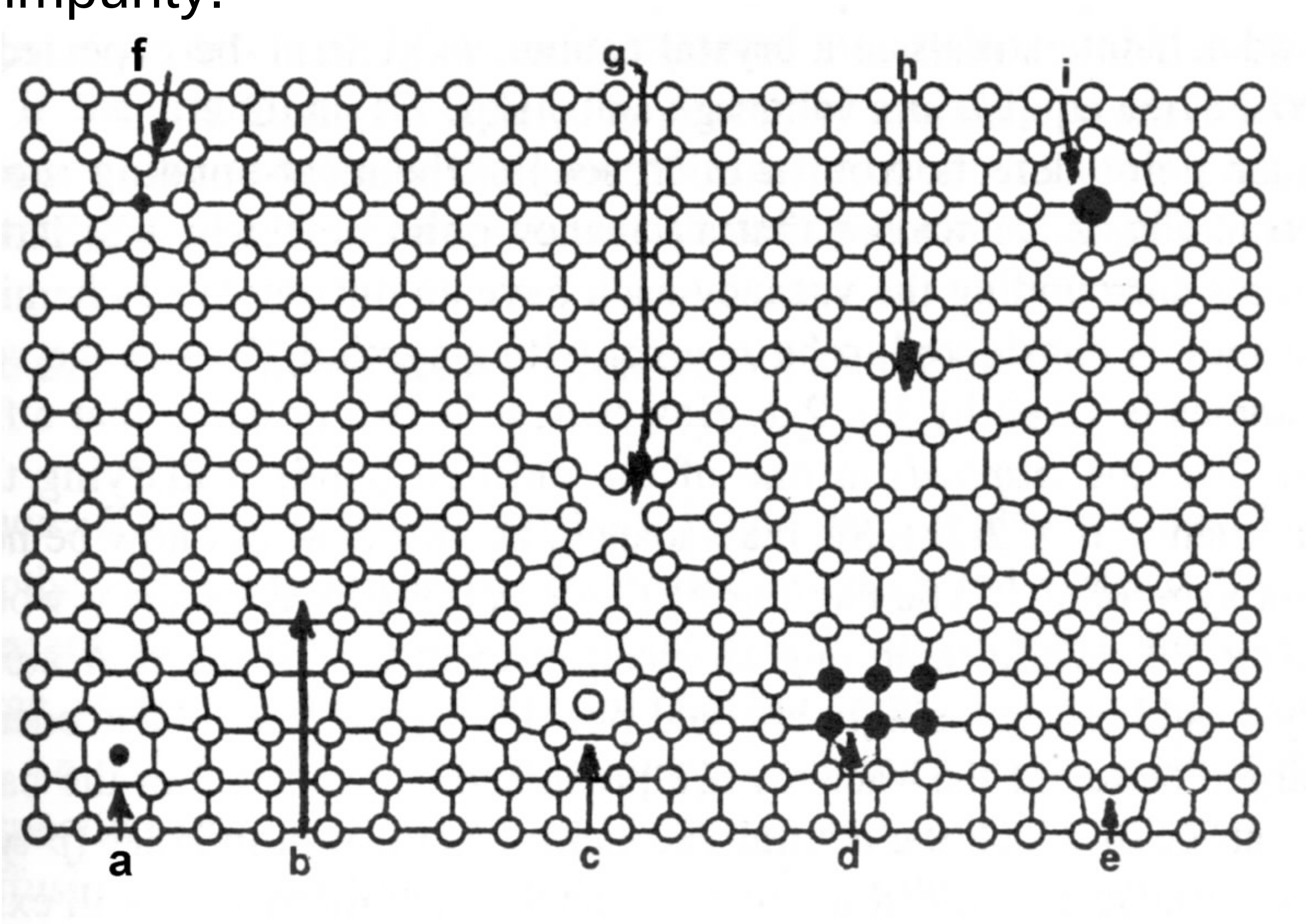


Figure 2.24 Projected life cycle from first production to peak production to phase out for various wafer sizes *(courtesy Semiconductor International [55])*.

Source: Campbell

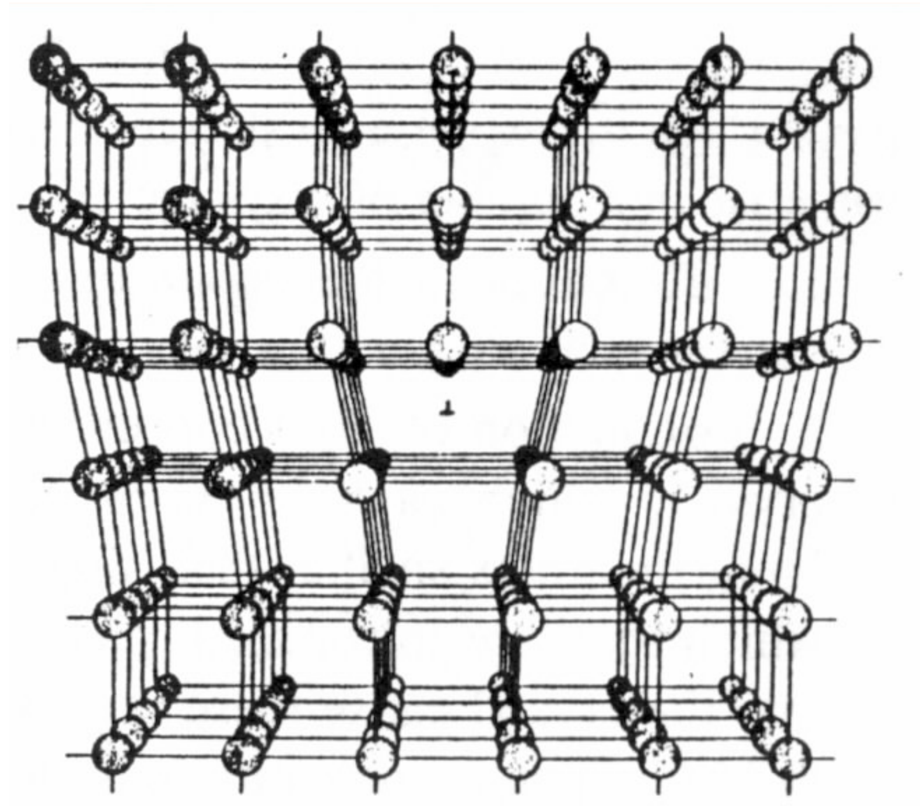
Crystal defects in Silicon: Point defects

i). Large substitutional impurity.
f). Small substitutional impurity.
c). Interstitial silicon atom.
a). Interstitial impurity.
g). Vacancy



Crystal Defects: Line defects

Example: edge dislocation



Crystal Defects: Area defects

Grain boundaries.
Surfaces.
….more…

Crystal Defects: Volume defects

Precipitates.
Voids.
….more…

Surface properties of silicon.

Surface structure and properties are critically important in semiconductor processing!

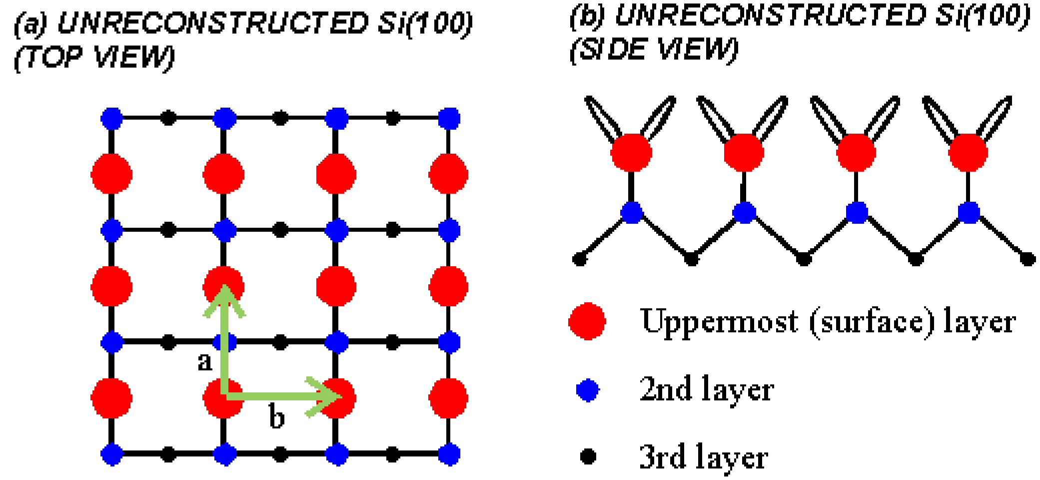
- Deposition and etch properties are highly dependent upon surface structure and chemistry.
- Epitaxial growth relies on surface structure.
- Junction properties can be influenced.

Surface structure can change through relaxation or through reconstruction or chemical reaction.

Structure influenced by crystal structure at and near the surface, energetics of bonding, chemical modification, etc.

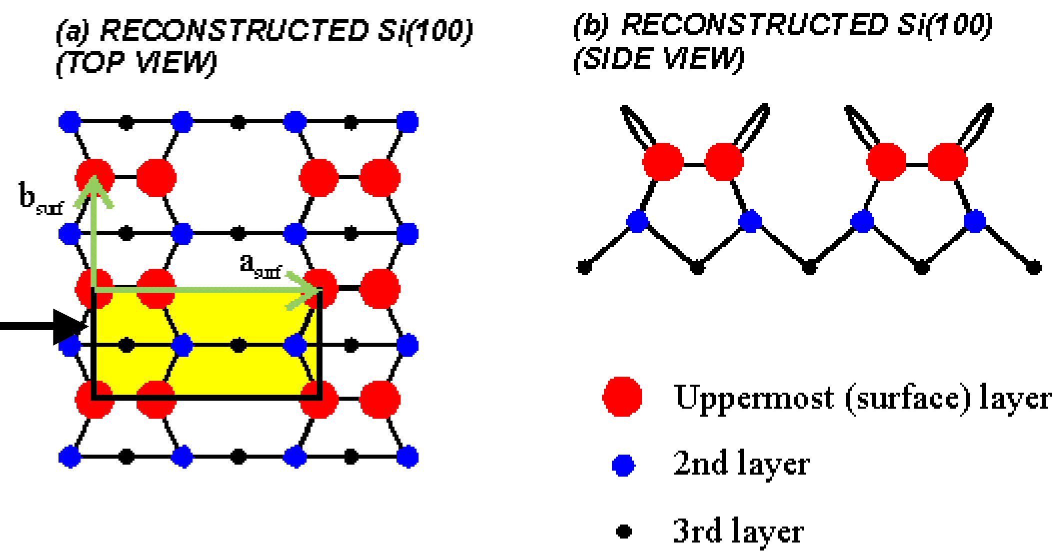
Much of this section adapted from http://www.nottingham.ac.uk/~ppzpjm/amshome.htm

Example: (1X2) reconstruction of Si (100).



