

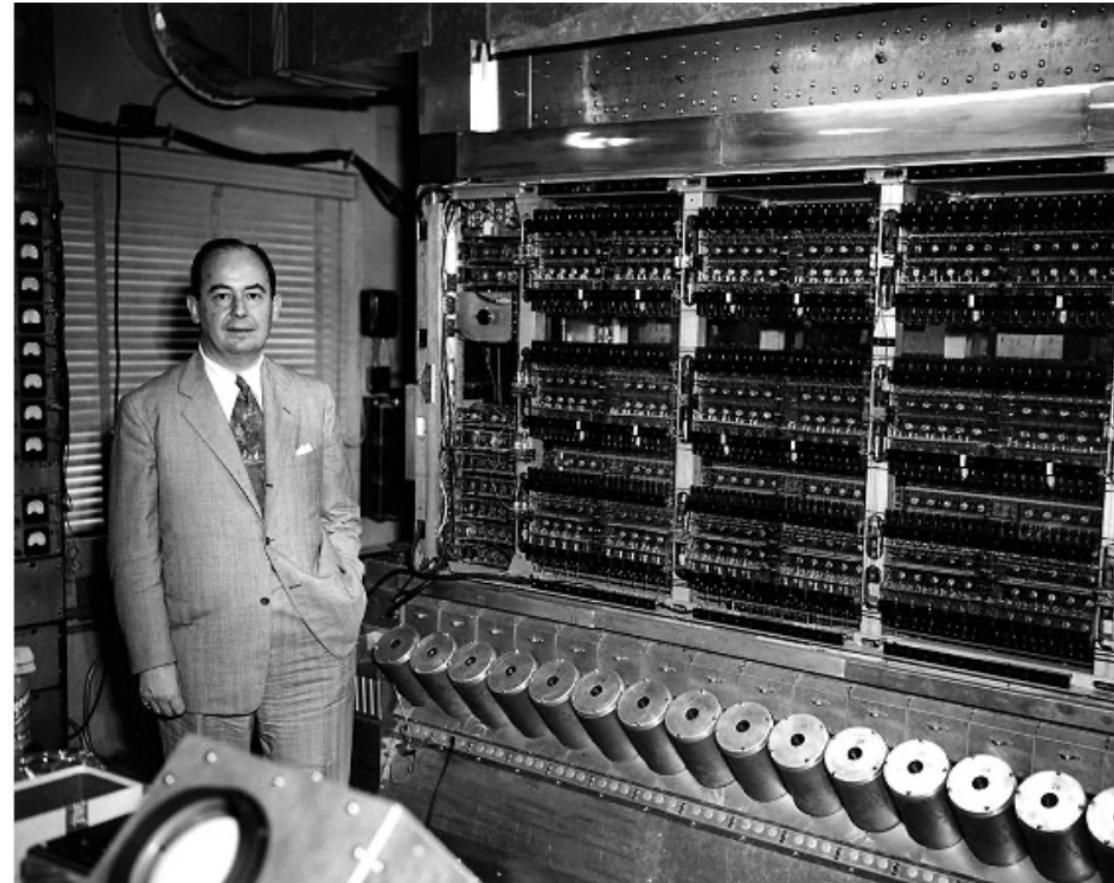
Microfabrication

Manhattan project (1940)

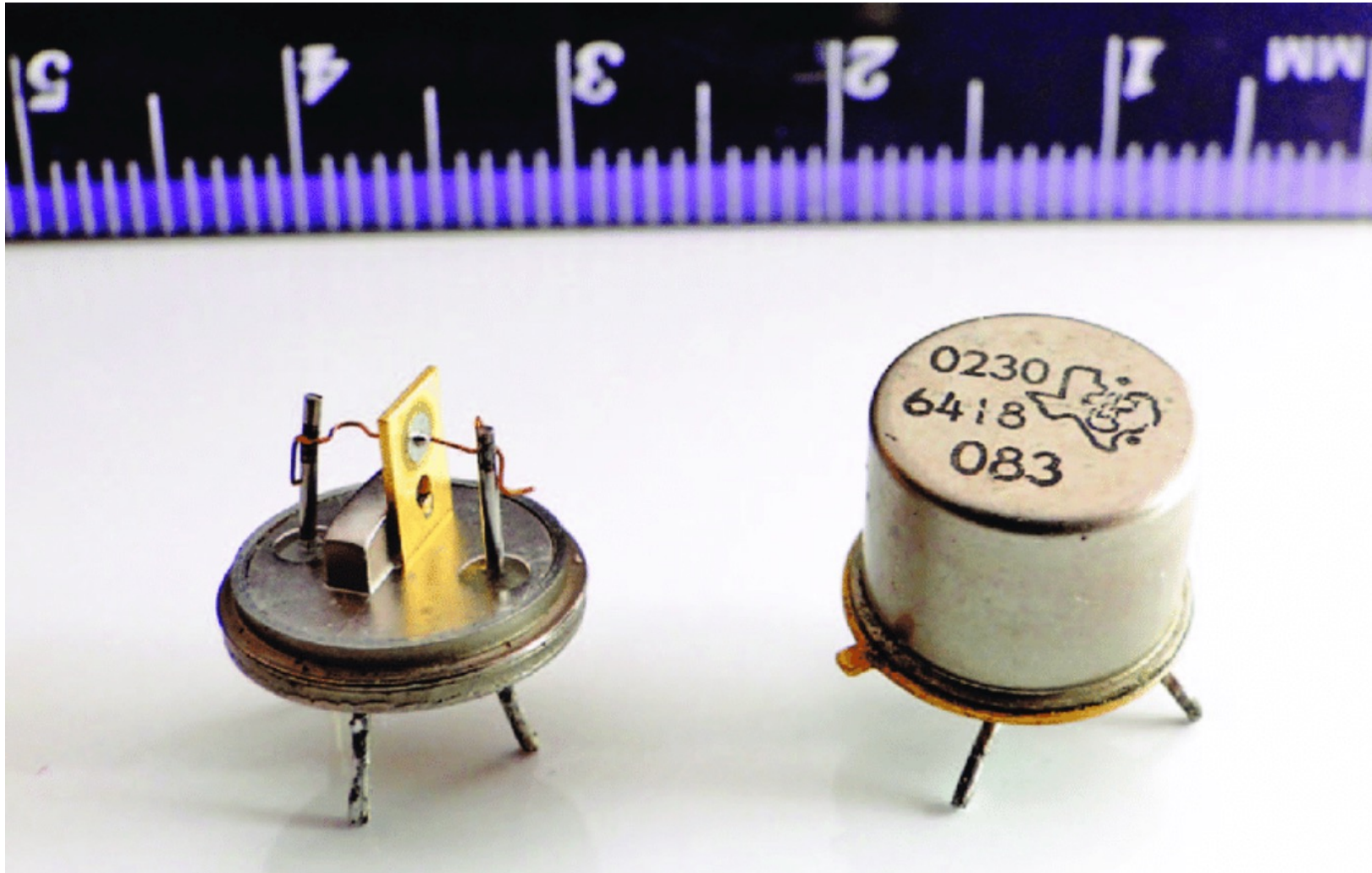


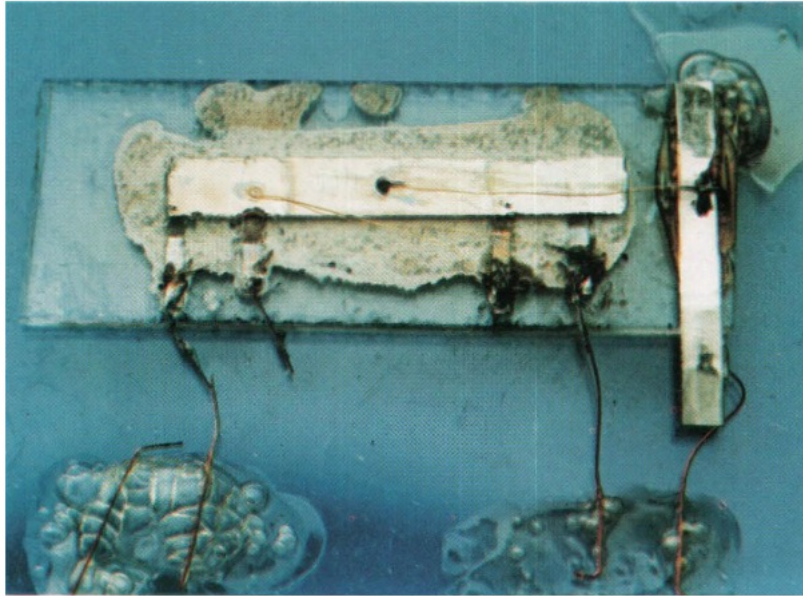
Had about 3500 relays. If each relay worked for 10 years, you change 150 relays a day!

Vacuum tubes were invented. It does not go bad so quickly. It can switch about 1000 times a second.

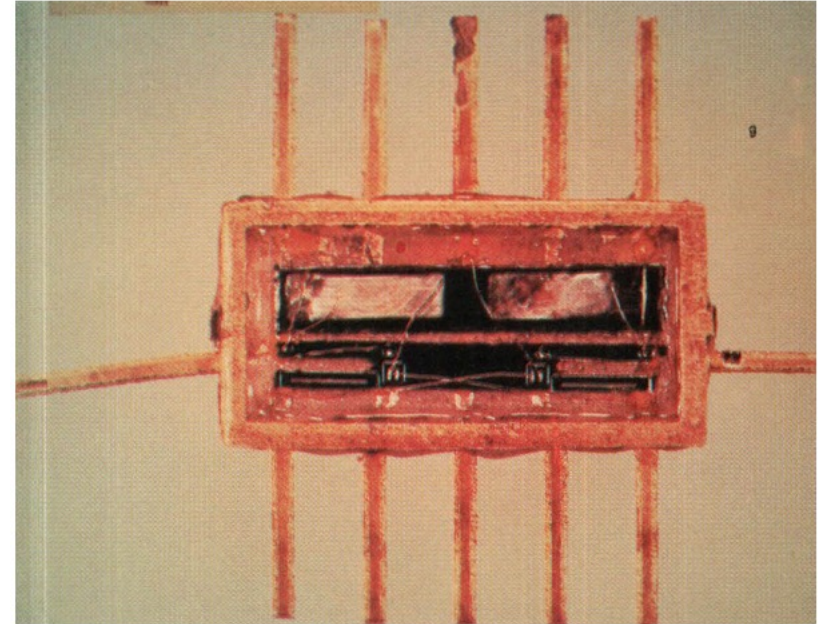


1959

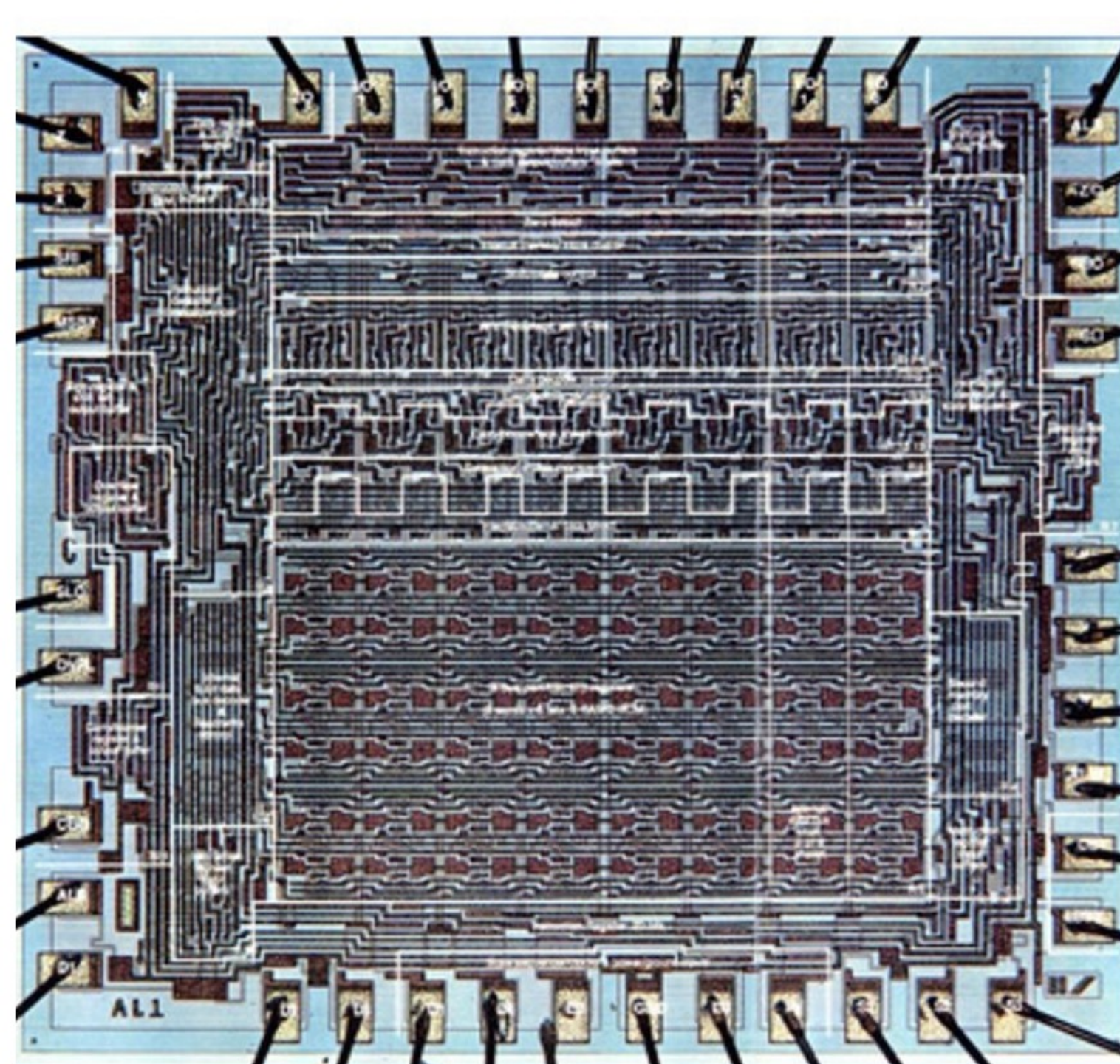




Jack Kilby's first IC – Phase shift oscillator



First Kilby style IC – Texas (1960)