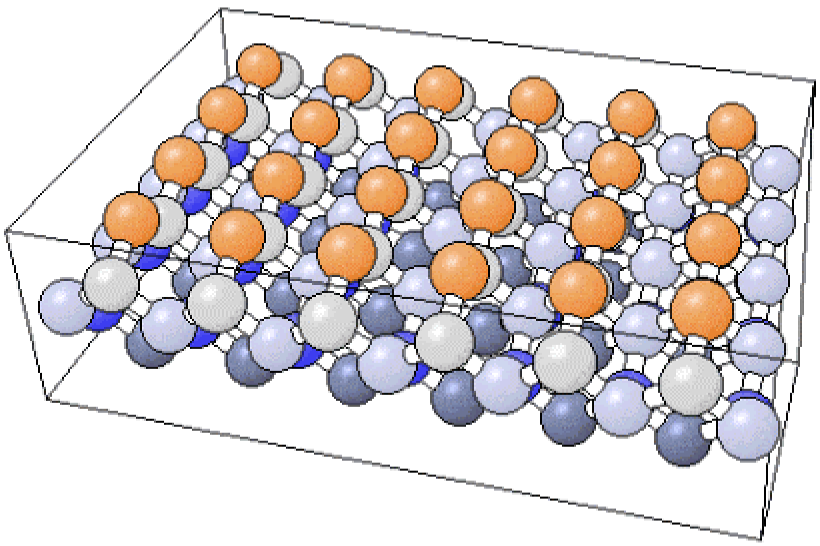
Surface can lower energy by forming Si-Si bonds, creating rows of "dimers".

1X2 reconstruction.

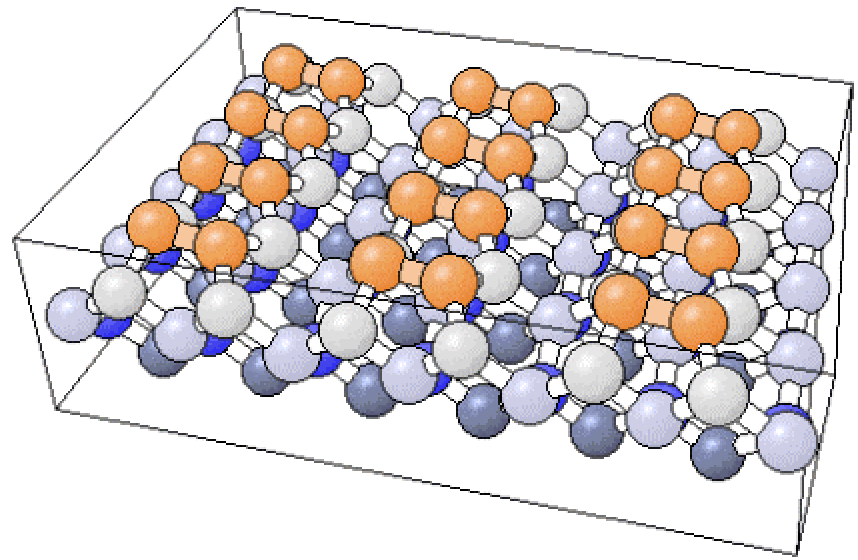


Example: (1X2) reconstruction of Si (100)…continued.

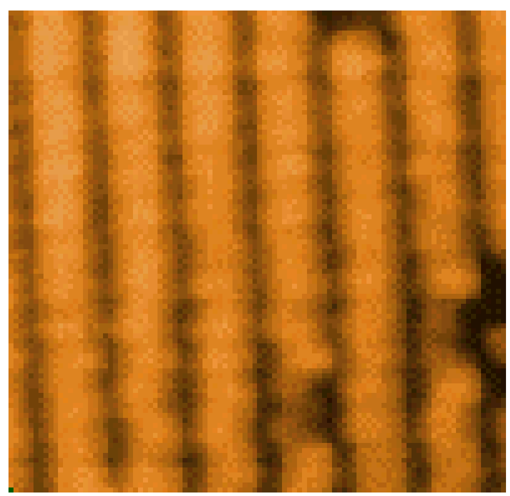
“Cleaved” (100) surface:

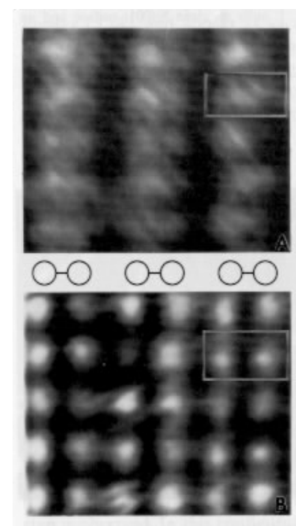


After reconstruction:

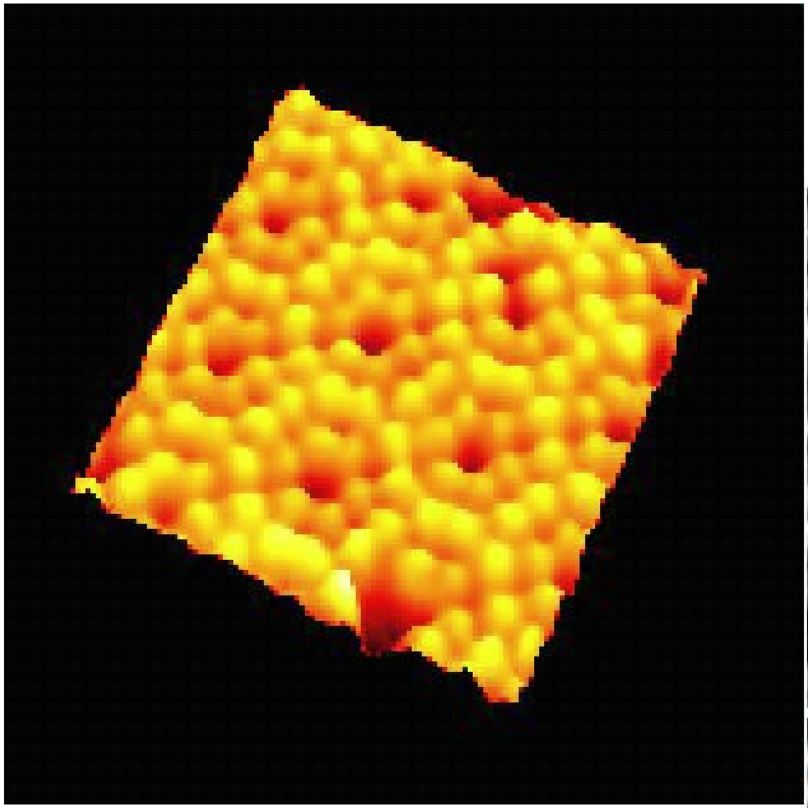


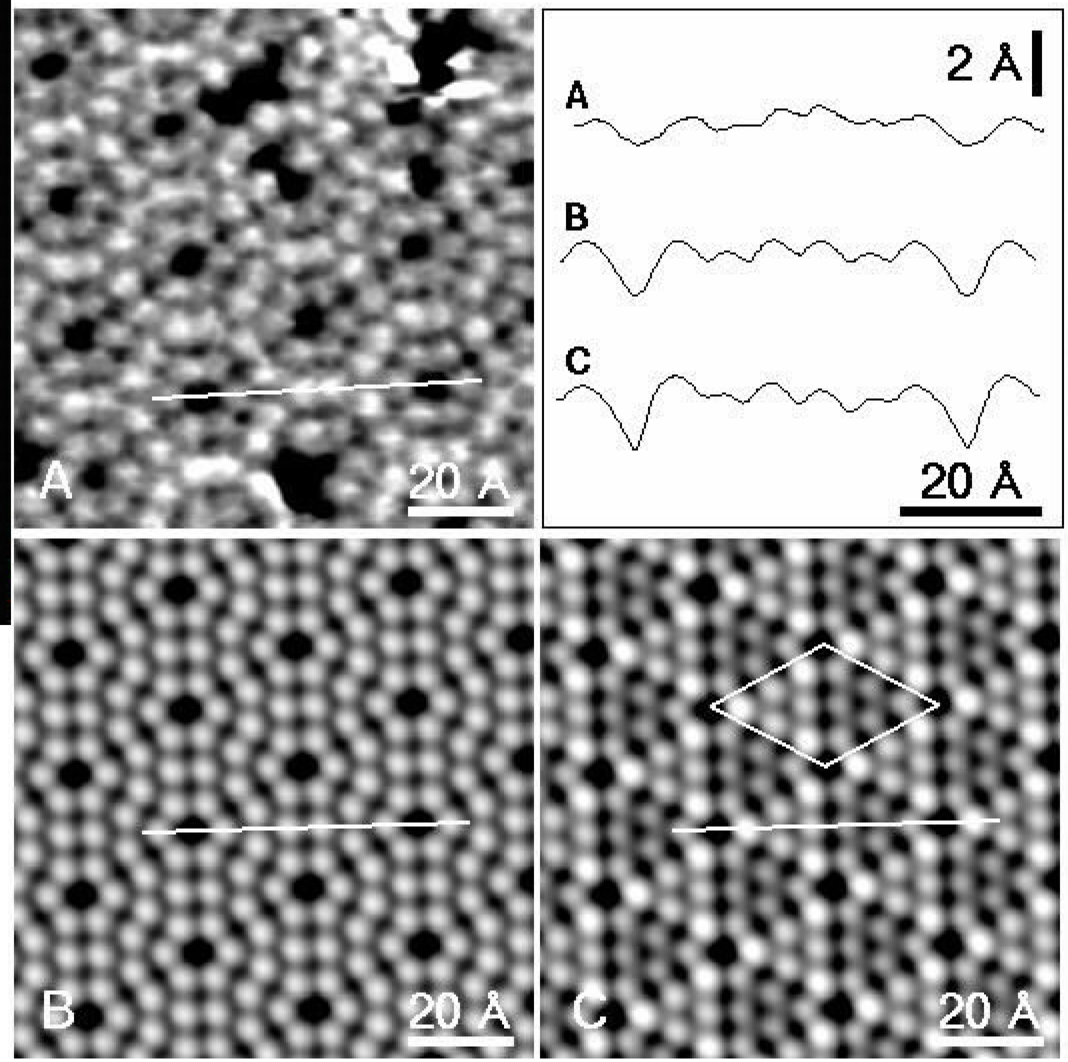
Scanning Tunneling Microscope (STM) images of Si(100) after reconstruction showing rows of dimers on surface.





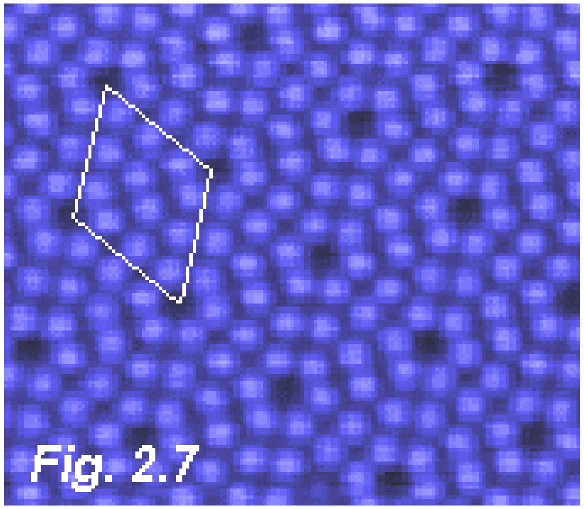
Complex example: (7X7) reconstruction of Si (111).

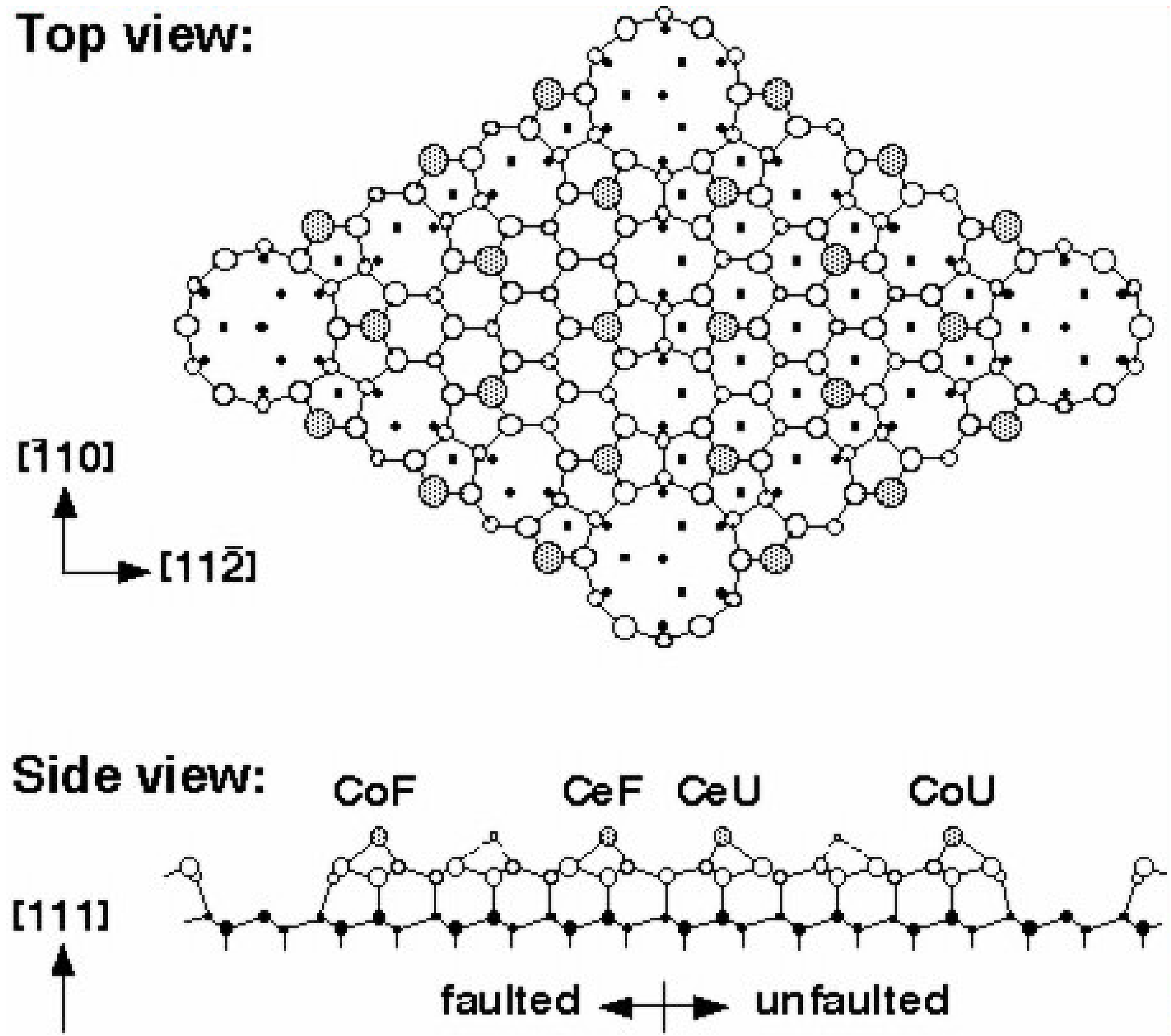




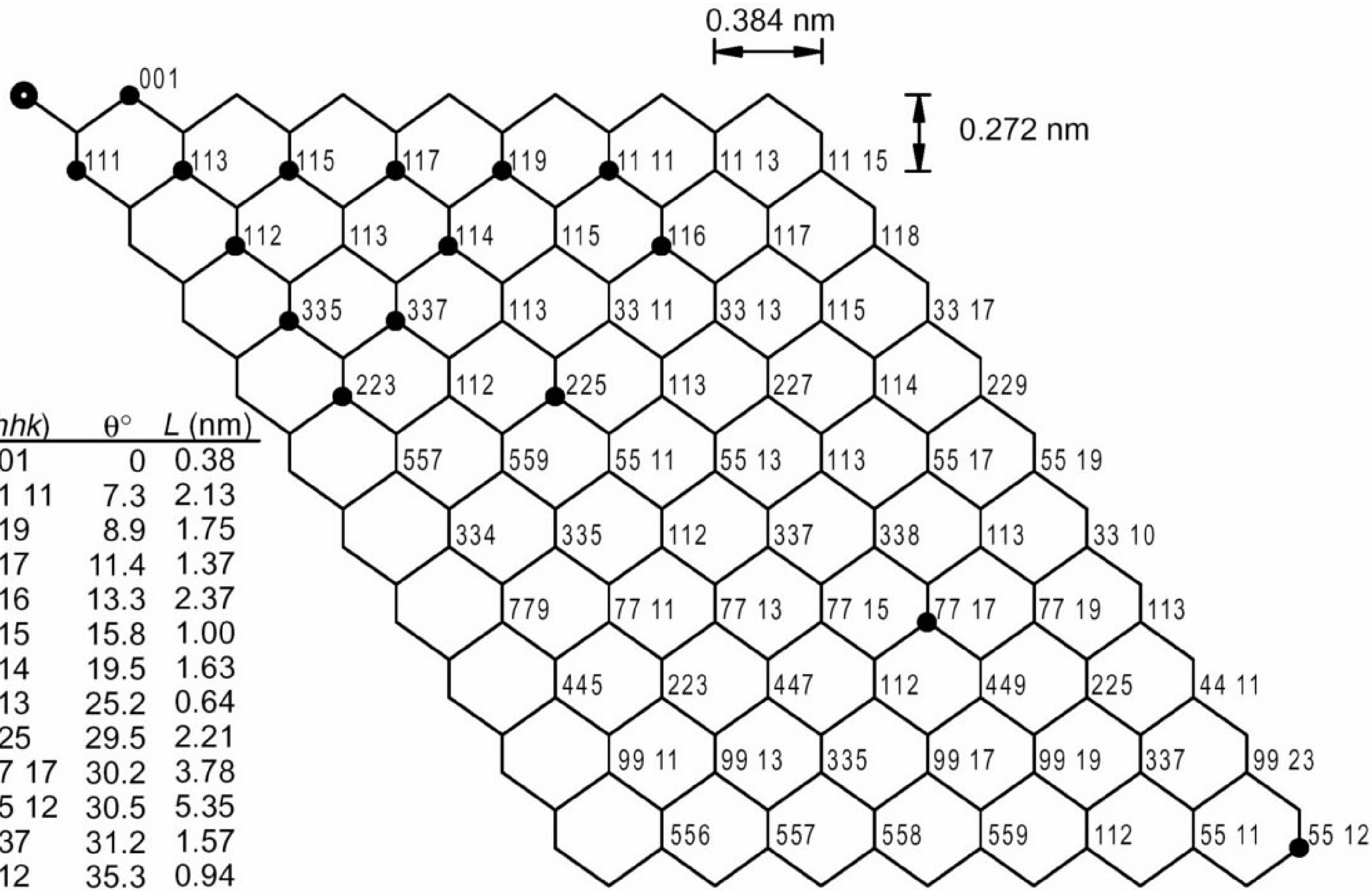
Note: elucidation of this structure has been subject of over 30 years of research.

(7X7) reconstruction of Si (111)….continued.





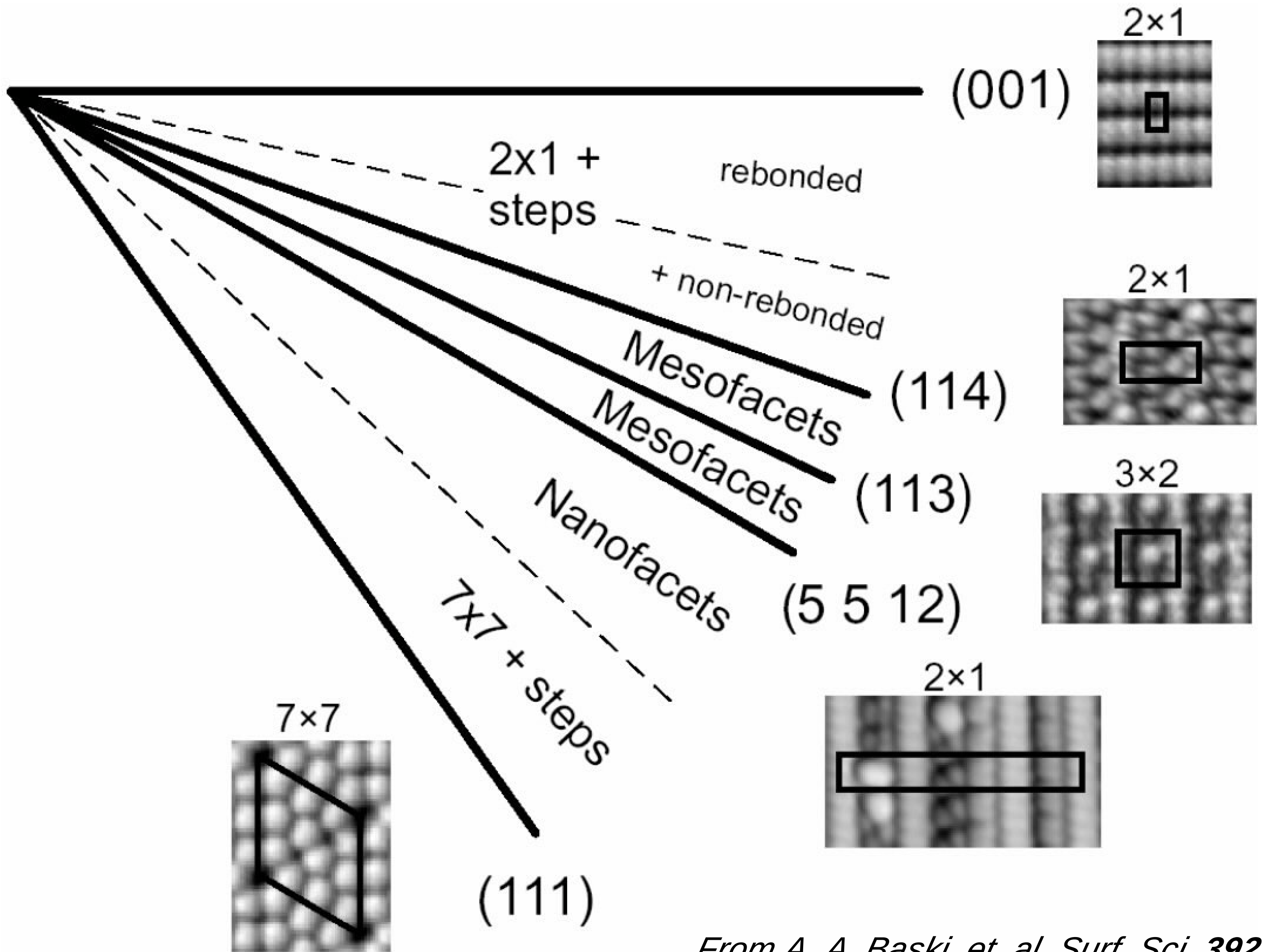
Influence of angle of cut on surface structure for Si.