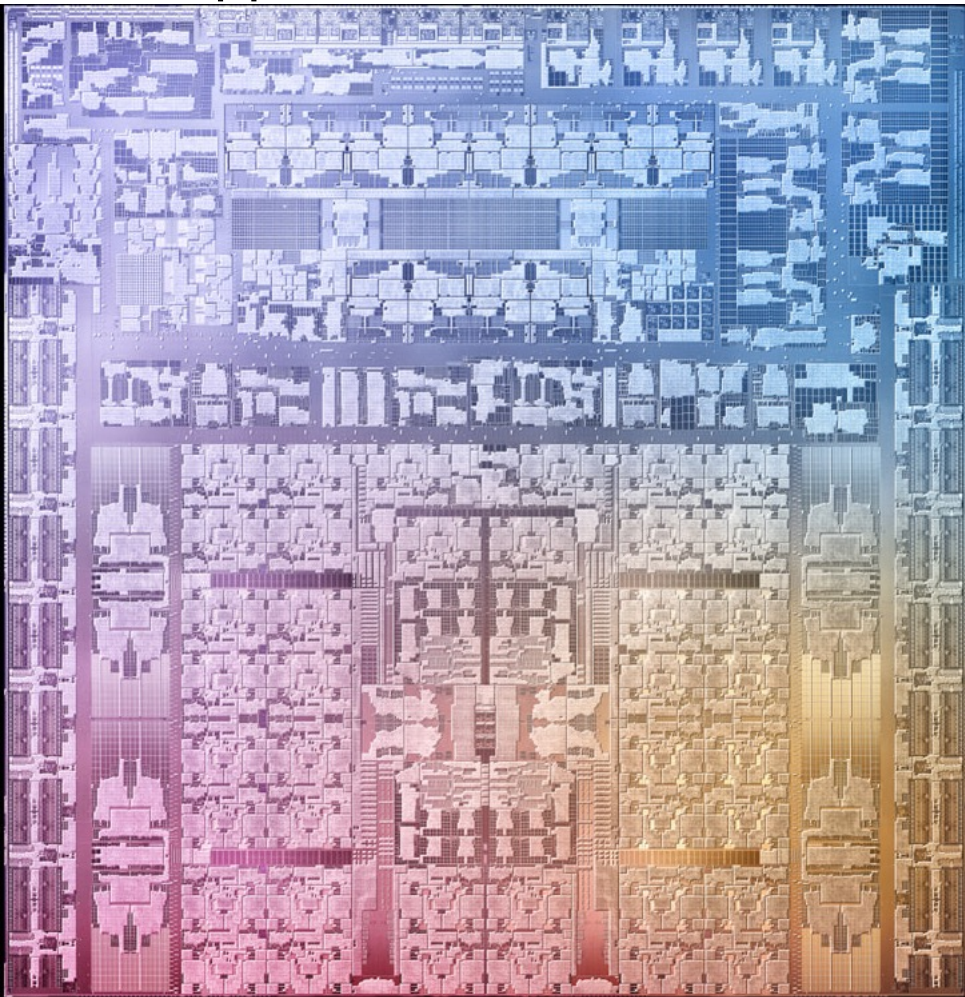


1971
Intel 4004
4 – bit processor
2300 transistors

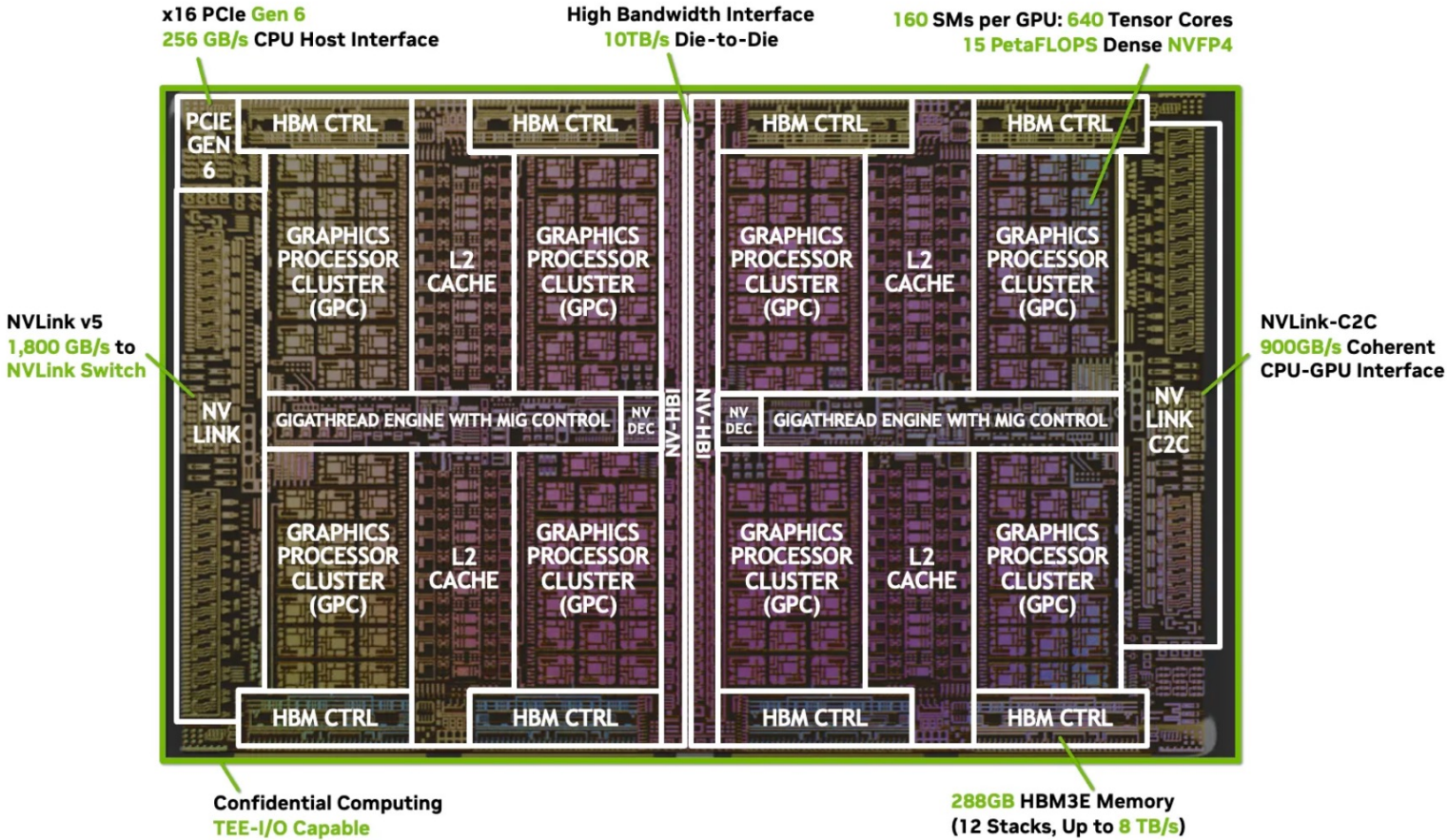
Just for the transistor

- 1833 – Michael Faraday – extra-ordinary conduction in AgS
- 1874 – Ferdinand Braun Semiconductor point contact rectifier
- 1901 – J. C. Bose Cat's whisker detector for Radio waves
- 1926 – Julius Lilienfeld Field Effect on electrical conduction
- 1931 – Alan Wilson – Theory of electronic conduction in semiconductors
- 1940 – Russel Ohl – Discovery of P-N junction in Si photovoltaics
- 1947 – Bardeen and Brattain – Transistor action with Ge point contact
- 1948 – W. Shockley – Detailed transistor model for current transport.

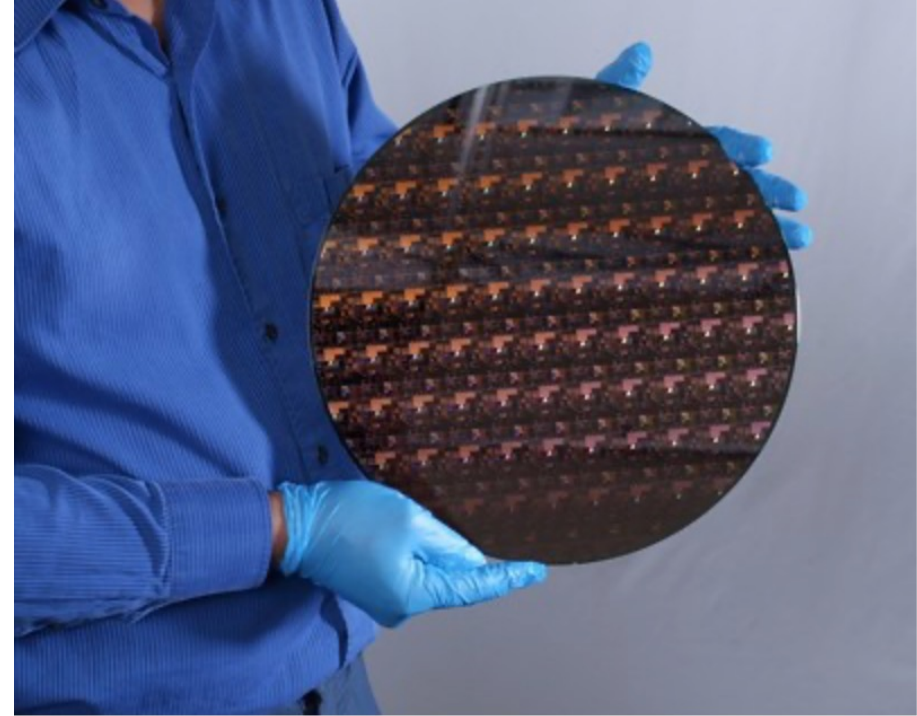
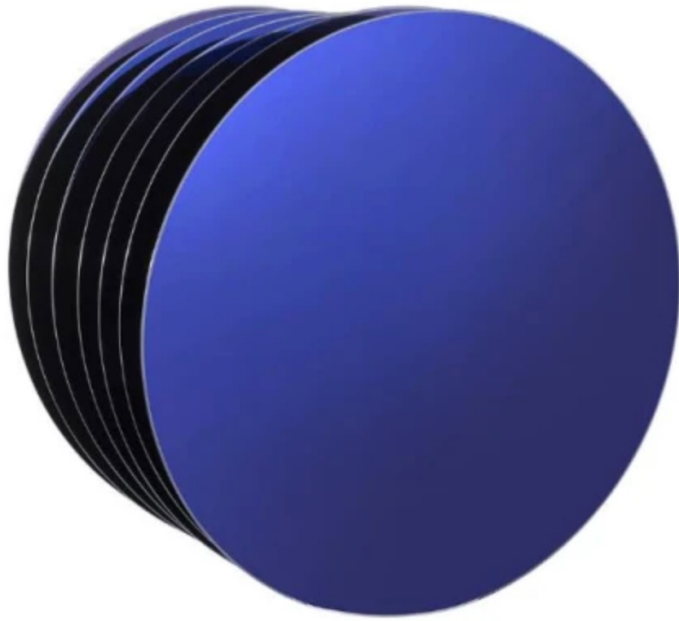
Apple M3



NVIDIA Blackwell Ultra GPU



It's a problem of what takes



Refresher

PERIODIC TABLE OF THE ELEMENTS

1 1.0079 H Hydrogen	Atomic number — 5 10.811 — Atomic mass B — Symbol Boron — Name																2 4.0026 He Helium															
3 6.941 Li Lithium	4 9.0122 Be Beryllium																	5 10.811 B Boron	6 12.011 C Carbon	7 14.007 N Nitrogen	8 15.999 O Oxygen	9 18.998 F Fluorine	10 20.180 Ne Neon									
11 22.990 Na Sodium	12 24.305 Mg Magnesium																	13 26.982 Al Aluminium	14 28.086 Si Silicon	15 30.974 P Phosphorus	16 32.065 S Sulfur	17 35.543 Cl Chlorine	18 39.948 Ar Argon									
19 39.098 K Potassium	20 40.078 Ca Calcium	21 44.956 Sc Scandium	22 47.867 Ti Titanium	23 50.942 V Vanadium	24 51.996 Cr Chromium	25 54.938 Mn Manganese	26 55.845 Fe Iron	27 58.933 Co Cobalt	28 58.693 Ni Nickel	29 63.546 Cu Copper	30 65.38 Zn Zinc	31 69.723 Ga Gallium	32 72.64 Ge Germanium	33 74.922 As Arsenic	34 78.96 Se Selenium	35 79.904 Br Bromine	36 83.798 Kr Krypton															
37 85.468 Rb Rubidium	38 87.62 Sr Strontium	39 88.906 Y Yttrium	40 91.224 Zr Zirconium	41 92.906 Nb Niobium	42 95.96 Mo Molybdenum	43 (98) Tc Technetium	44 101.07 Ru Ruthenium	45 102.91 Rh Rhodium	46 106.42 Pd Palladium	47 107.87 Ag Silver	48 112.41 Cd Cadmium	49 114.82 In Indium	50 118.71 Sn Tin	51 121.76 Sb Antimony	52 127.60 Te Tellurium	53 126.90 I Iodine	54 131.29 Xe Xenon															
55 132.91 Cs Caesium	56 137.33 Ba Barium	57 - 71 La-Lu Lanthanide	72 178.49 Hf Hafnium	73 180.95 Ta Tantalum	74 183.84 W Tungsten	75 186.21 Re Rhenium	76 190.23 Os Osmium	77 192.22 Ir Iridium	78 195.08 Pt Platinum	79 196.97 Au Gold	80 200.59 Hg Mercury	81 204.38 Tl Thallium	82 207.20 Pb Lead	83 208.98 Bi Bismuth	84 (209) Po Polonium	85 (210) At Astatine	86 (222) Rn Radon															
87 (223) Fr Francium	88 (226) Ra Radium	89 - 103 Ac-Lr Actinide	104 (267) Rf Rutherfordium	105 (268) Db Dubnium	106 (271) Sg Seaborgium	107 (272) Bh Bohrium	108 (277) Hs Hassium	109 (276) Mt Meitnerium	110 (281) Ds Darmstadtium	111 (280) Rg Roentgenium	112 (285) Cn Copernicium	113 (284) Nh Nihonium	114 (289) Fl Flerovium	115 (288) Mc Moscovium	116 (292) Lv Livermorium	117 (294) Ts Tennesine	118 (294) Og Oganesson															
																		57 138.91 La Lanthanum	58 140.12 Ce Cerium	59 140.91 Pr Praseodymium	60 144.24 Nd Neodymium	61 (145) Pm Promethium	62 150.36 Sm Samarium	63 151.96 Eu Europium	64 157.25 Gd Gadolinium	65 158.93 Tb Terbium	66 162.50 Dy Dysprosium	67 164.93 Ho Holmium	68 167.26 Er Erbium	69 168.93 Tm Thulium	70 173.05 Yb Ytterbium	71 174.97 Lu Lutetium
																		89 (227) Ac Actinium	90 232.04 Th Thorium	91 231.04 Pa Protactinium	92 238.03 U Uranium	93 (237) Np Neptunium	94 (244) Pu Plutonium	95 (243) Am Americium	96 (247) Cm Curium	97 (247) Bk Berkelium	98 (251) Cf Californium	99 (252) Es Einsteinium	100 (257) Fm Fermium	101 (258) Md Mendelevium	102 (259) No Nobelium	103 (262) Lr Lawrencium