(*hhk*)	θ°	*L* (nm)
001	0	0.38
11 11	7.3	2.13
119	8.9	1.75
117	11.4	1.37
116	13.3	2.37
115	15.8	1.00
114	19.5	1.63
113	25.2	0.64
225	29.5	2.21
77 17	30.2	3.78
55 12	30.5	5.35
337	31.2	1.57
112	35.3	0.94
335	40.3	1.26
223	43.3	1.59
111	54.7	0.33

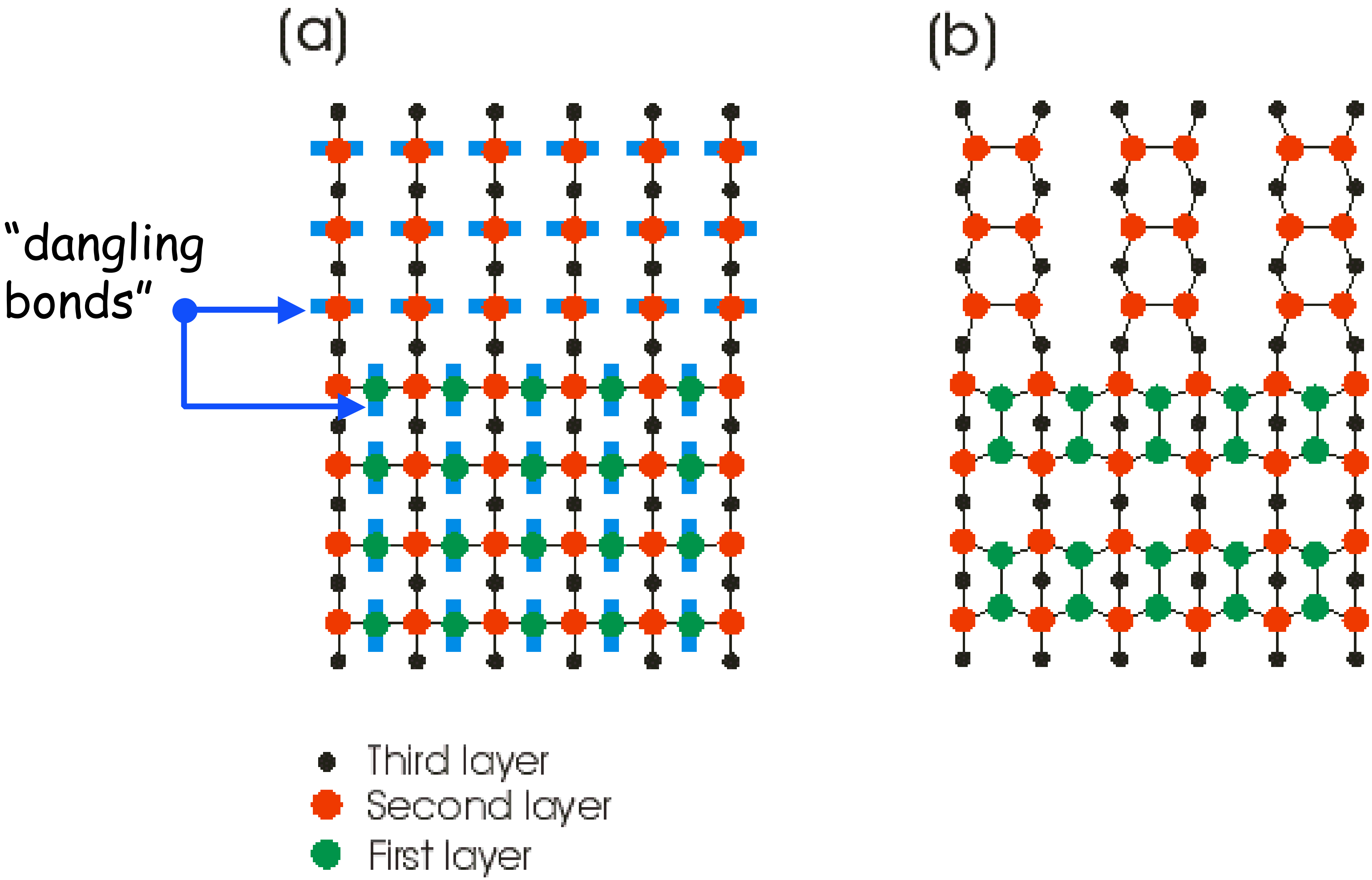
From A. A. Baski, et. al. Surf. Sci. ***392****, 69 (1997).*

Summary: surface reconstruction for Si cut at various angles.



From A. A. Baski, et. al. Surf. Sci. ***392****, 69 (1997).*

Steps and defects in surface structure.



Steps and defects in surface structure.

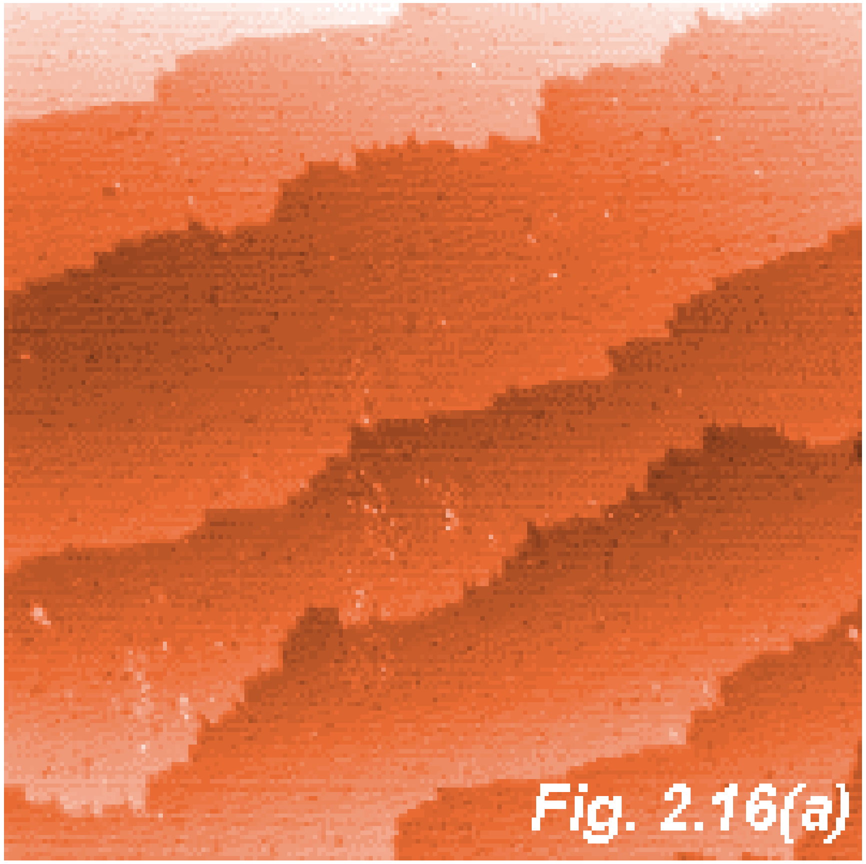


Fig. 2.16(a)

150 nm

STM of Si(100) showing 6 atomic steps.