ENERGY LEVELS ELEMENTS 1-20

HYDROGEN

1



1.01

HELIUM

2



4.00

LITHIUM

3



6.94

BERYLLIUM

4



9.01

BORON

5



10.81

CARBON

6



12.01

NITROGEN

7



14.01

OXYGEN

8



16.00

FLUORINE

9



19.00

NEON

10



20.18

SODIUM

11



22.99

MAGNESIUM

12



24.31

ALUMINUM

13



26.98

SILICON

14



28.09

PHOSPHORUS

15



30.97

SULFUR

16



32.07

CHLORINE

17



35.45

ARGON

18



39.95

POTASSIUM

19



39.10

CALCIUM

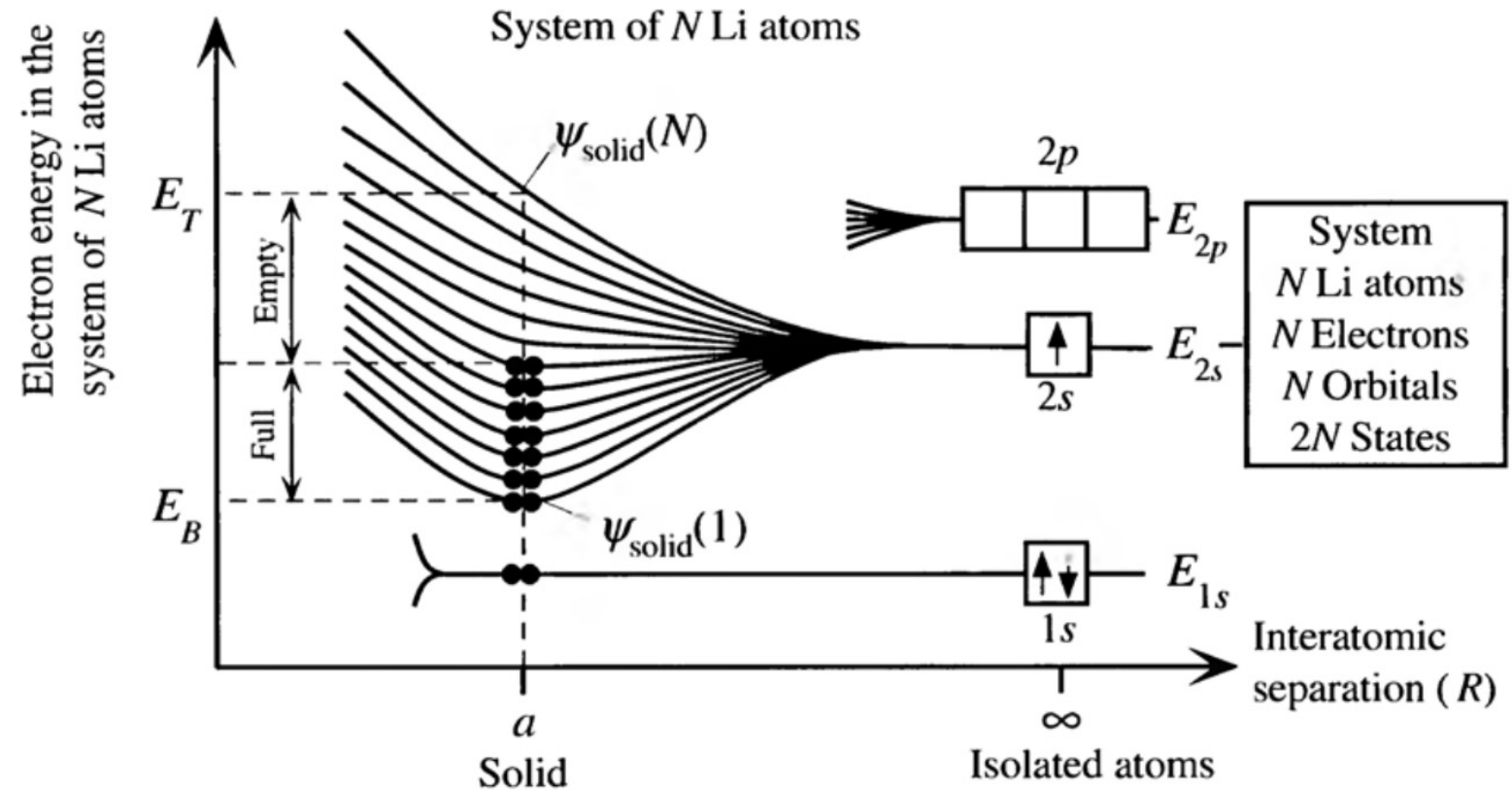
20



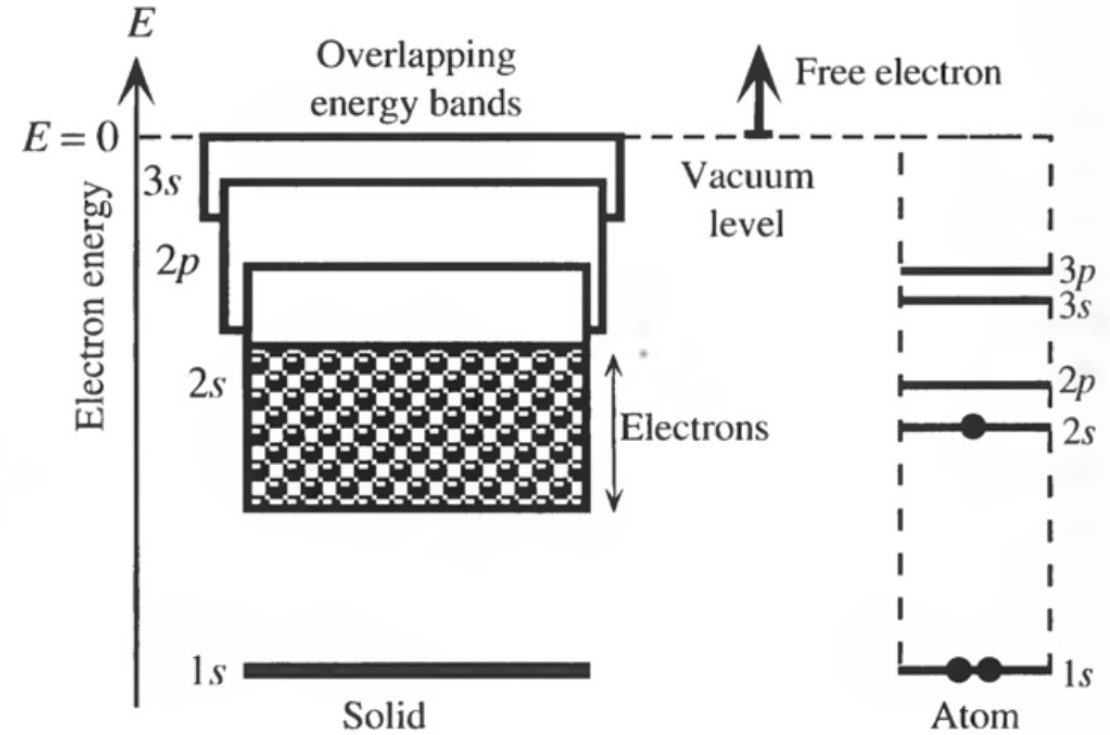
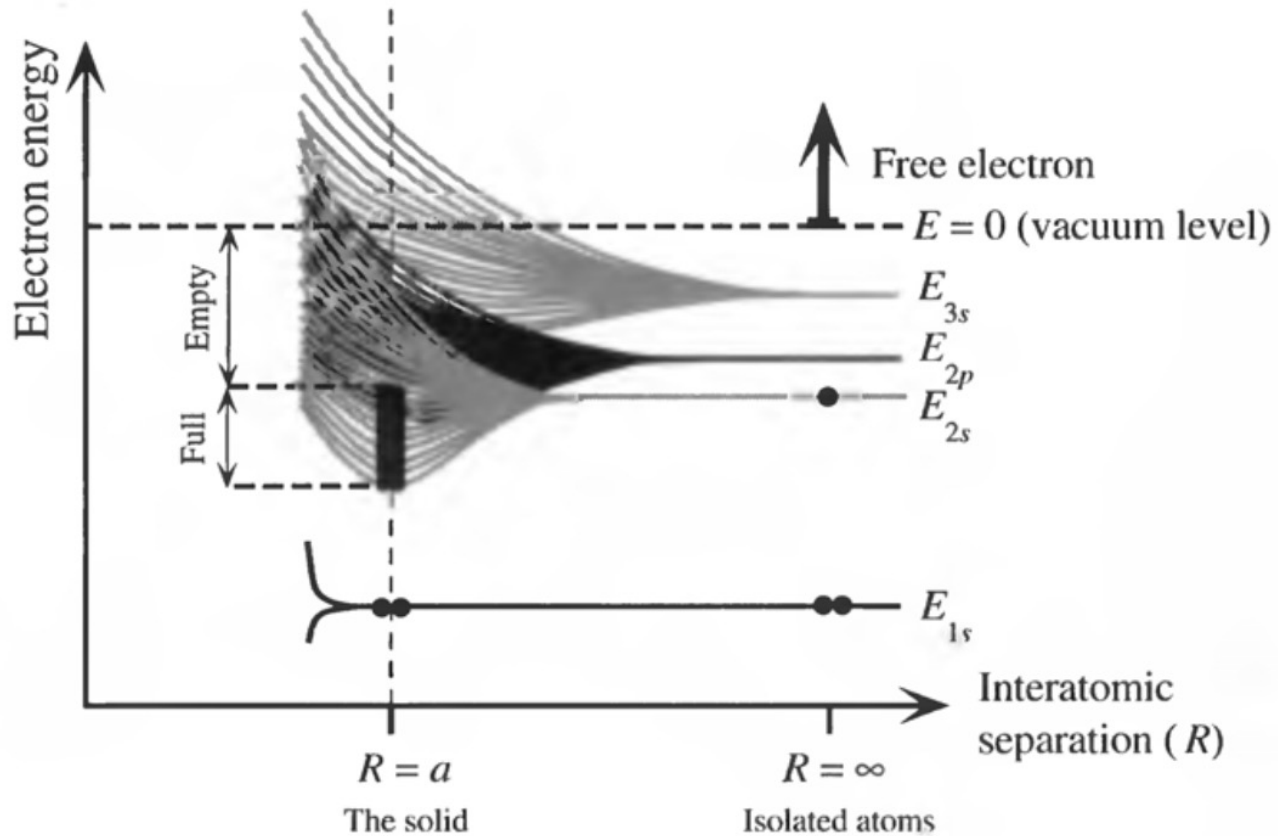
40.08

Metals

- 1s electrons behave like He
 - They start splitting, but at a smaller inter-atomic distance.
- Before that distance is reached, 2s electrons interact.
 - They behave like 1s of hydrogen
 - N 2s states are seen whose separation depends on the interatomic distance.
- A stable Li solid is formed, if the last filled state has a summed energy lesser than the individual summation!

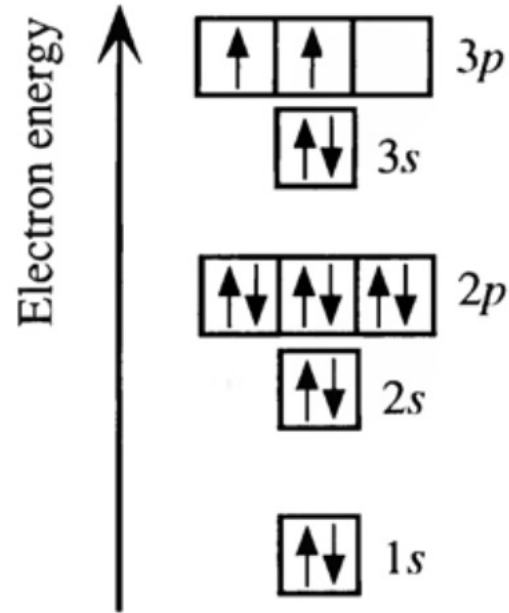


Energy bands in a metal

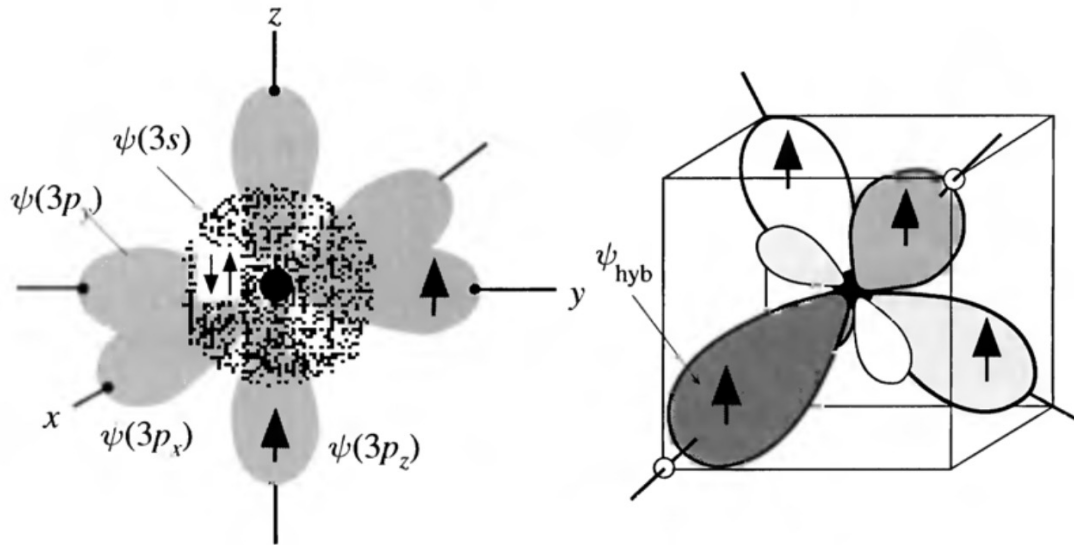


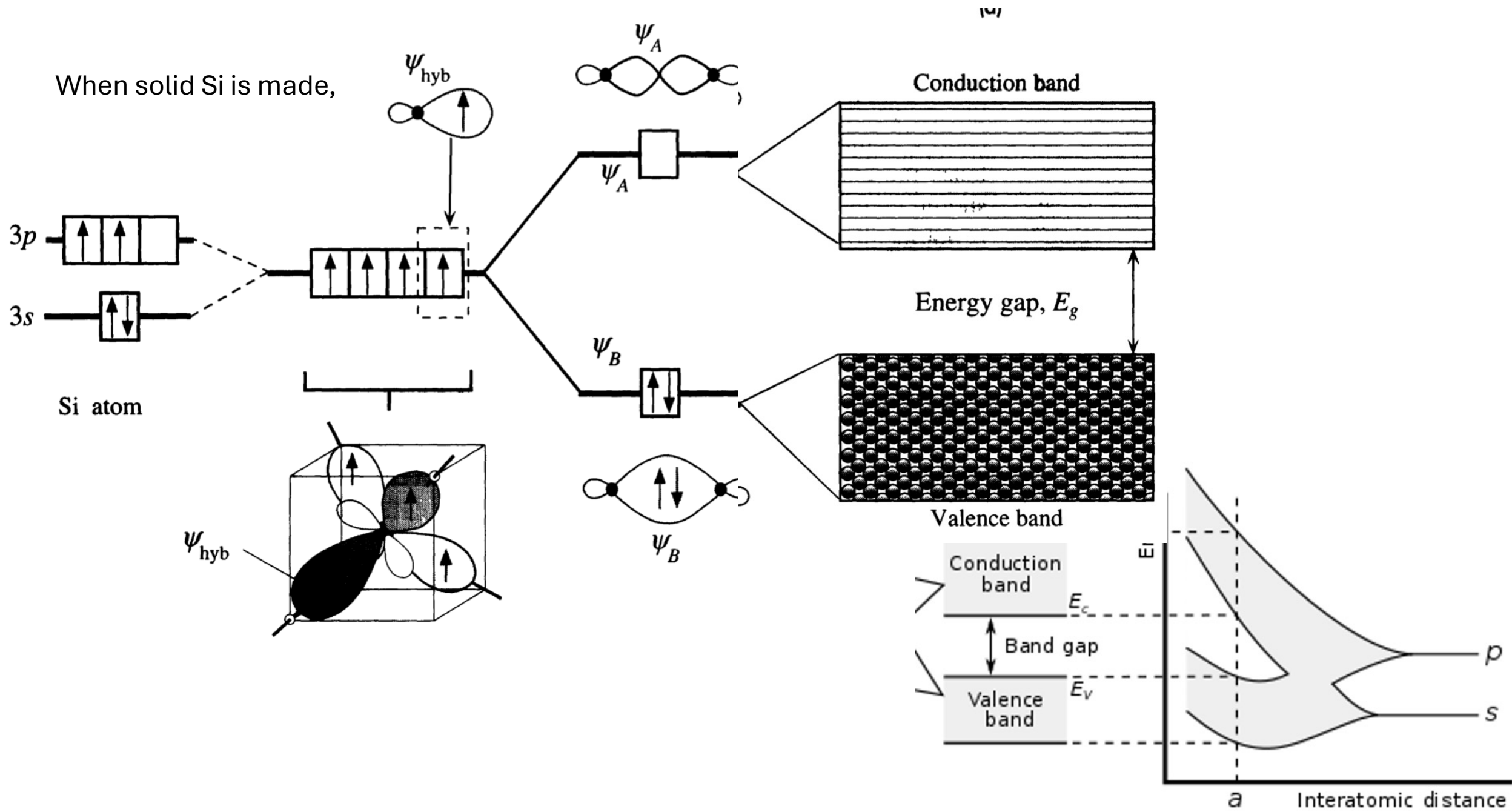
- All the valence electrons in the metal are delocalized.
- Last occupied energy level at 0K – Fermi Level

A Semiconductor

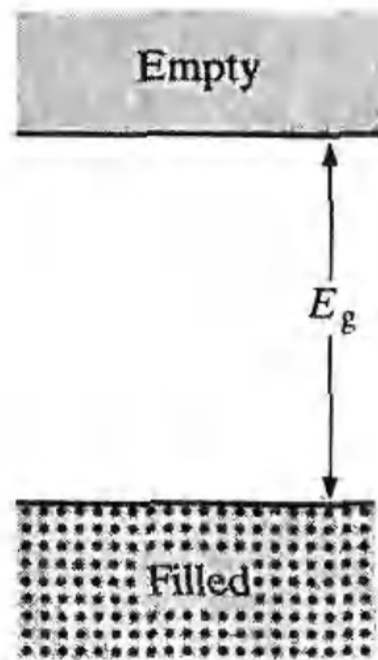


- Let us take the example of Si
- $3s$ is occupied. Only $3p$ is in valence!.
- However, $3s$ and $3p$ hybridize.
 - $3p$ states and $3s$ state combine to form 4 sp^3 states.

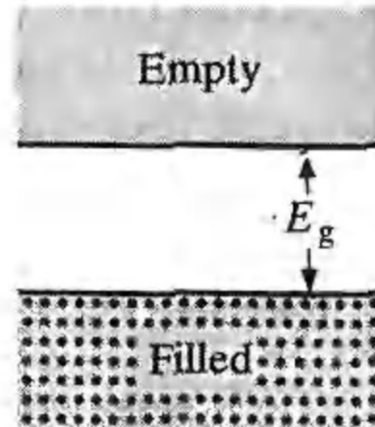




Band structure of different materials



Insulator

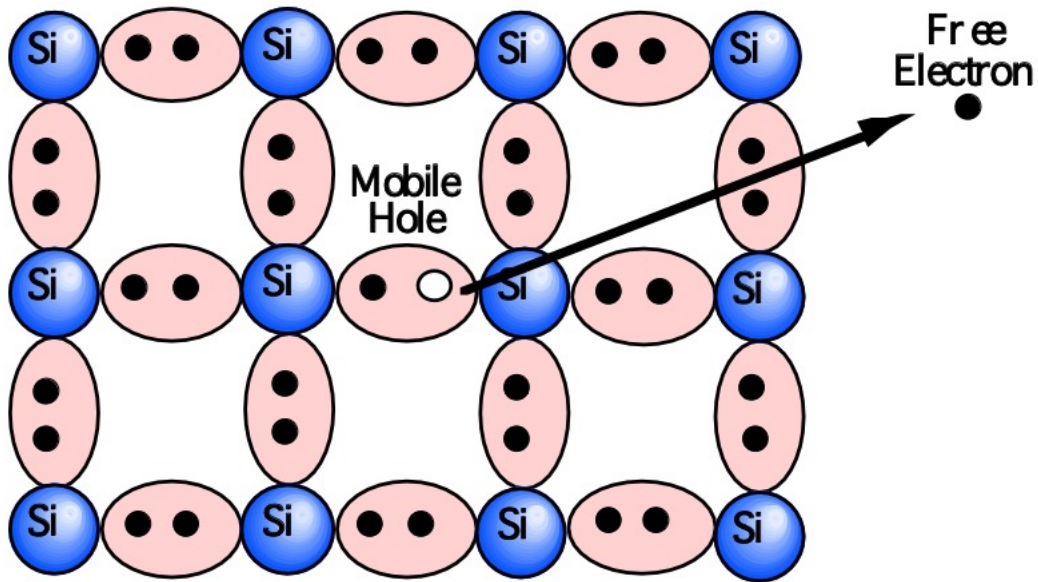


Semiconductor

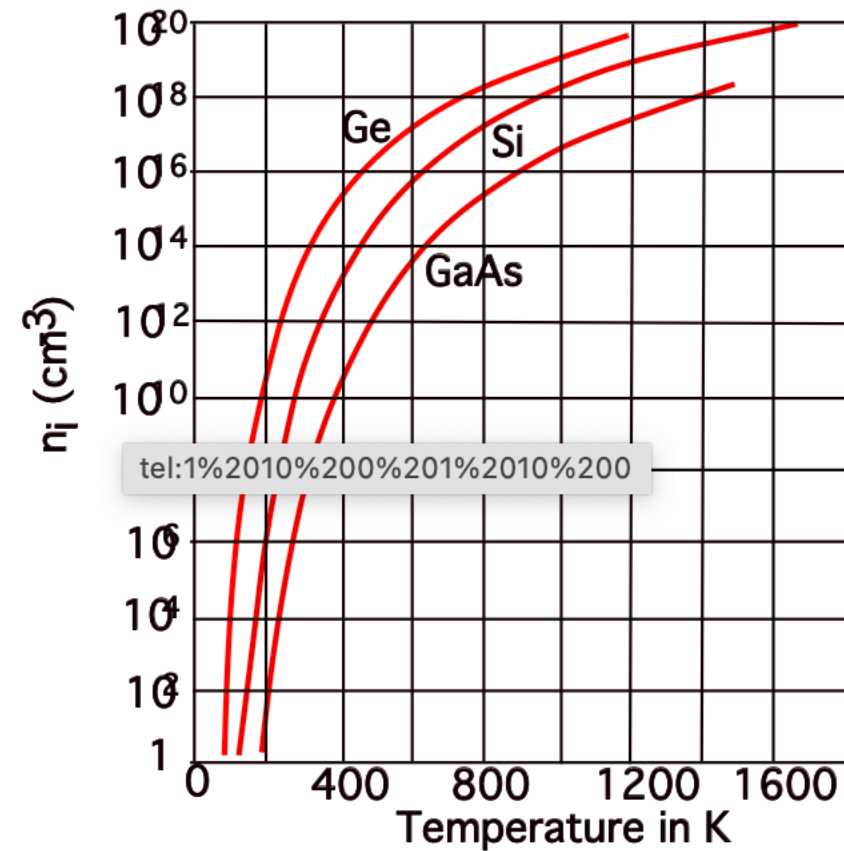


Metal

Intrinsic Conductivity



$$\text{Resistivity } \rho = \frac{1}{nq\mu}$$



Intrinsic carrier concentration is n_i

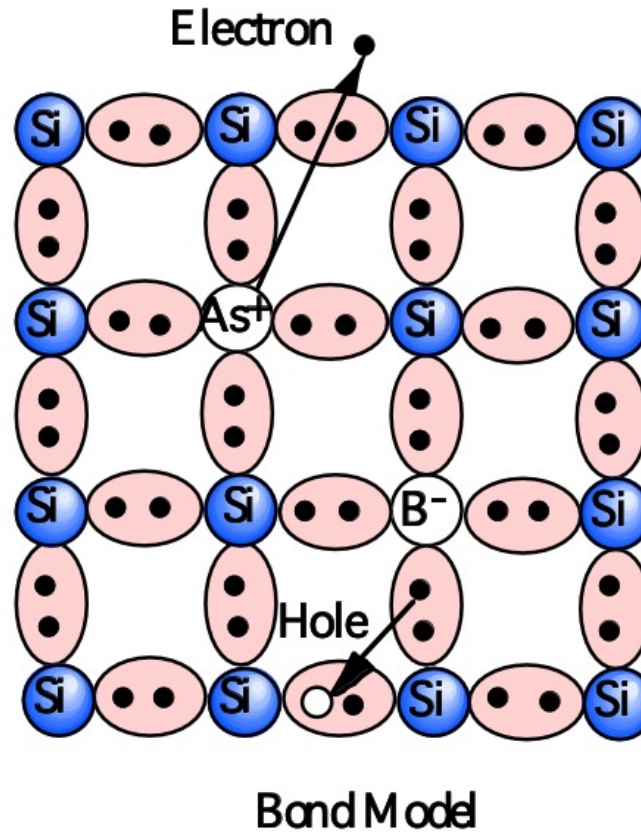
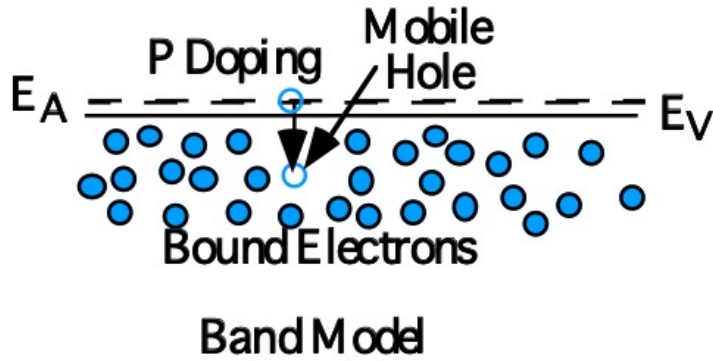
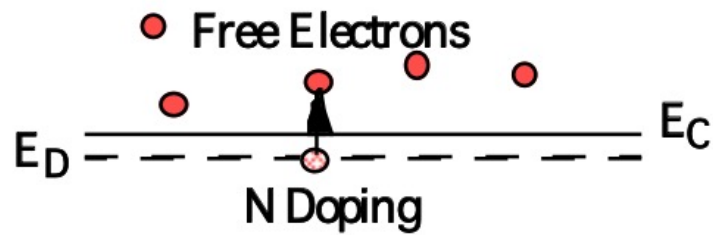
Intrinsic density of different semiconductors

Material	E_G at Room Temp	n_i at Room Temp
Germanium	0.66	$2.5 \times 10^{13} \text{ cm}^{-3}$
Silicon	1.12	$1.45 \times 10^{10} \text{ cm}^{-3}$
GaAs	1.42	$2 \times 10^6 \text{ cm}^{-3}$

- For Si, the expression for intrinsic carrier density is

$$n_i = 3.9 \times 10^{16} T^{\frac{3}{2}} e^{-\frac{0.603}{kT}}$$

Doping of semiconductors



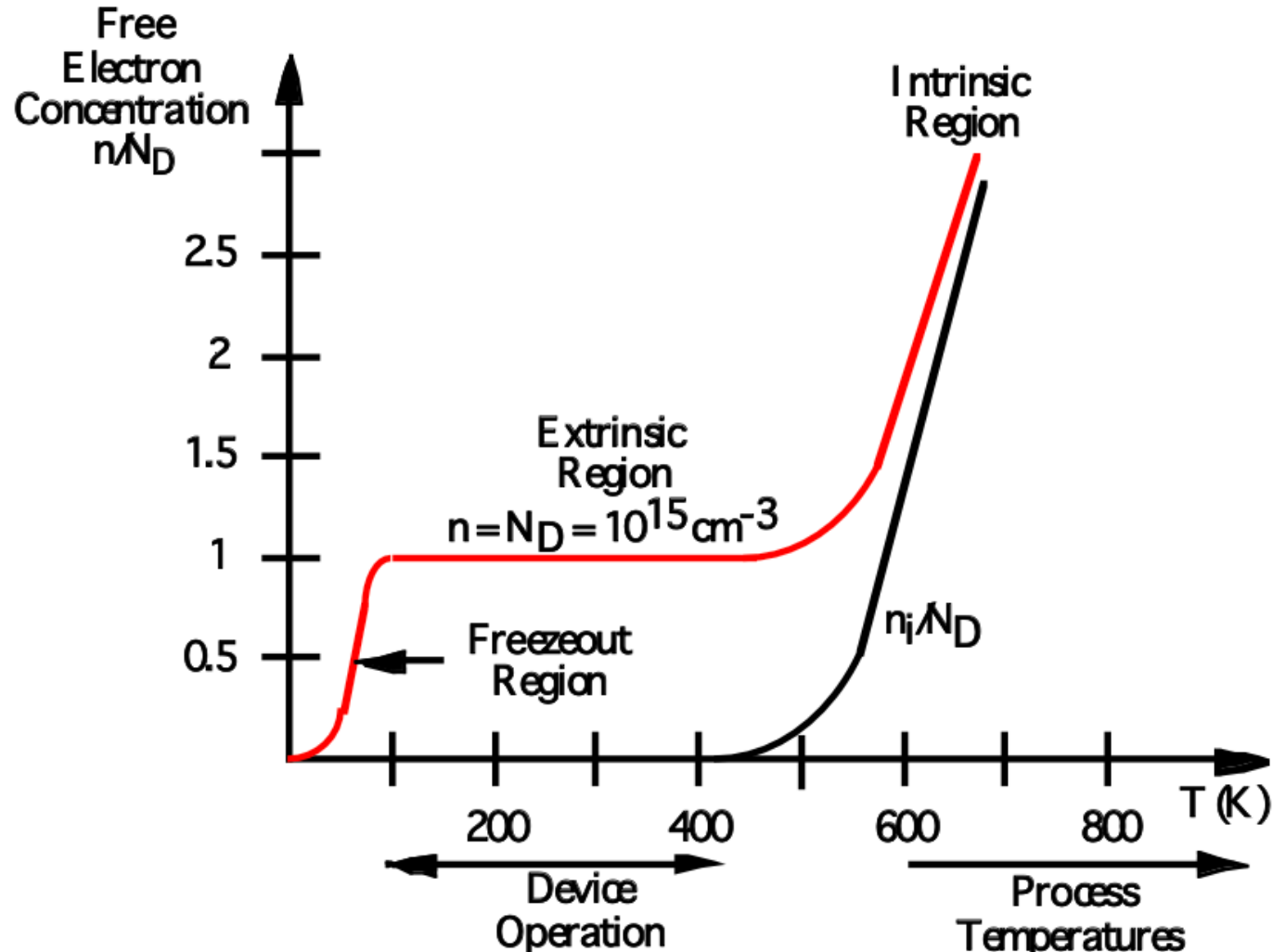
When As is added



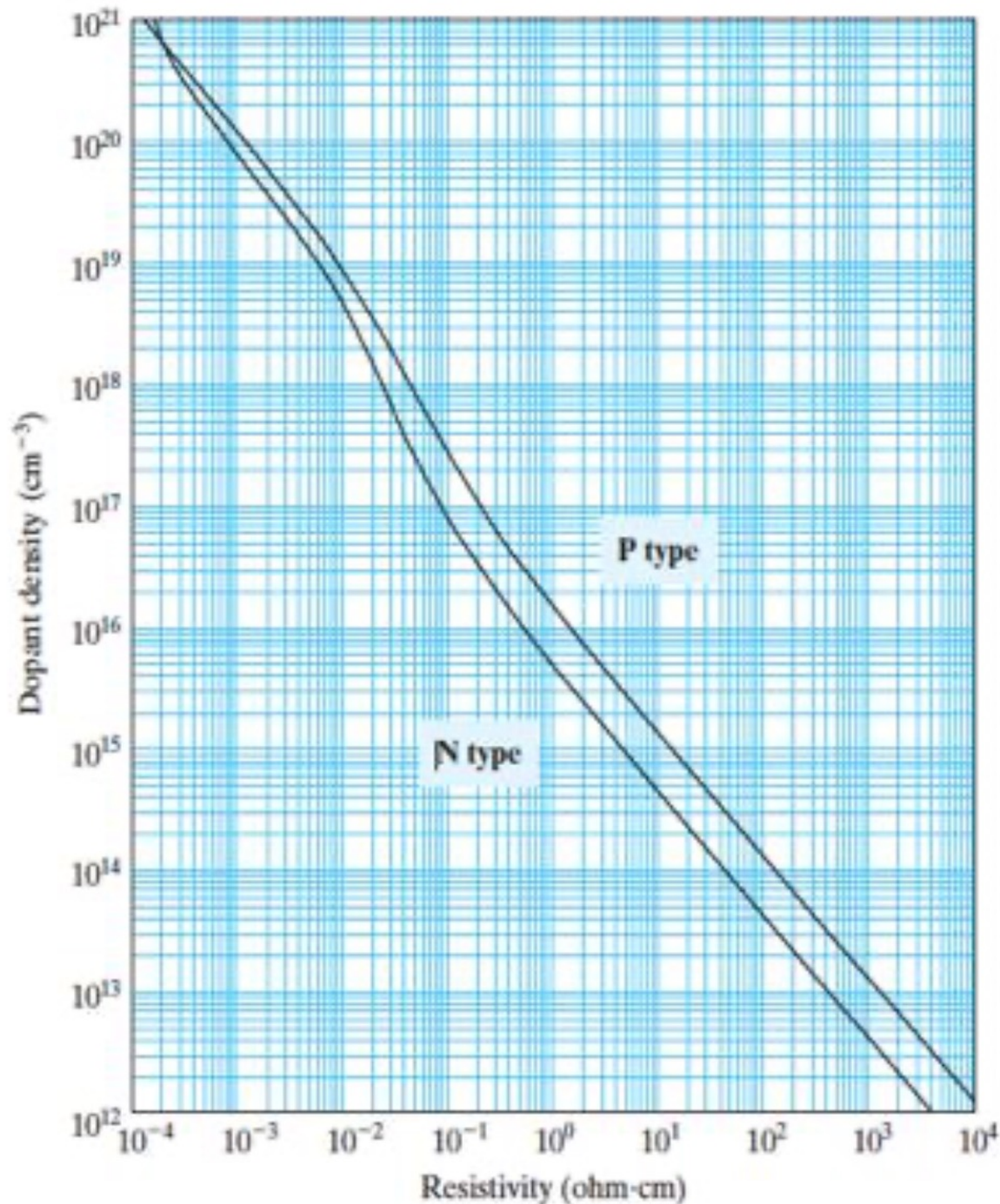
The electron is free to move throughout the material!

Increasing conductivity

Extrinsic is not always Extrinsic!