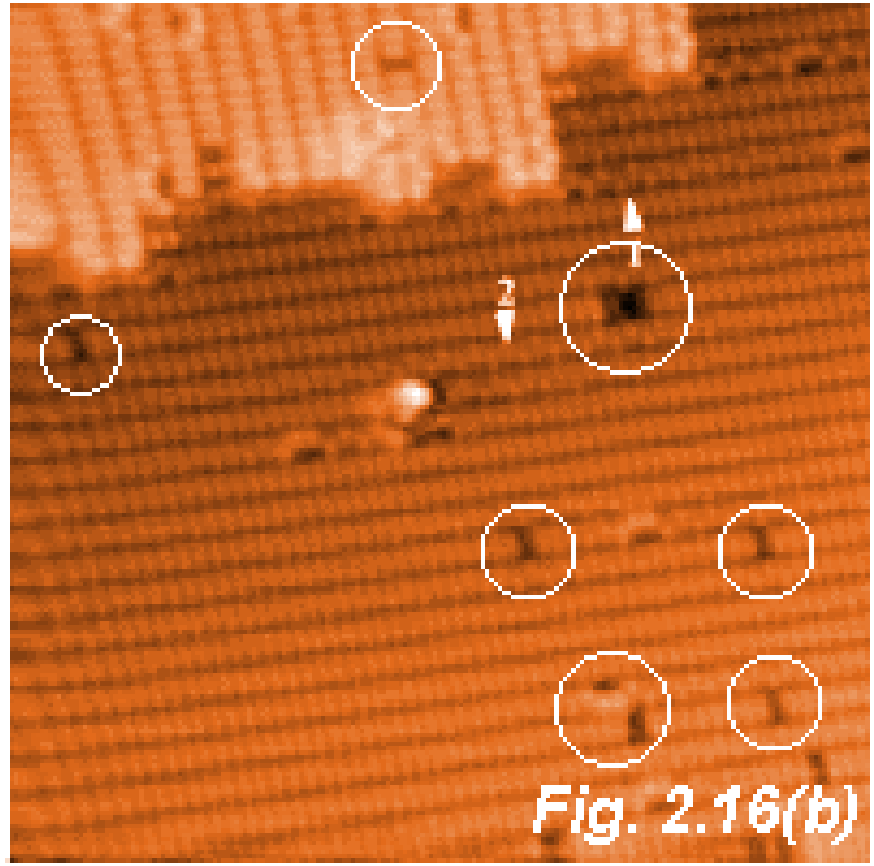


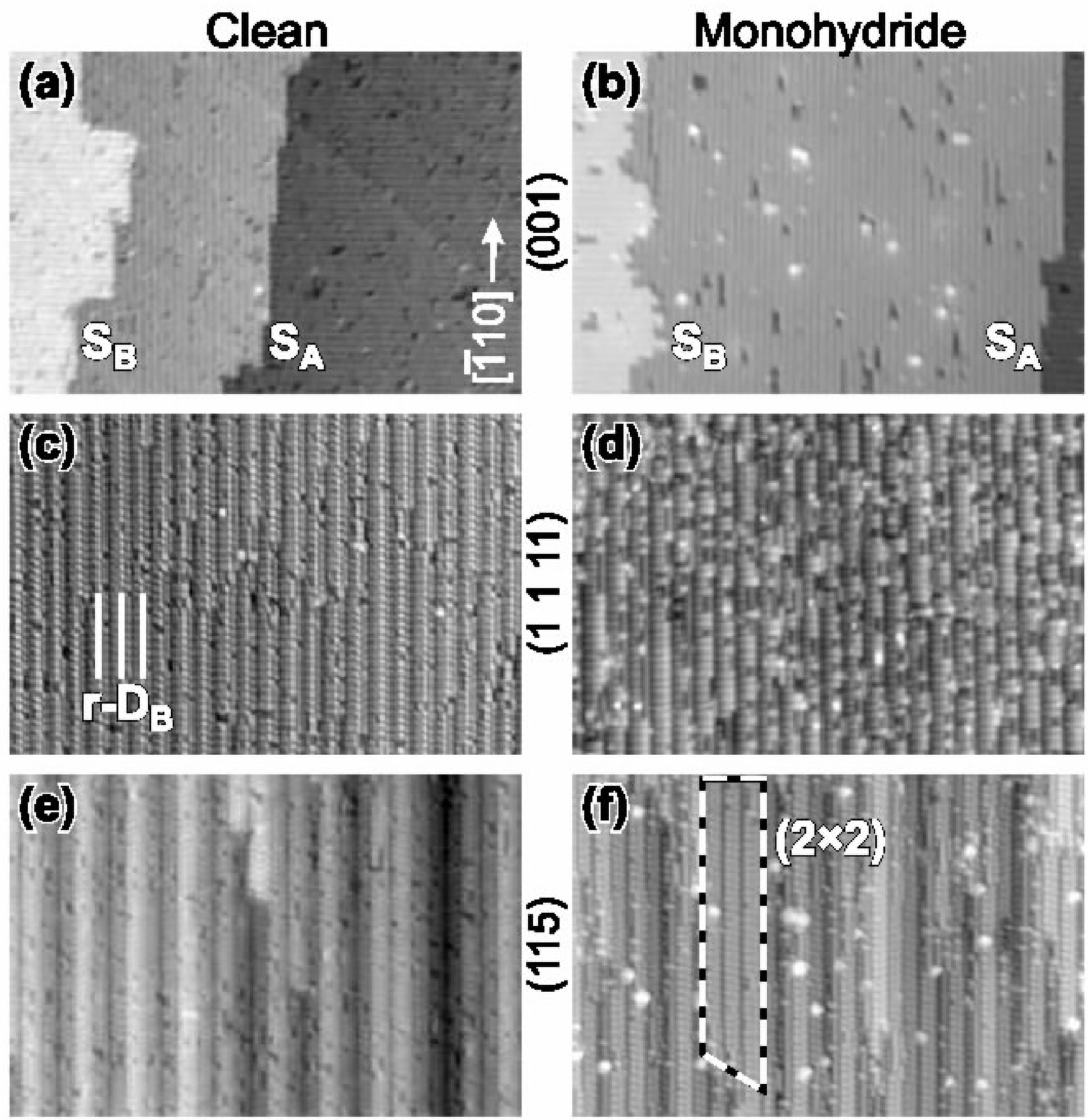
Fig. 2.16(b)

~15 nm

Expanded STM of Si(100) showing dimer structure of adjacent atomic steps and other defects.

STM is scanning tunneling microscope.

Influence of chemical modification on surface structure.



From A. Laracuente and L. J. Whitman, Surf. Sci. ***476,*** *L247 (2001).*

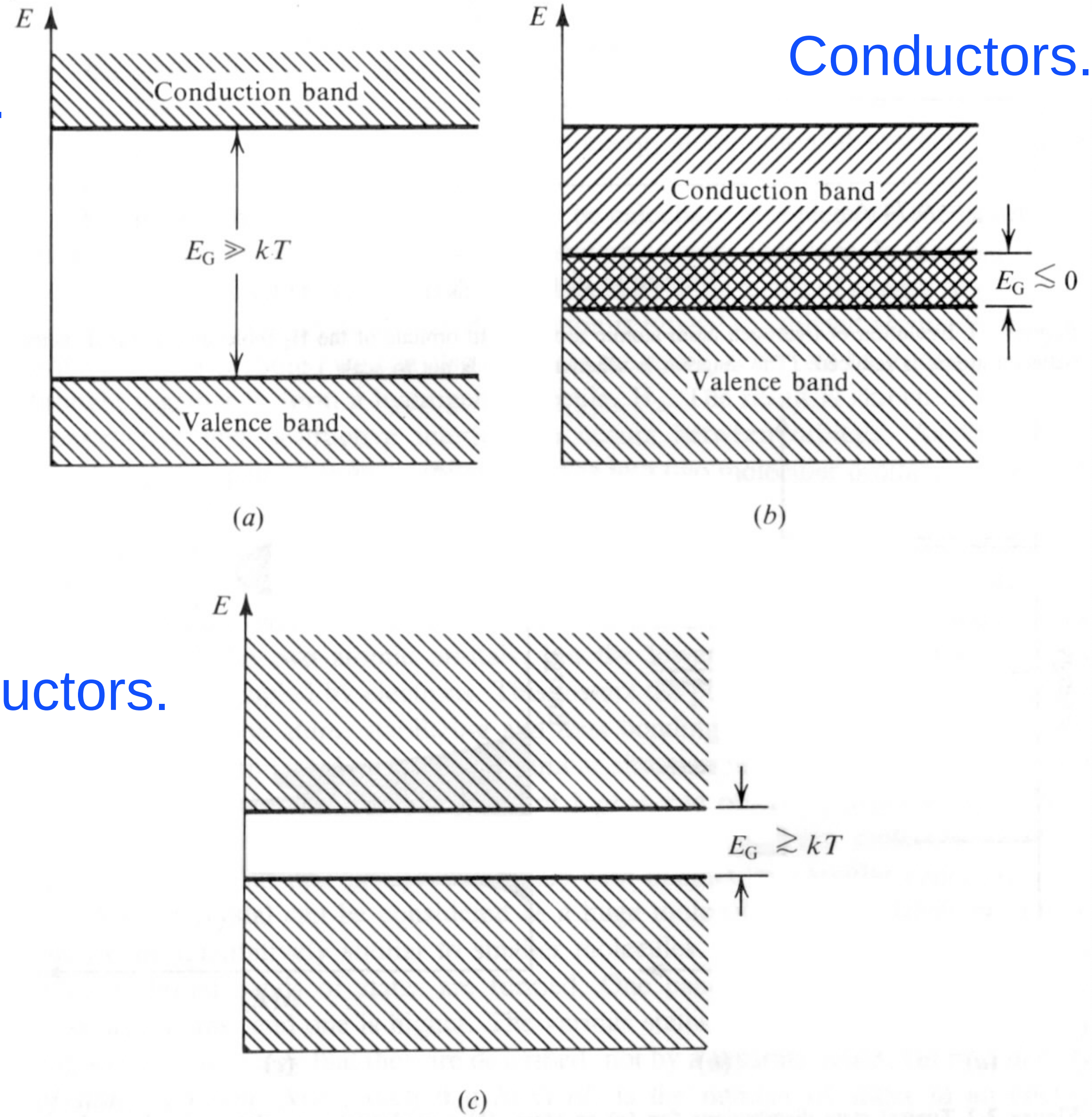
Electronic Properties of Silicon and Related Materials

Electronic properties of materials – general case.

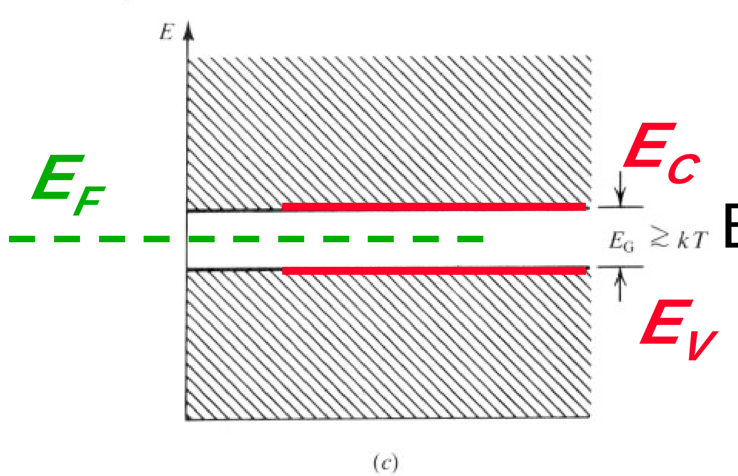
Insulators.

Conductors.

Semi-conductors.



Electronic properties: Silicon in general.



E_G = 1.12 eV

Boltzman constant: k = 8.62 10^{-5} eV/^oK

Fundamental materials property:

$$n = N_c \times e^{(E_c - E_F)/kT}$$

Where n = concentration of negative (electron) carriers (typically in cm^{-3})
E_c is the energy level of the conduction band
E_F is the Fermi level.
N_c is the intrinsic density of states in the conduction band (cm^{-3}).

Similarly,

$$p = N_V \times e^{(E_F - E_V)/kT}$$

Where p = concentration of positive (hole) carriers (typically in cm^{-3})
E_V is the energy level of the valence band
N_V is the intrinsic density of states in the valence band (cm^{-3}).

Electronic properties: intrinsic (undoped) silicon.

Density of states in conduction band, N_C (cm^{-3})	3.22E+19
Density of states in valence band, N_V (cm^{-3})	1.83E19

Note: at equilibrium, $n = p \equiv n_i$ where n_i is the intrinsic carrier concentration.