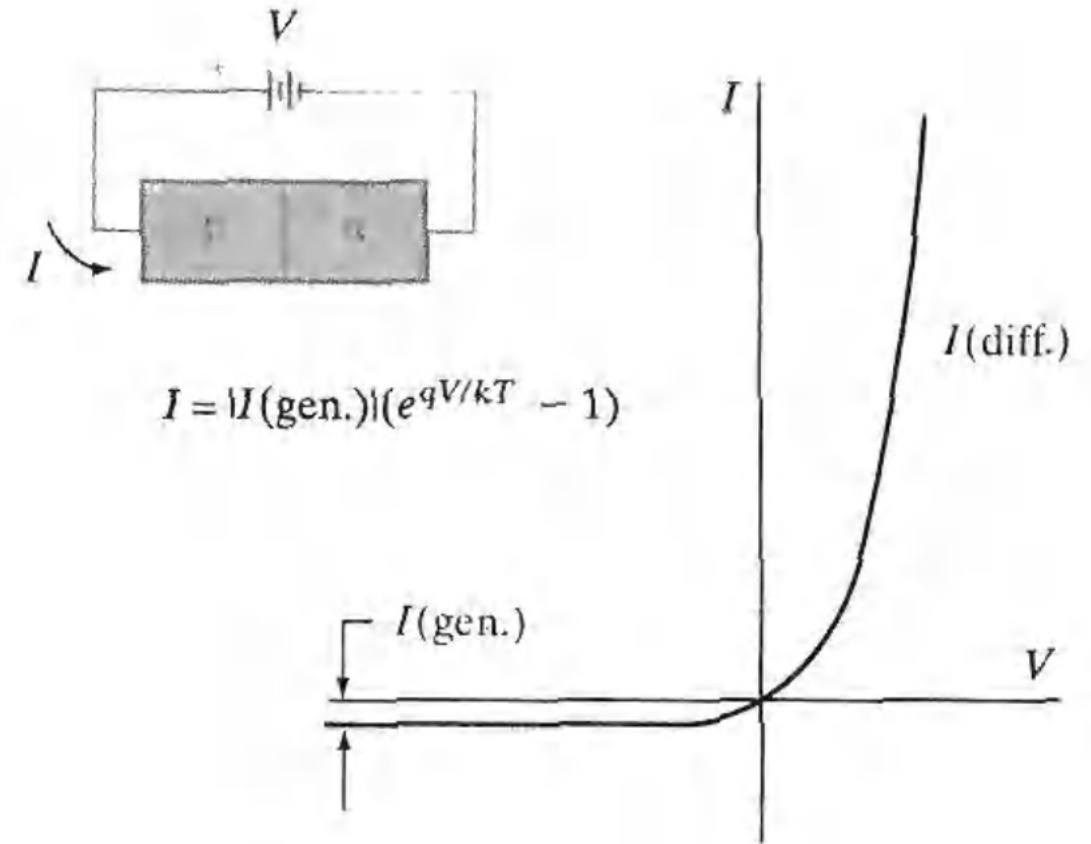
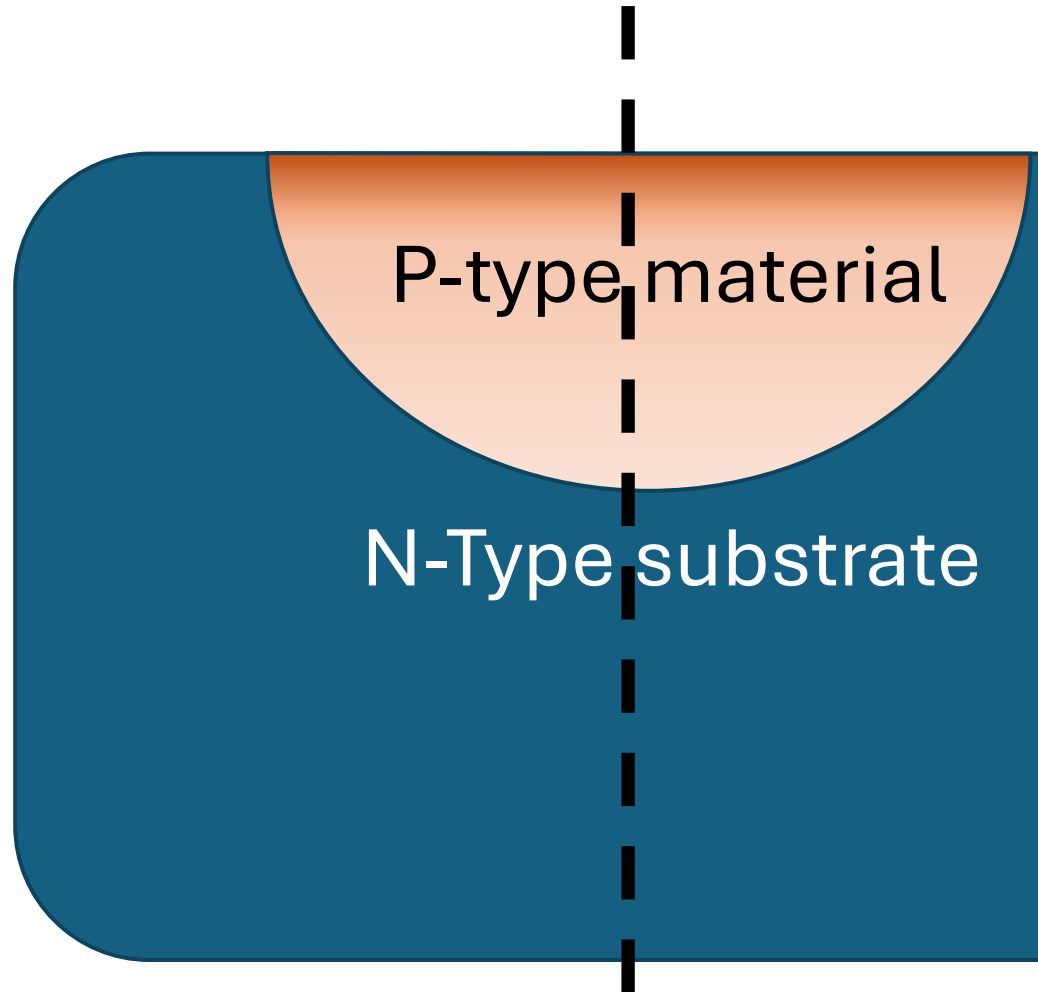
- An extrinsic semiconductor is characteristically different only under specific temperatures!

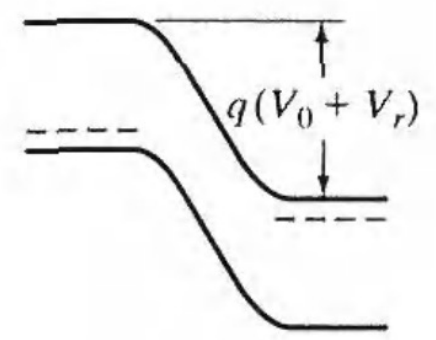
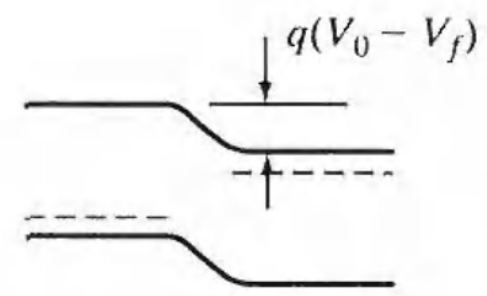
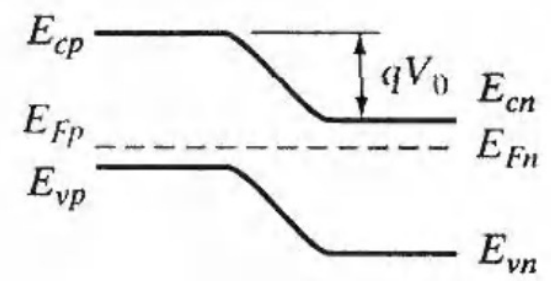
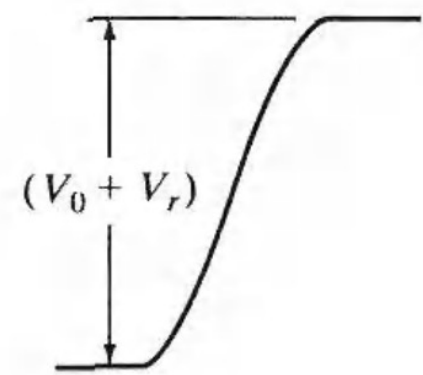
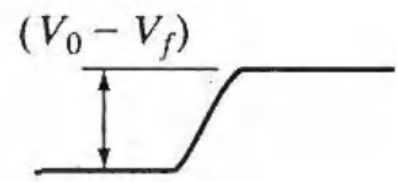
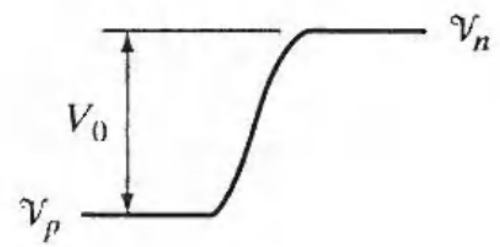
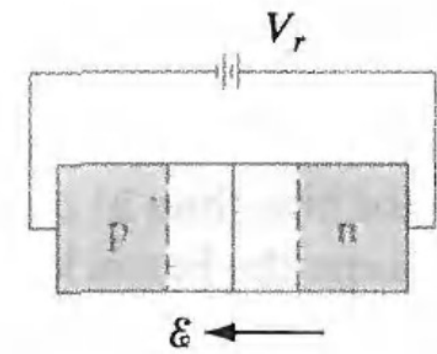
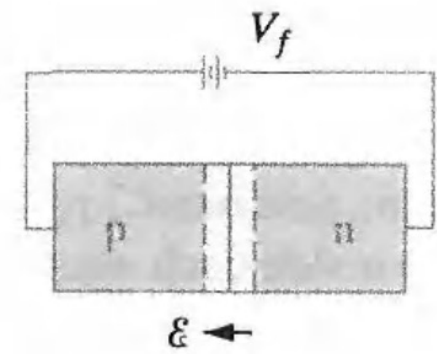
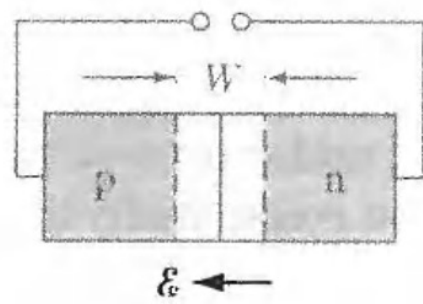


Resistivity

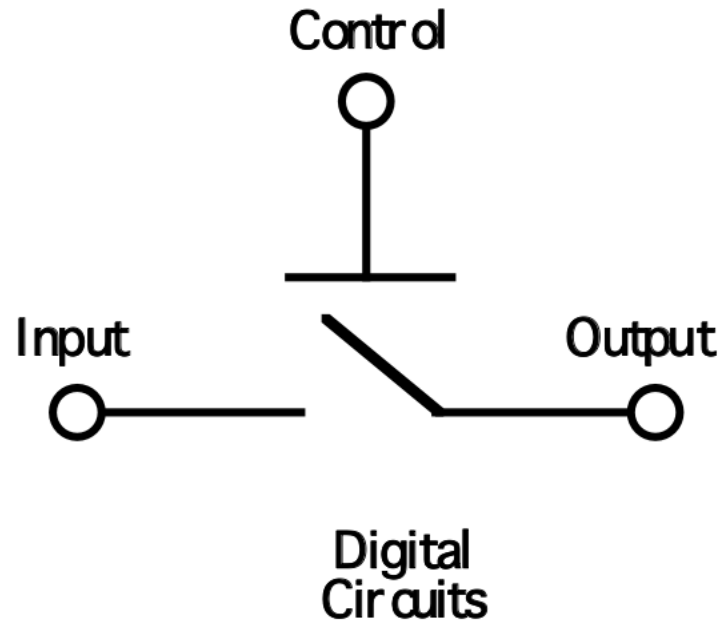
- Resistance is measured.
- $R = \frac{\rho l}{A}$
 - Where, A is the cross section of current conduction
 - L – length of conducting region.
 - ρ is called resistivity (Material property)
 - $\rho = \frac{1}{nq\mu}$

Semiconducting Device

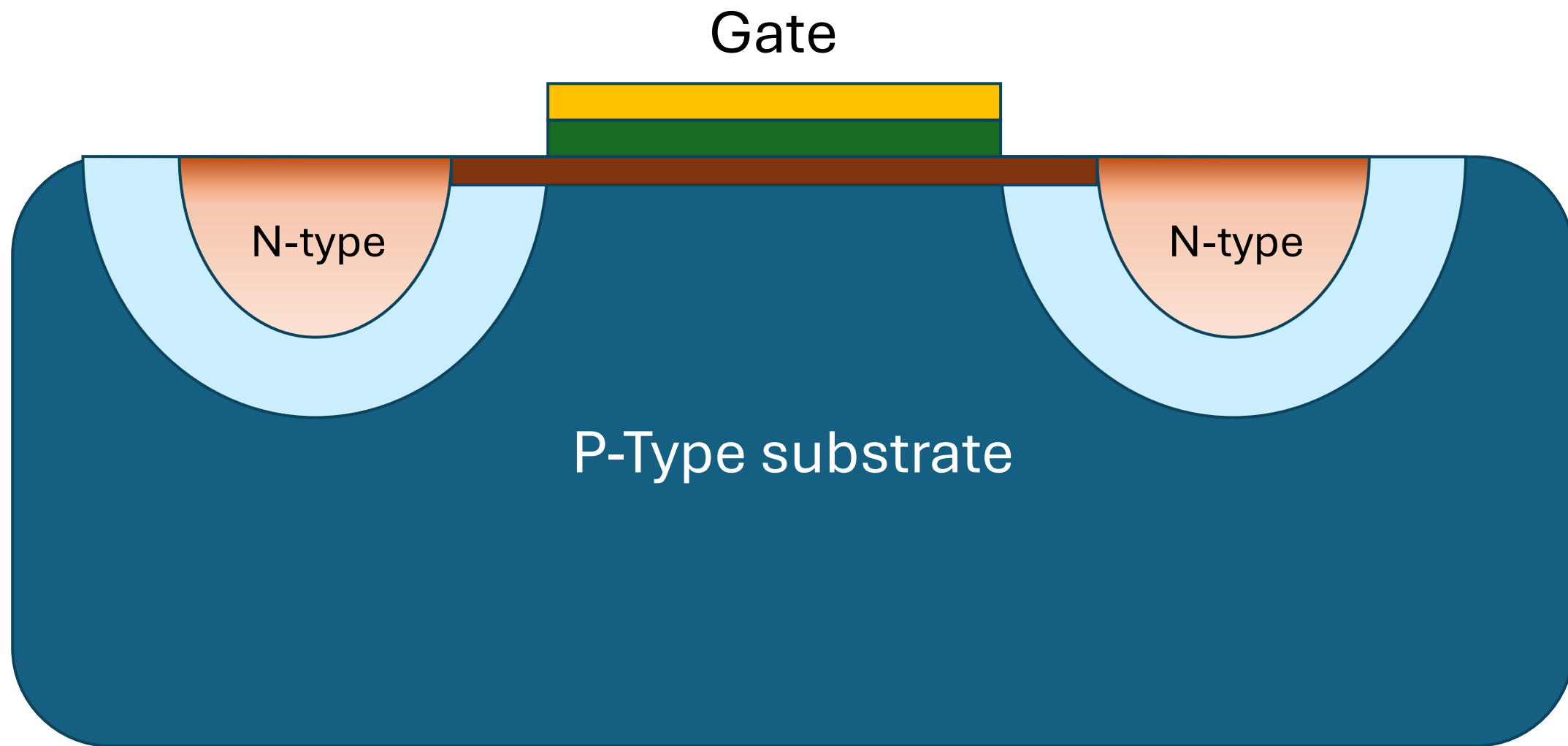




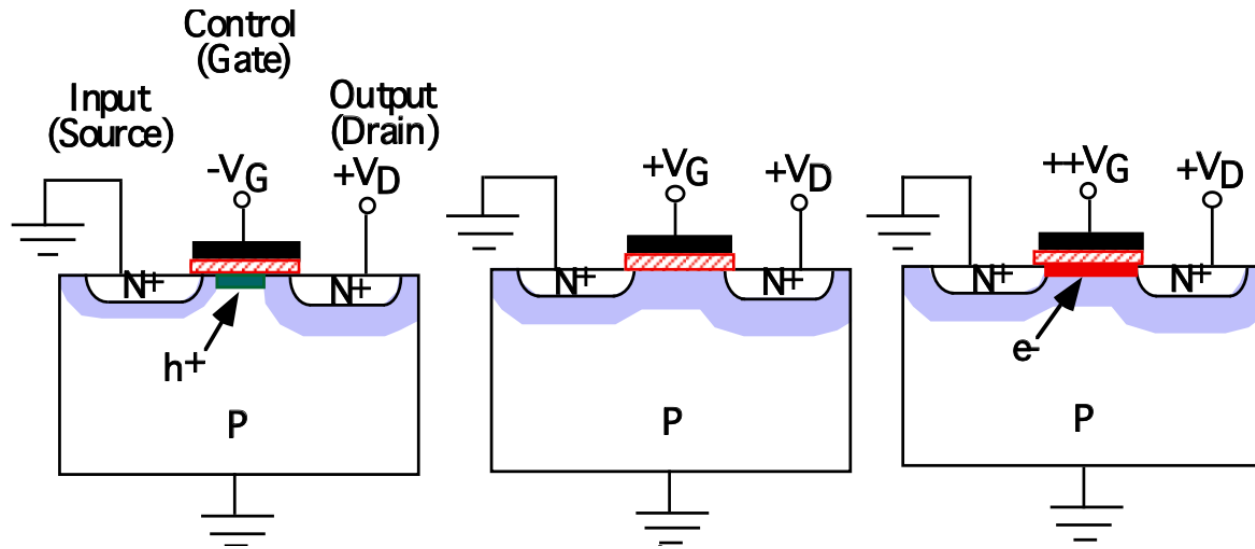
Three Terminal



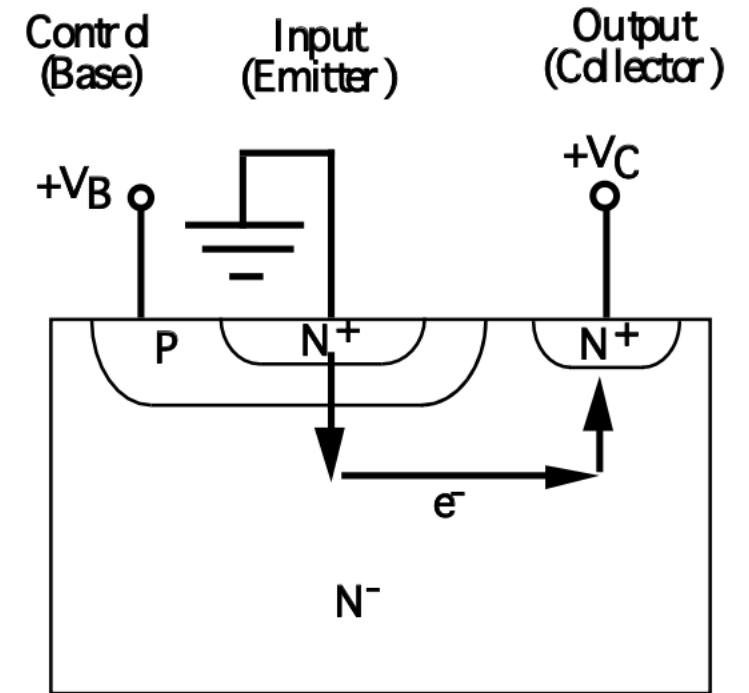
- The question is then, how do we realize this in practice ?