For pure silicon, then

$$n_i^2 = N_c N_V \exp(-E_G / kT)$$

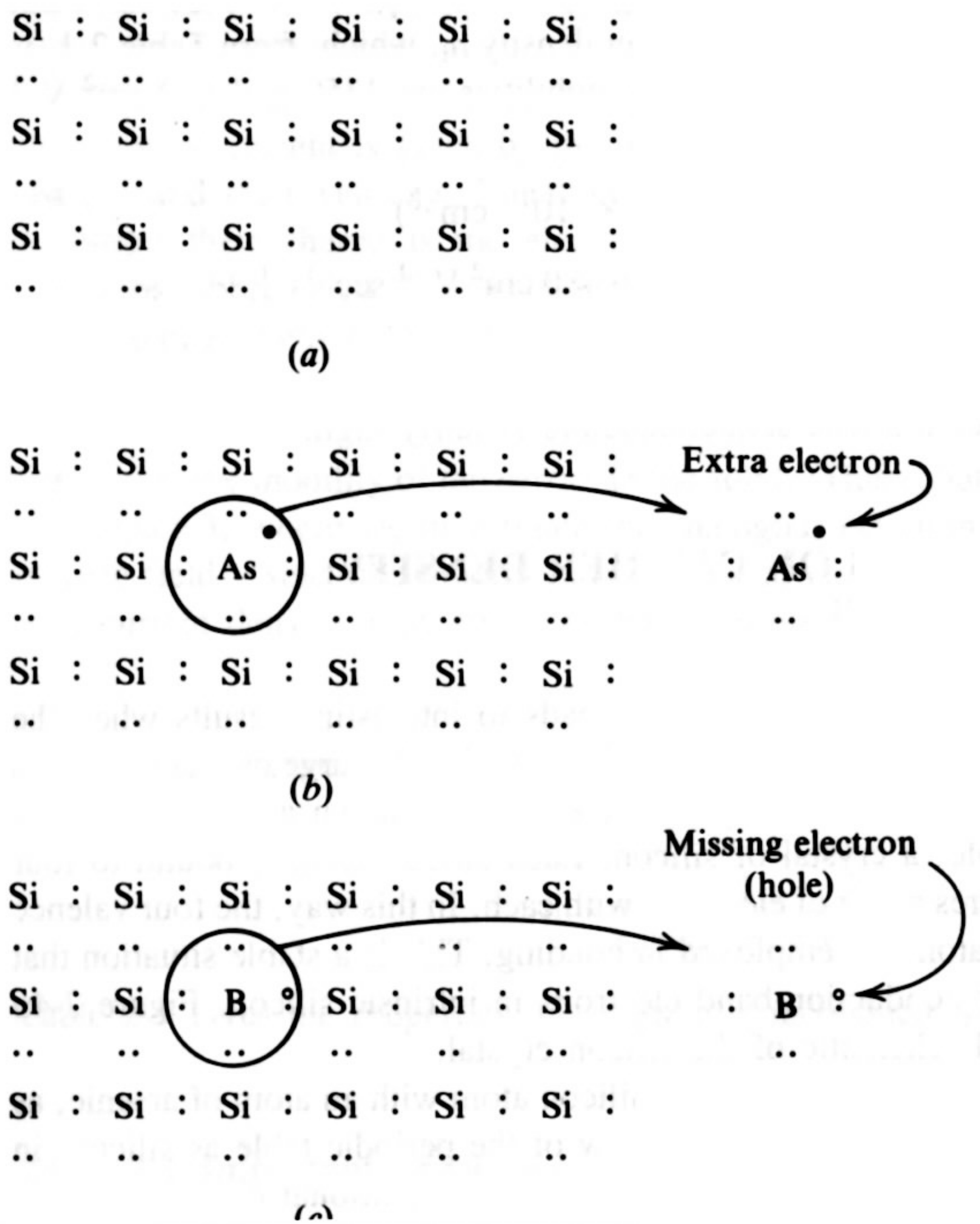
Thus $n_i = 9.6\ 10^9\ cm^{-3}$

Similarly the Fermi level for the intrinsic silicon is,

$$E_i = E_V + (E_C - E_V)/2 + (1/2)kT\ln(N_V / N_C)$$

Where we have used E_i to indicate intrinsic Fermi level for Si.

Electronic properties of doped silicon – qualitative picture.



Influence of dopants on Fermi level and carrier concentration.

Consider doping with n-type (or electron donating) dopant (such as Arsenic).

Then $n \approx N_D$ where N_D is the arsenic doping concentration.

The injection of negative (electron) carriers dramatically alters the Fermi level of the system since there are now a significant sea of negative carriers available.

We can determine the new Fermi level as well as the resulting change in positive carriers.

$$n_i^2 = pn = N_c N_V \exp(-E_G / kT)$$

Thus $p = n_i^2 / N_D$.

And $E_F = E_i + kT \ln(N_D / n_i)$

Influence of dopants on resistance.

Correspondingly, for p-type (acceptor) dopants such at B:

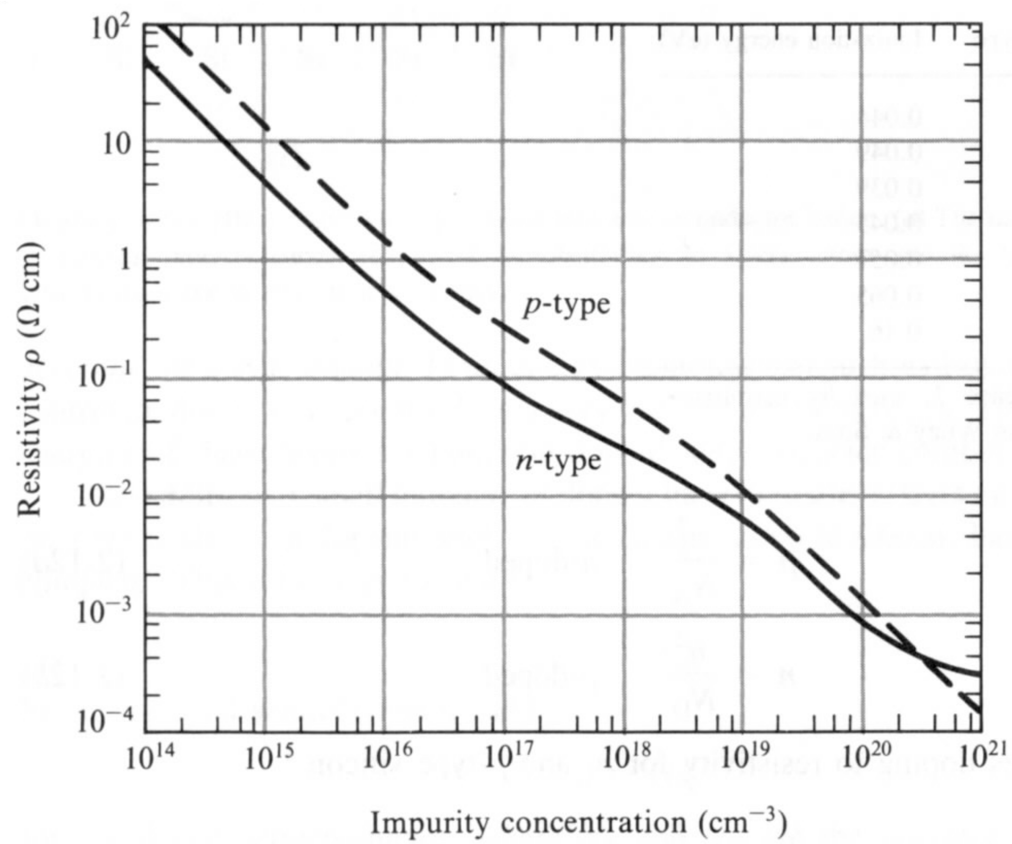
Thus $n = n_i^2/N_A$.

And $E_F = E_i - kT \ln(N_A/n_i)$

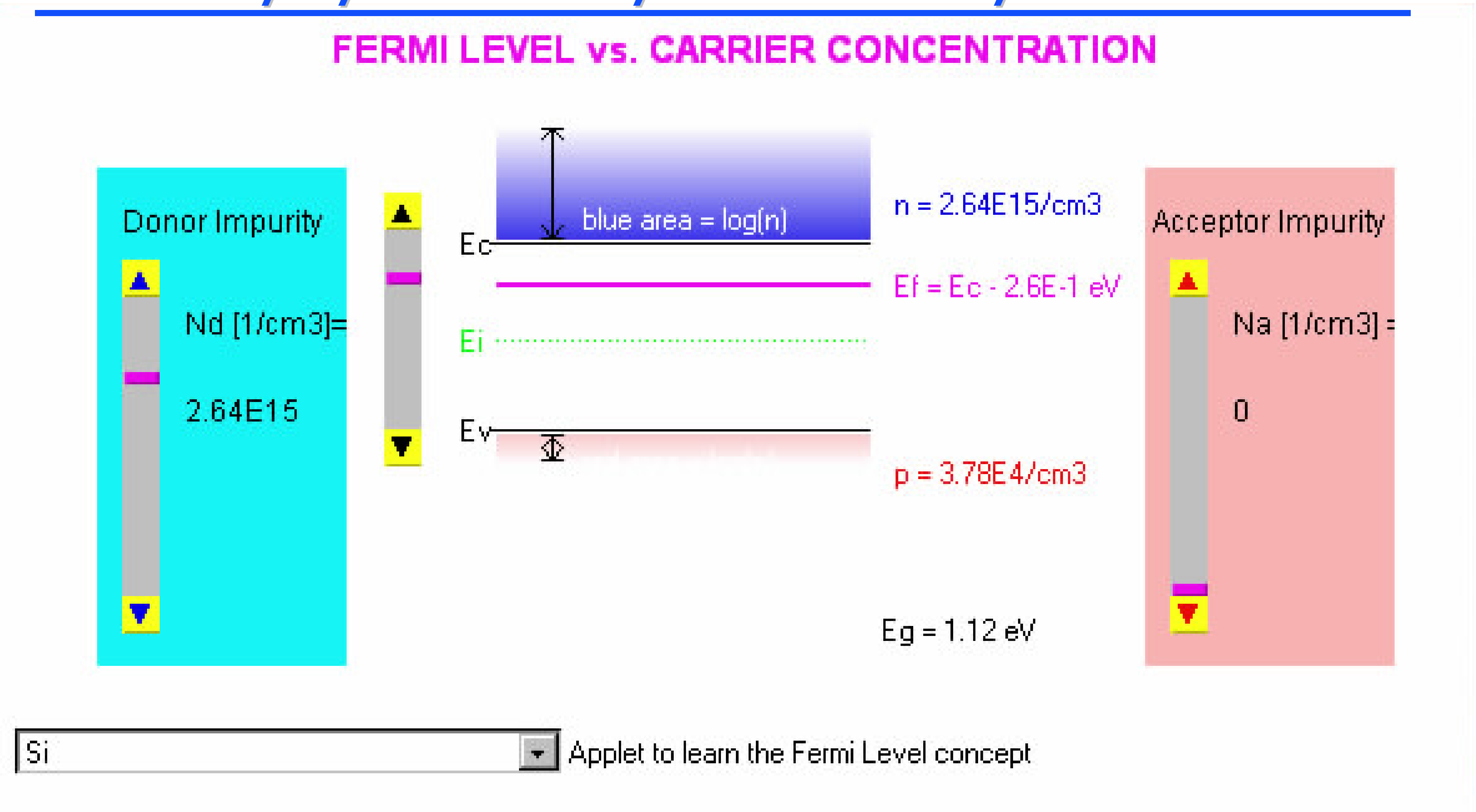
Resistivity

$$\rho = \frac{1}{q(n\mu_n + p\mu_p)}$$

Where q is electron charge and μ are mobilities.