MOSFET – Metal Oxide Field Effect Transistor



BJT – Bipolar Junction Transistor

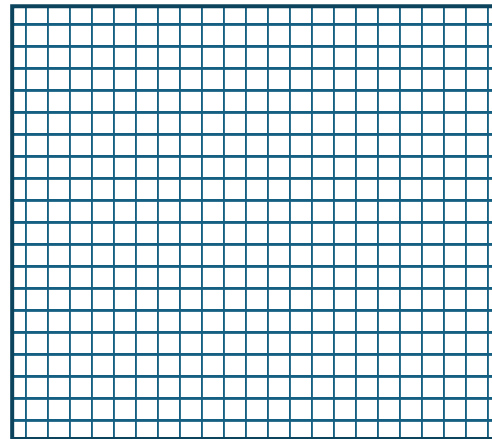


Reason For Need for MicroFabrication (Obvious)

- The need for computational power and memory increases exponentially
- The compute station also needs to be portable!
- There is an obvious need for shrinking!

Imagine, if we want to store – 1 GB of data in 1 meter²

1 bit will then be stored in ?



There must be about
30000 rows and columns!

So, each row must be $33\mu m$

Other additional constraints

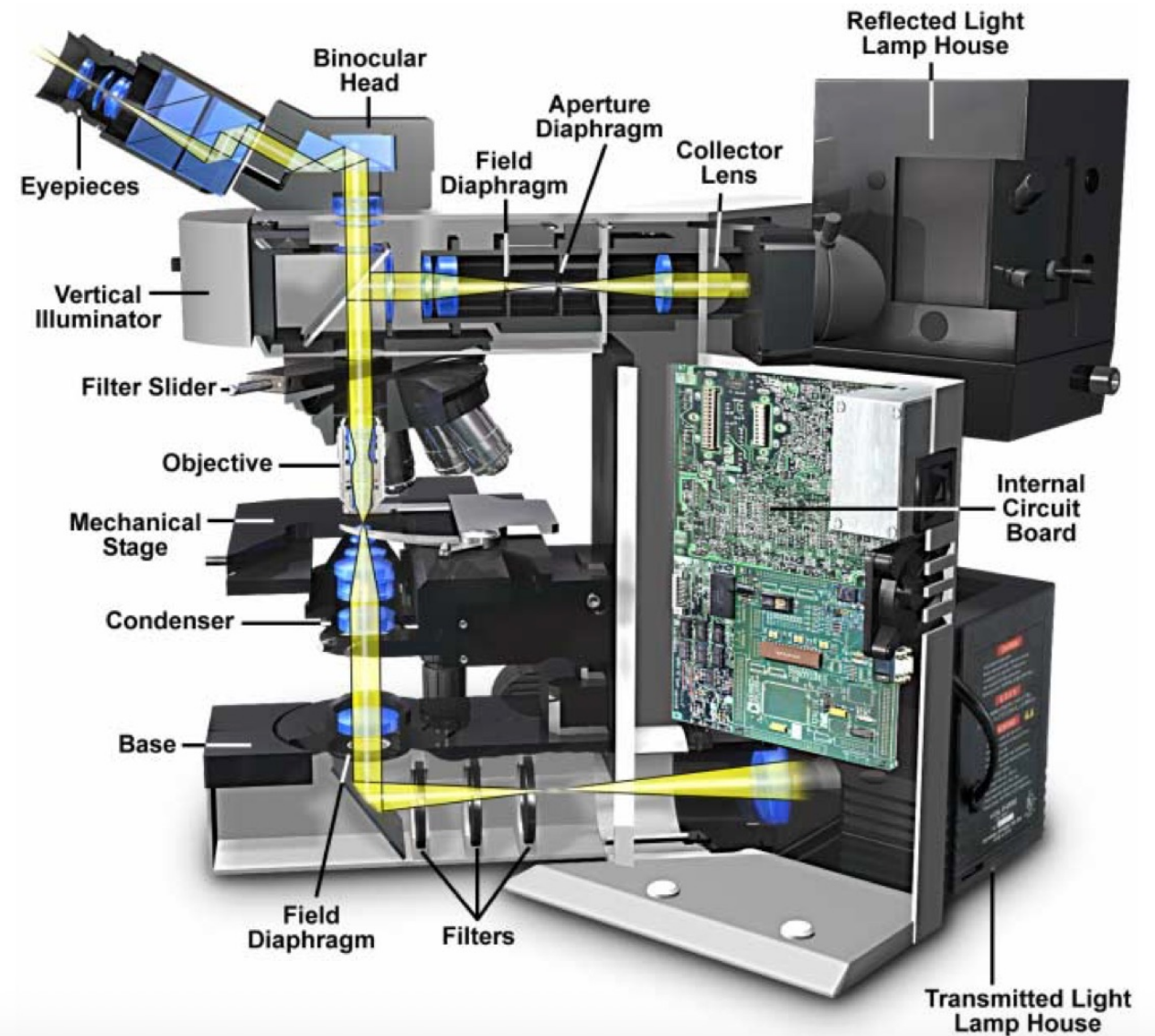
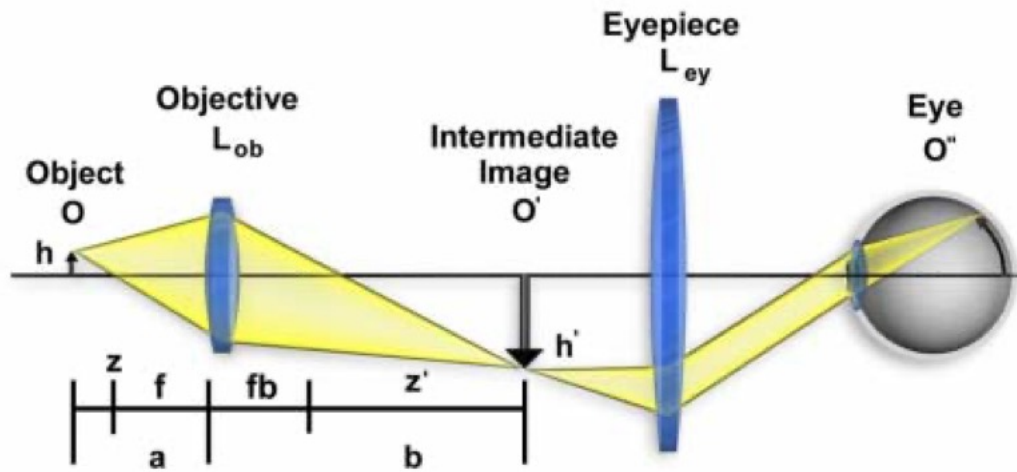
- Speed:
 - The total current in a Mosfet $I_D = \frac{\mu C_{ox} W}{L} (V_G - V_{th})^2$
 - Shorter transistor will carry more current
 - Larger current means faster transistor
 - Lower voltage and power requirements!
- Reliability
 - Smaller systems have precision movements. – Lower Inertia
 - Smaller systems have lower thermal distortion
- Cost
 - Accessible for mass/batch production.

Microcharacterization and metrology

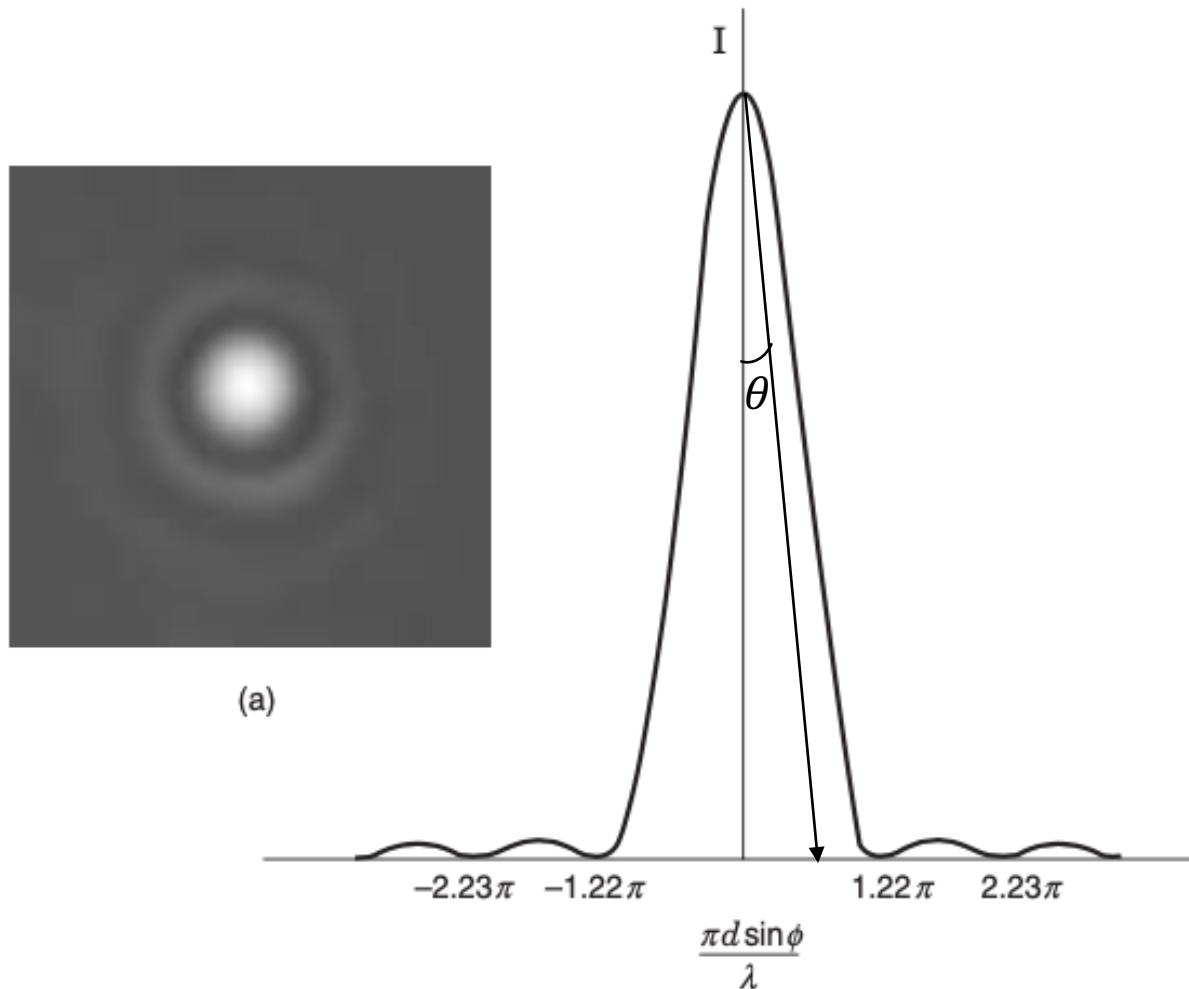
Various microcharacterization techniques

- Microscopy and visualization
- Lateral and vertical dimension measurements
- Optical material analysis
- Electrical characterization
- Other physical and chemical analysis.

Light Microscope and limitations



Diffraction from a circular slit



The intensity profile is an Airy disk

$$I(\theta) = I_o \left(\frac{2J_1\left(\frac{2\pi a}{\lambda} \sin \theta\right)}{\frac{2\pi a}{\lambda} \sin \theta} \right)^2$$

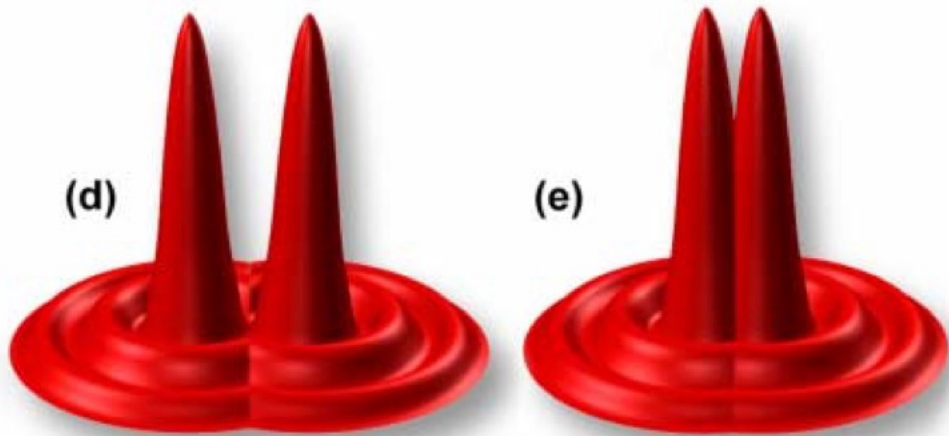
Where a is the radius of the aperture.

HW: plot the function for different disk openings ' a '

Resolution limits



The smallest disk that be formed by a light of wavelength λ is given by $\frac{0.61\lambda}{NA}$



Two spots are resolvable if they barely touch each other!

Abbe's criteria

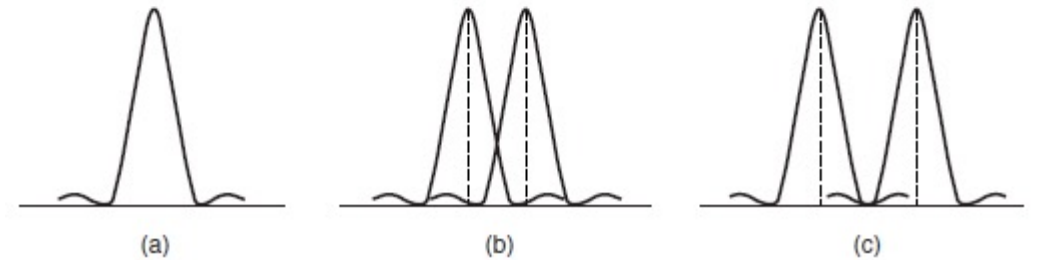
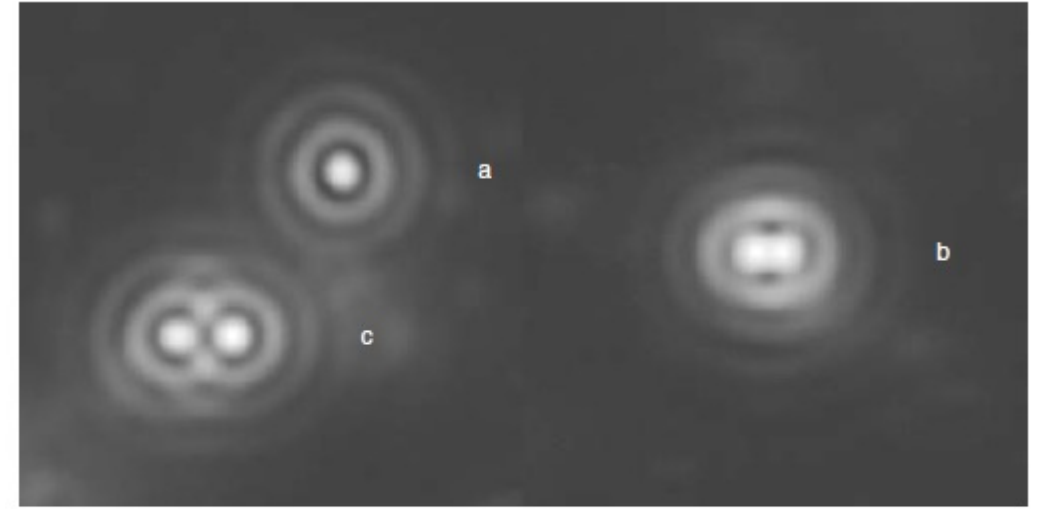


- Bright field (0^{th} order diffracted beam cannot form a distinct image)
- Collection of at least the first order forms a defined image
- Higher the number of diffracted beams captured, better is the resolution.
- Fortunately, the intensity of diffracted beams fall quickly with order, so first few orders are the most prominent
- However, smaller the particle size, larger the angle of diffraction
 - This means, even the first order diffracted line will be farther for smaller particles

If an object doesn't diffract light/ the objective lens does not collect diffracted light, no image is formed.

Spatial Resolution of a microscope

- A point in the image plane (due to converging light beams of λ) will have a minimum diameter $0.61 \frac{\lambda}{NA}$
- Two bright points in the image plane is considered to be resolved, when the peak of the second coincides with the first minima of the first source.



Remember, the limit is not about resolving the smallest particle!

It is about identifying two close lying particles are two separate particles.

Electron Microscopy

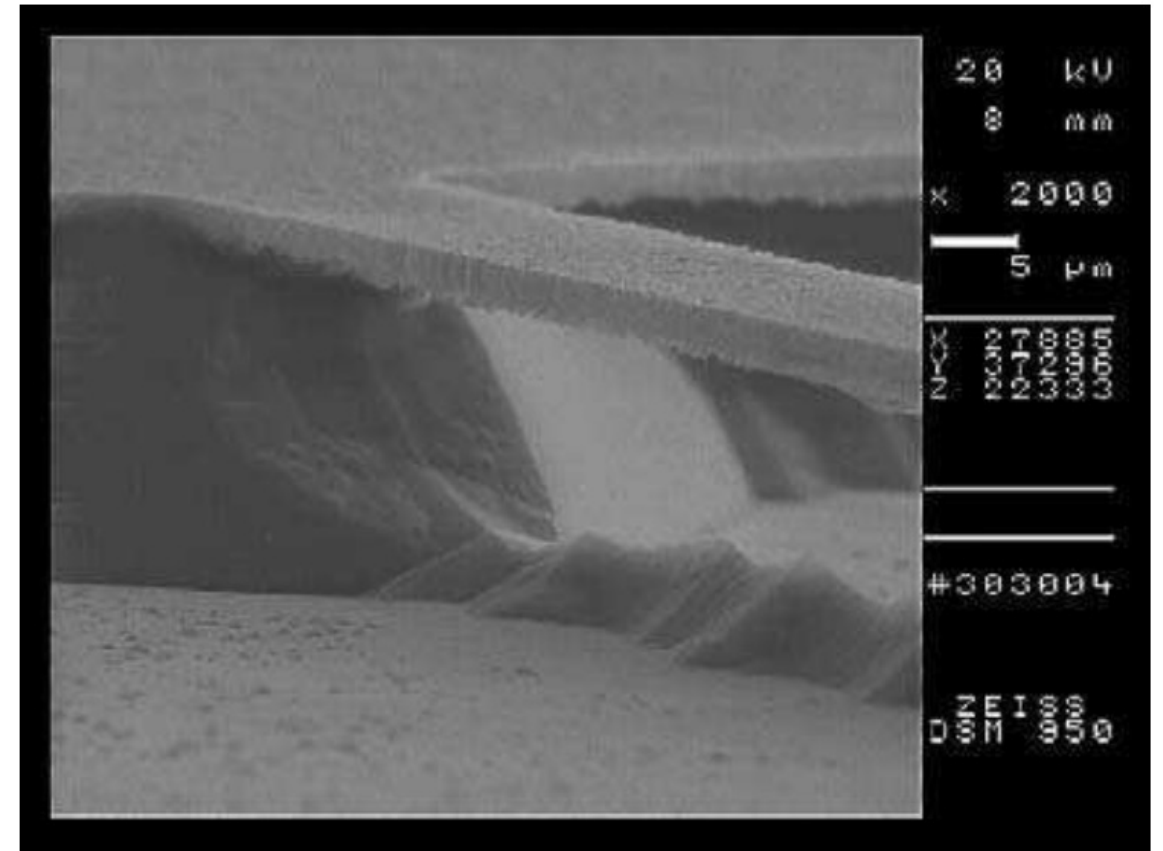
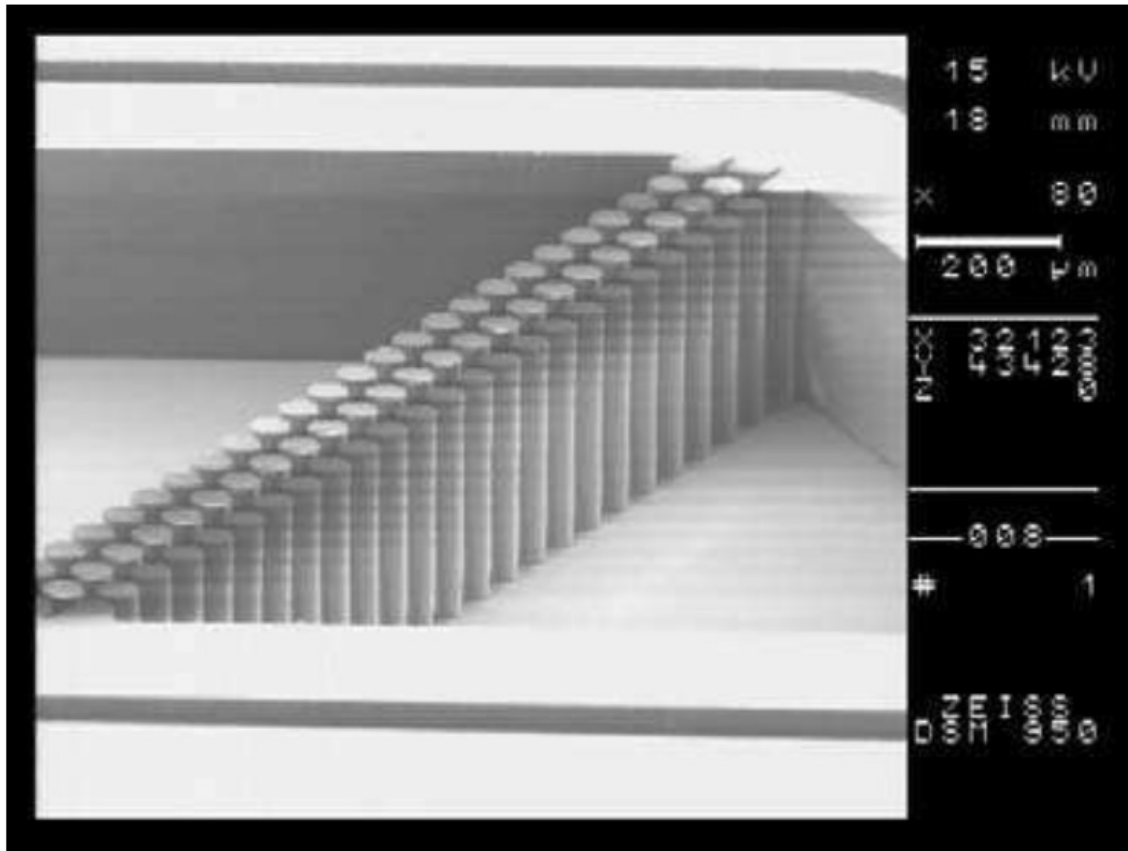
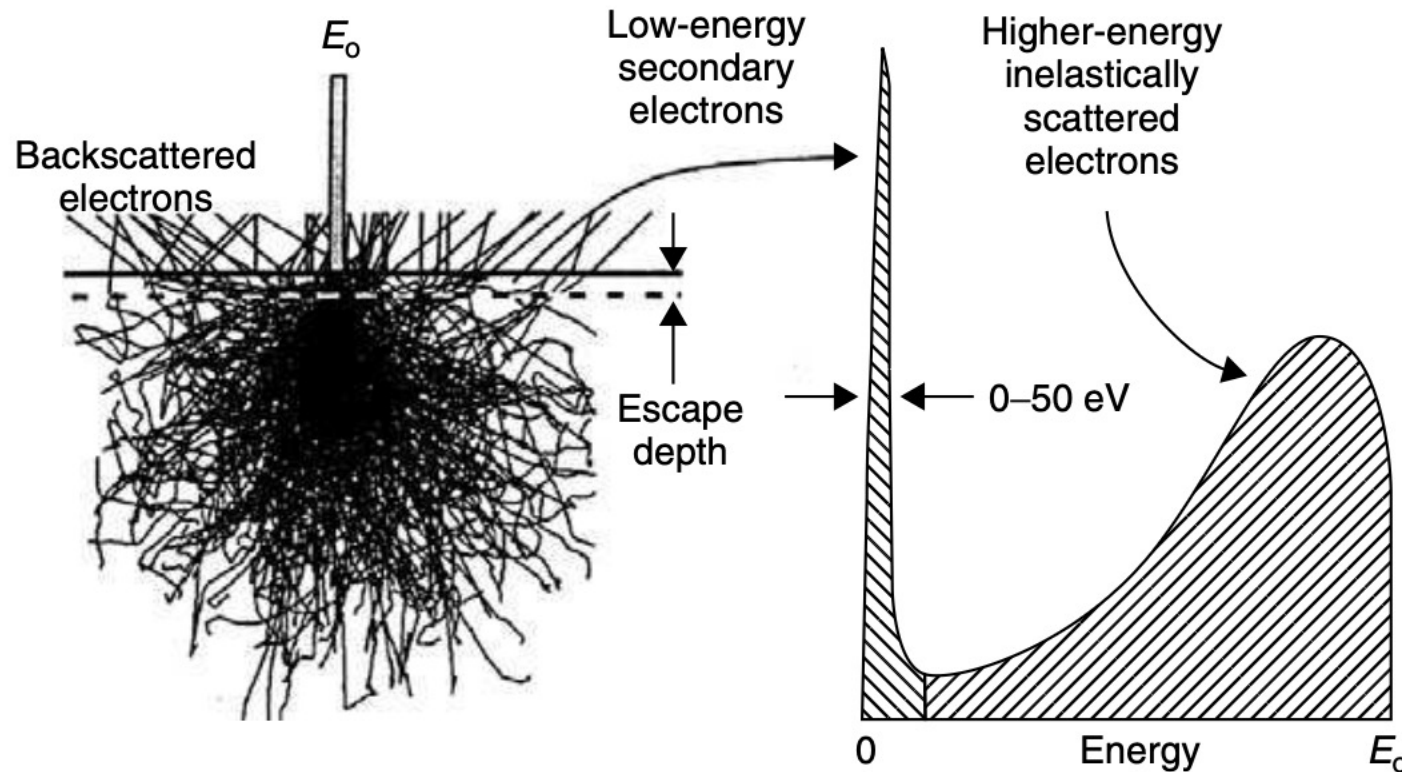


Photo courtesy Kostas
Grigoras, Helsinki University of Technology

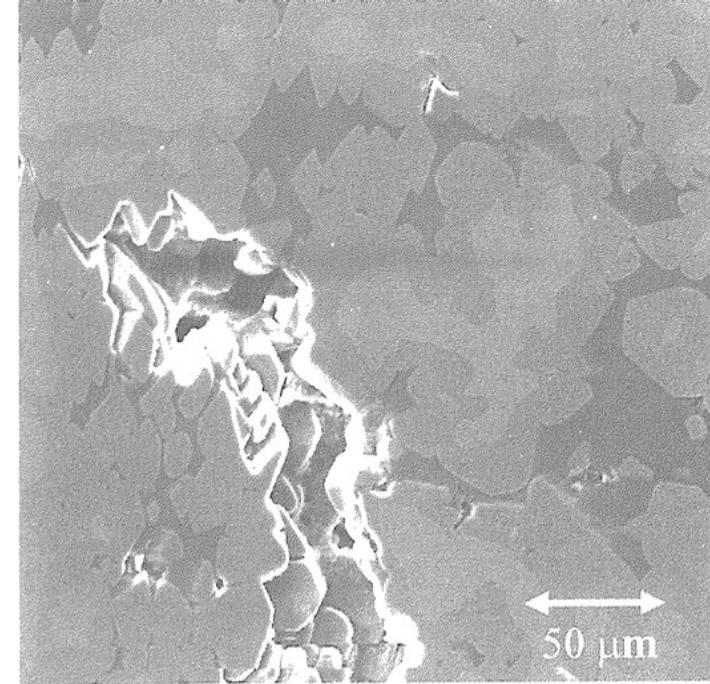
Different measurements using an electron microscope



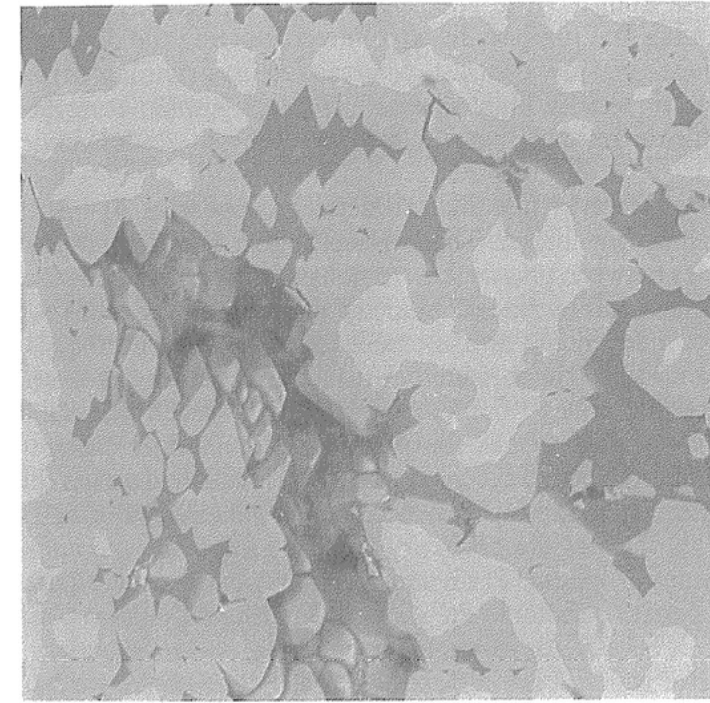
- Elemental analysis
- Physical property measurements using cathodoluminescence
- Electron-Diffraction and other measurements

Detectors tell it all

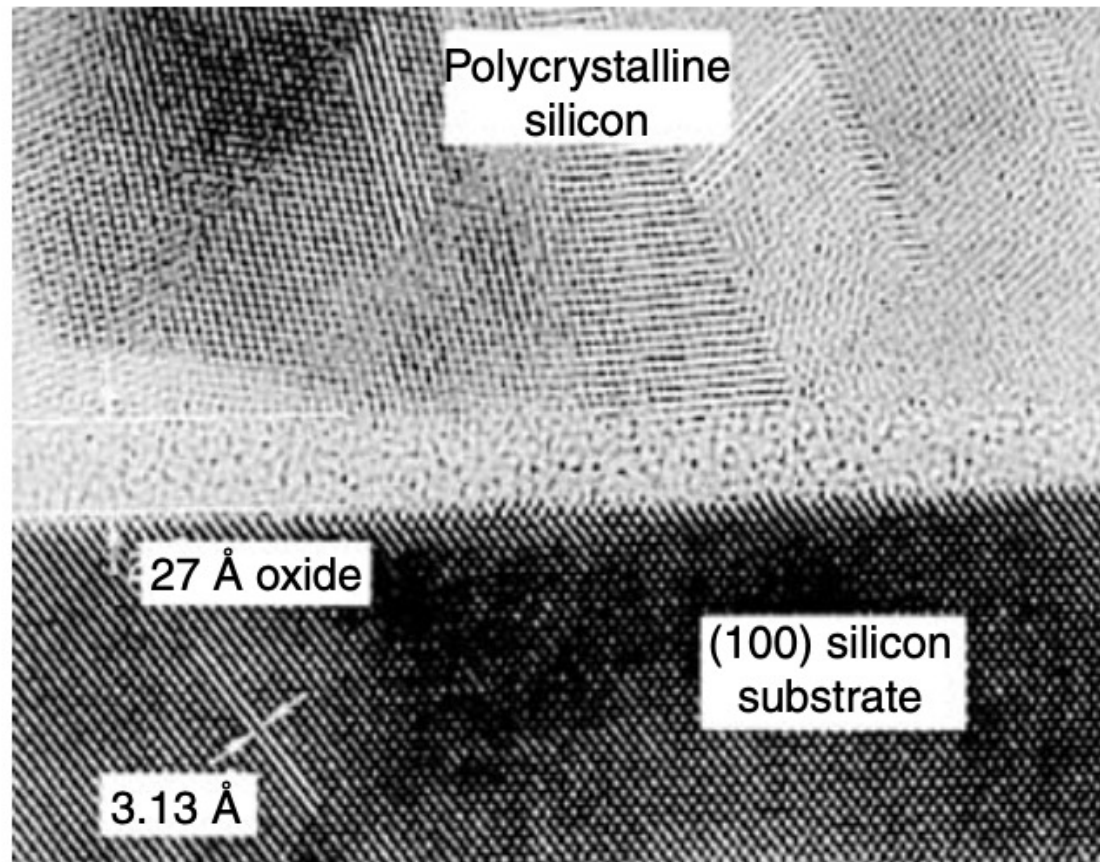
Sno	Detector	Sensitivity
1	BSE	Atomic number contrast
2	ET (-ve bias) ET (+ve bias)	Atomic number contrast Dominating topological contrast.
3	In-Lens	SE-I topological contrast (you see what the beam sees)