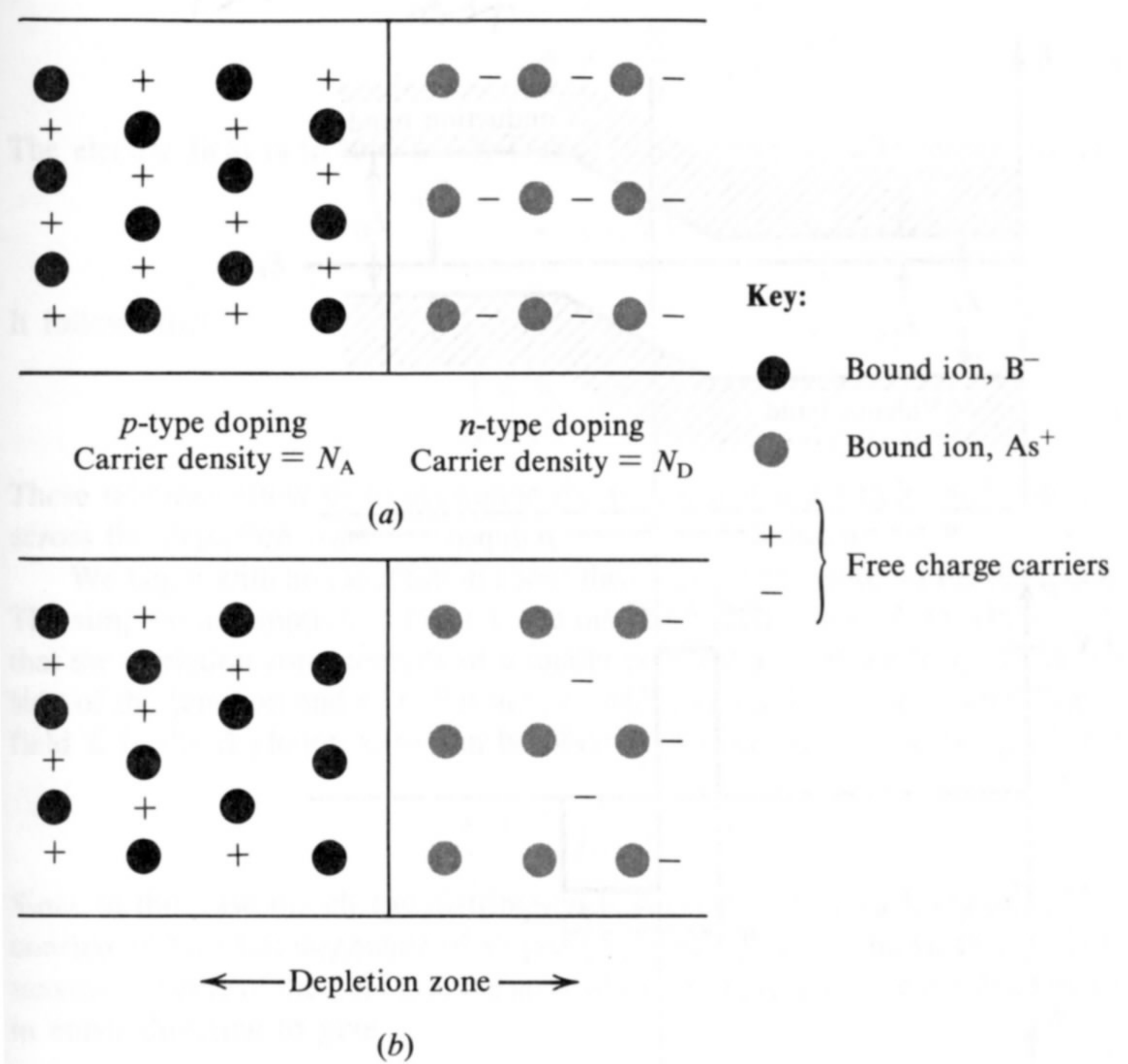
Electronic properties of doped silicon: a quantitative look.



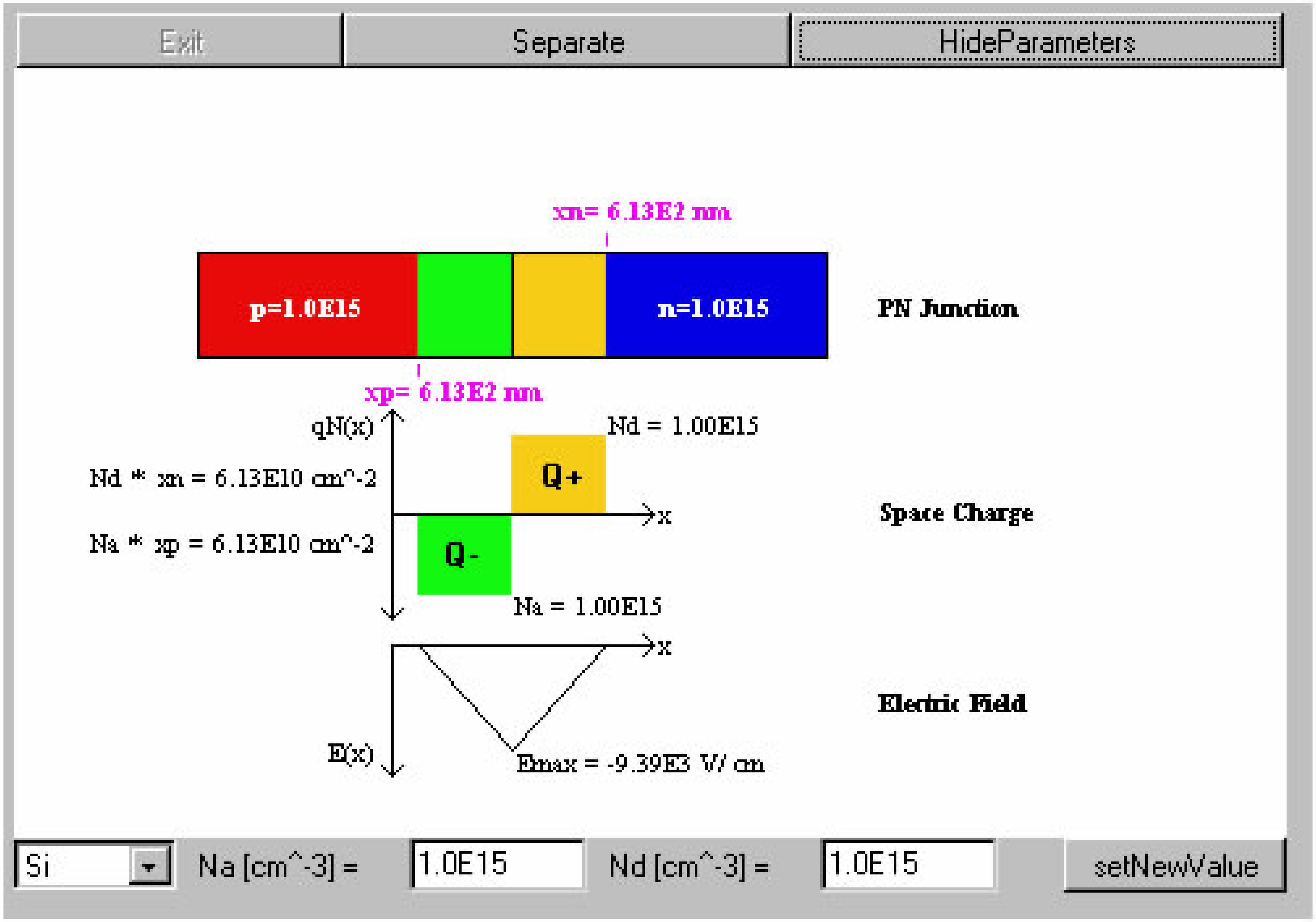
Fermi levels in silicon: hyperlinks\fermi level applet\fermi.html

Source of applet is Semiconductor Applet Service, SUNY, Buffalo: http://jas2.eng.buffalo.edu/applets/education/semicon/fermi/bandAndLevel/fermi.html

The pn junction: a qualitative view.



The pn junction: a more quantitative view.



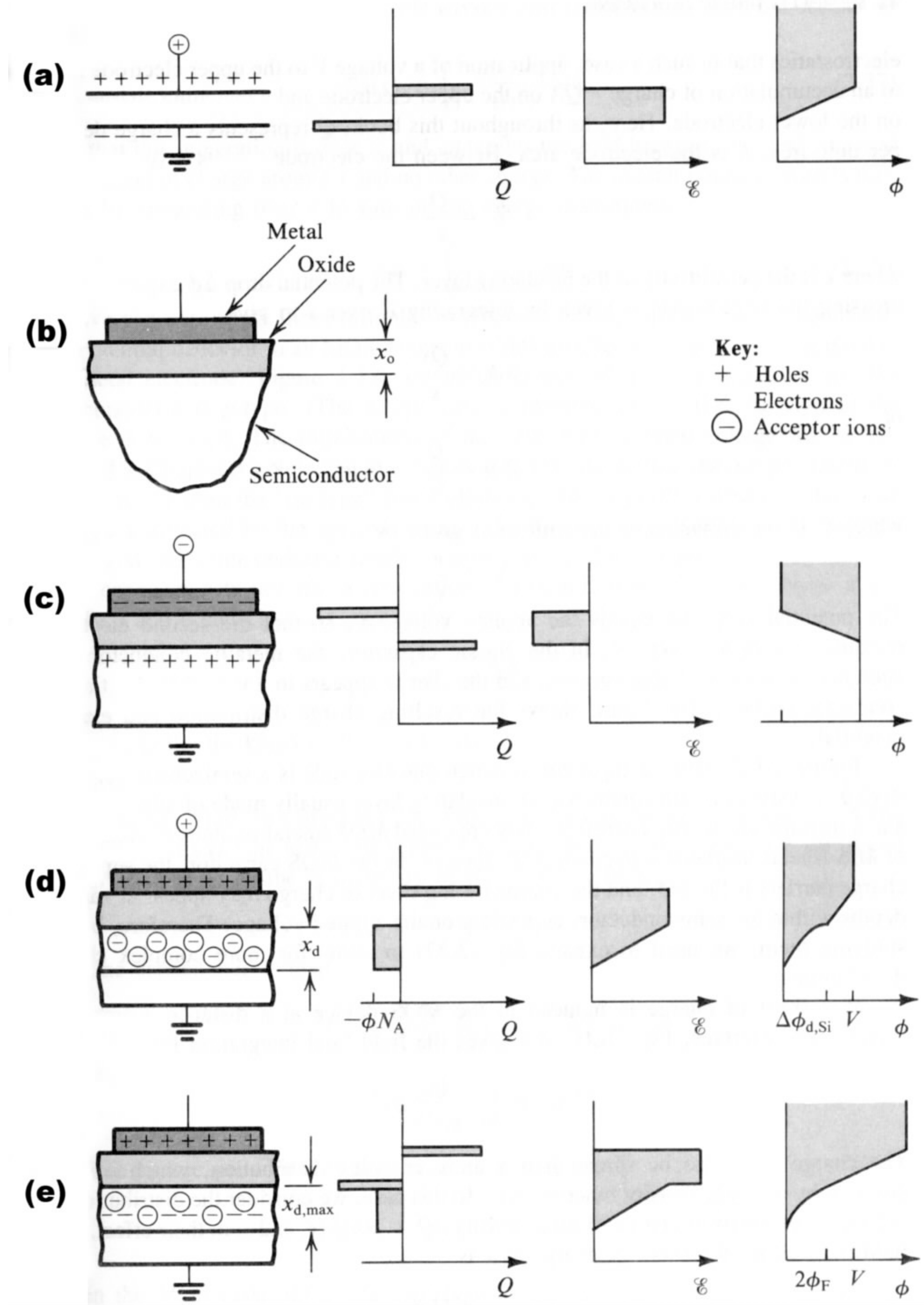
Link to pn junction: hyperlinks\pn junction\pnformation2.htm

Source of applet is Semiconductor Applet Service, SUNY, Buffalo: http://jas2.eng.buffalo.edu/applets/education/pn/pnformation2/pnformation2.html

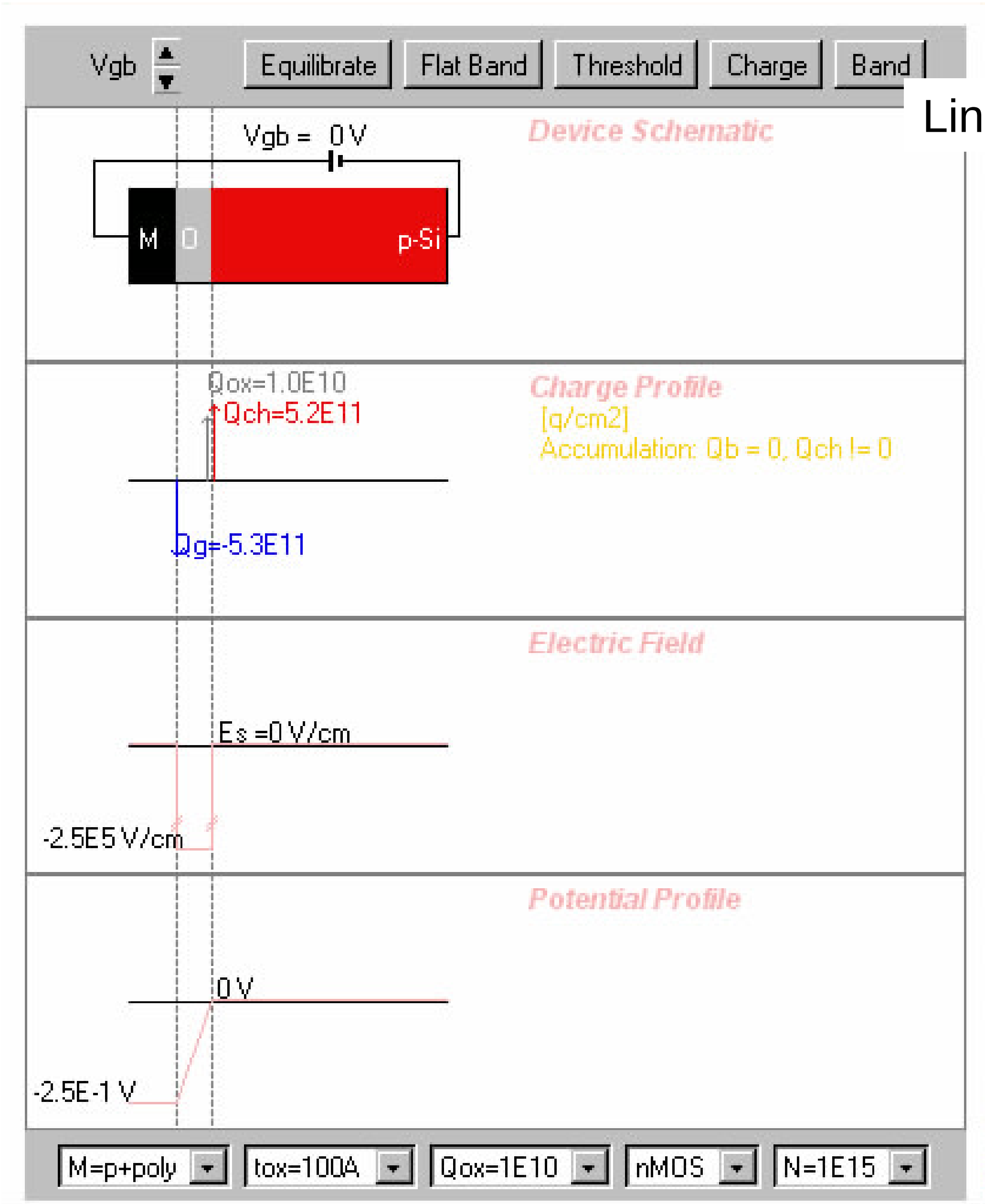
The c-mos capacitor: qualitative view.

P-type MOS capacitor.

(a) Simple capacitor.
(b) P-type MOS capacitor.
(c) Negative bias:
  accumulation
(d) Positive bias:
  charge stored as depletion.
(e) Positive bias – inversion.
  Charge as depletion as well as minority carriers.



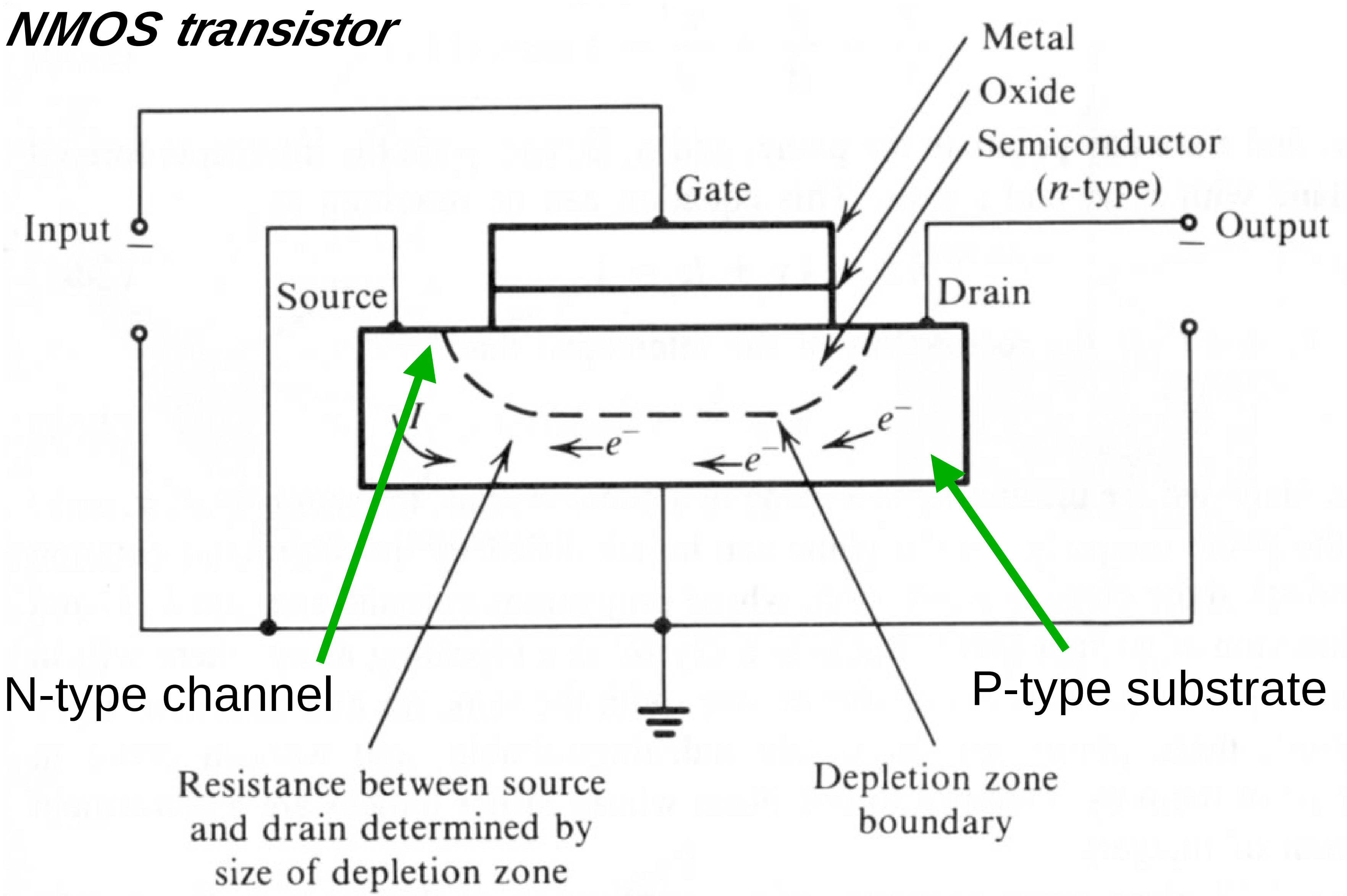
The c-mos capacitor: slightly more quantitative view.



Link: [hyperlinks\mos2\biasPot10.htm](hyperlinks\mos2\biasPot10.htm)

MOS devices and how they work…simple picture.

NMOS transistor



Bipolar transistors: basic description

PNP transistor