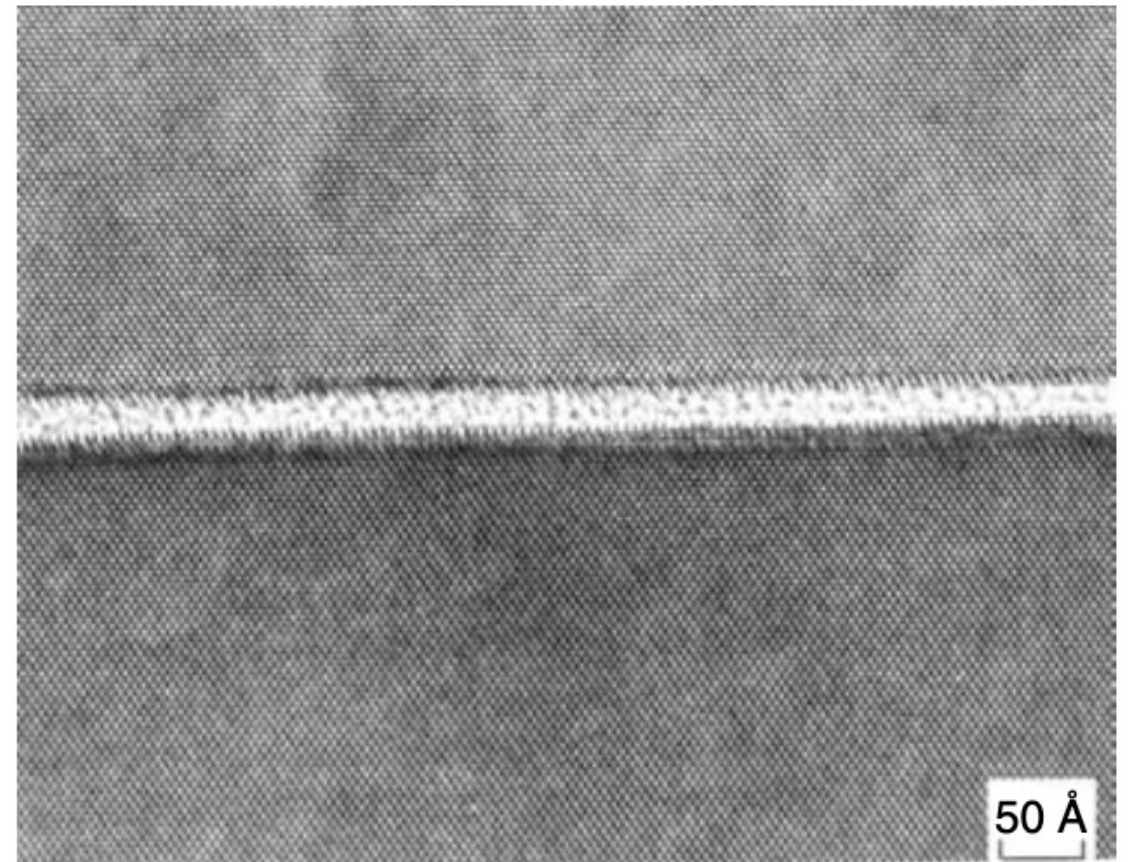
a



High resolution transmission electron measurements

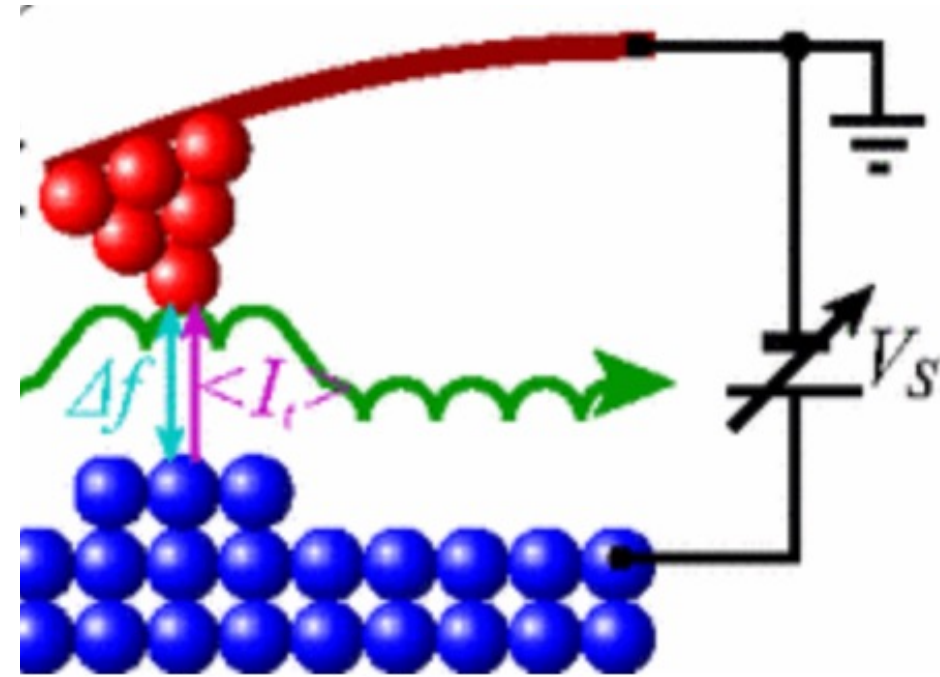
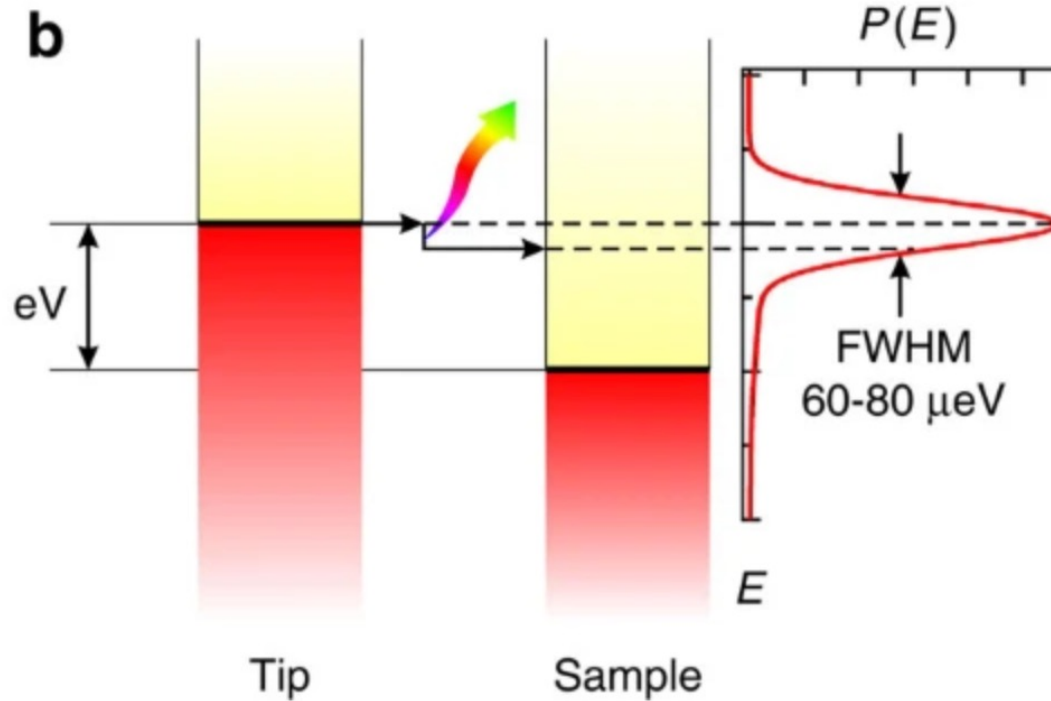
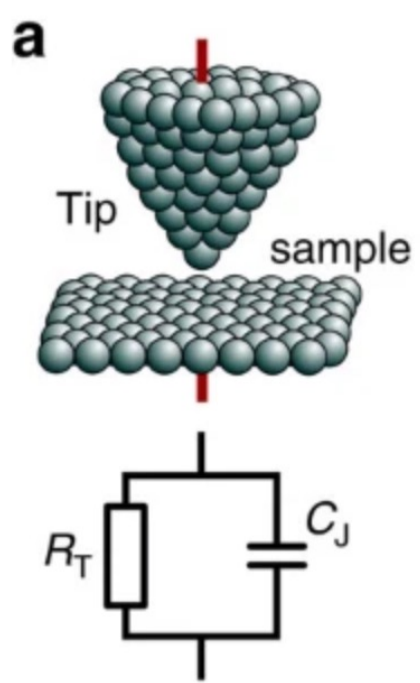


(a)

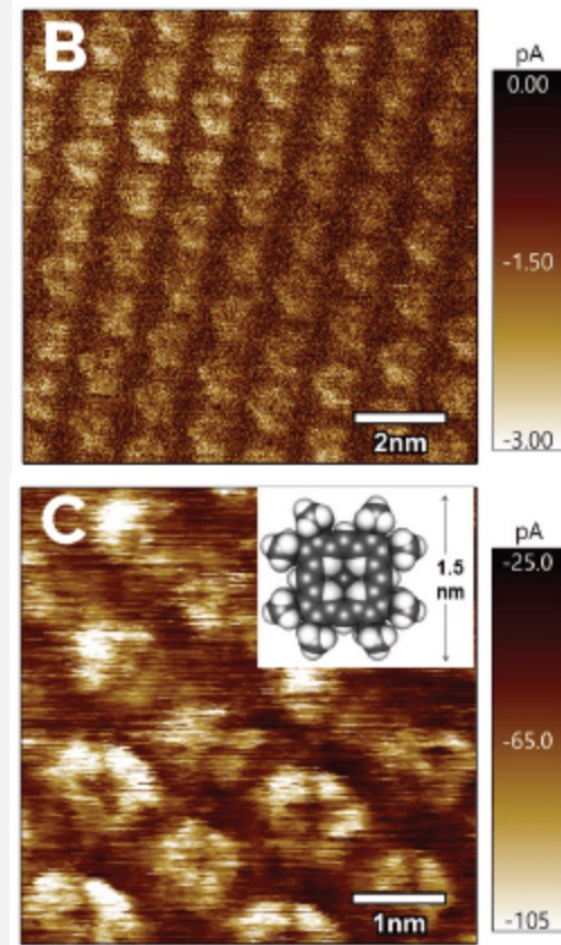
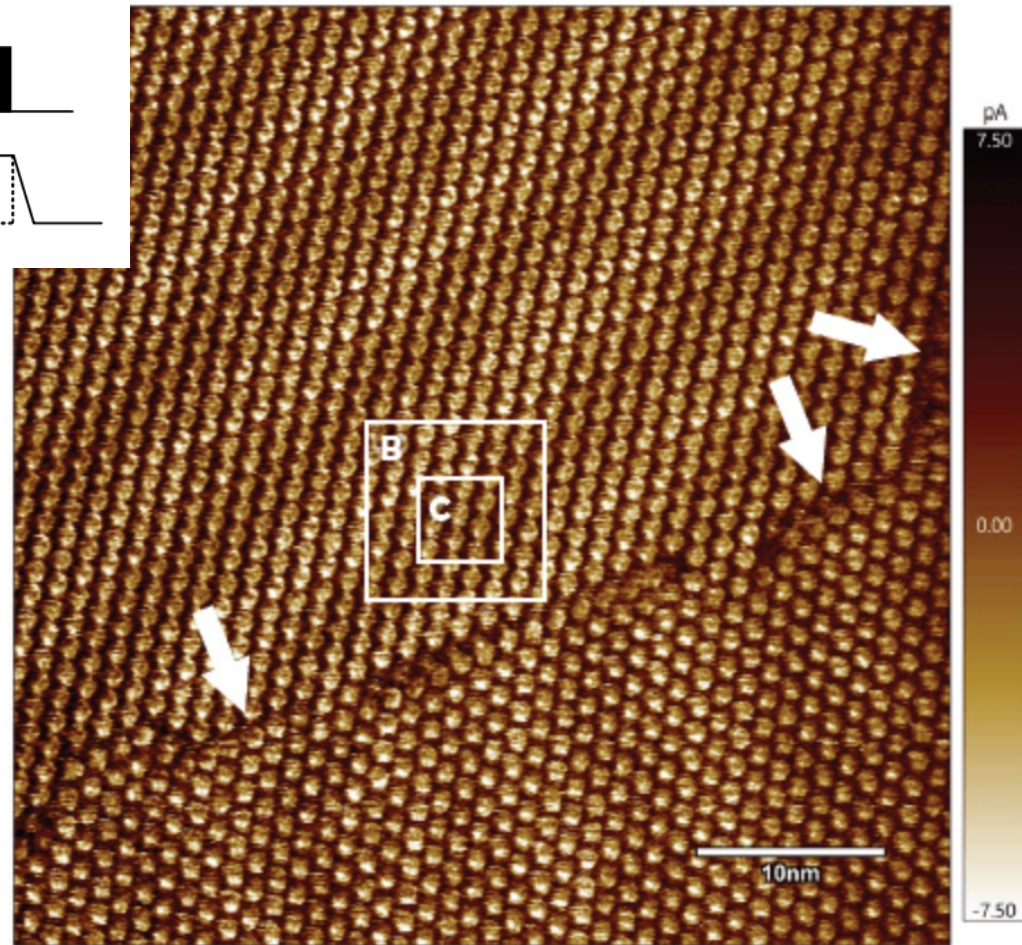
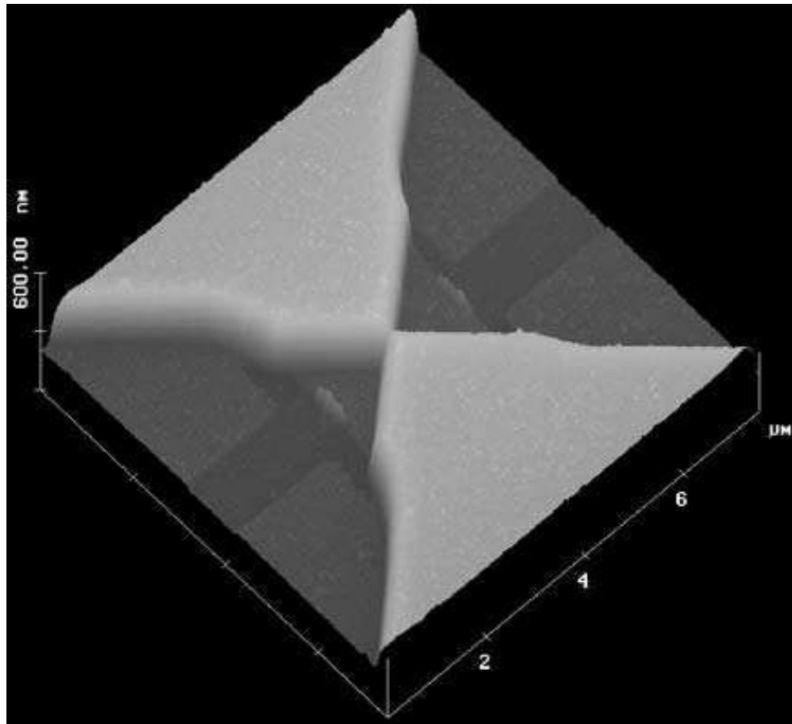
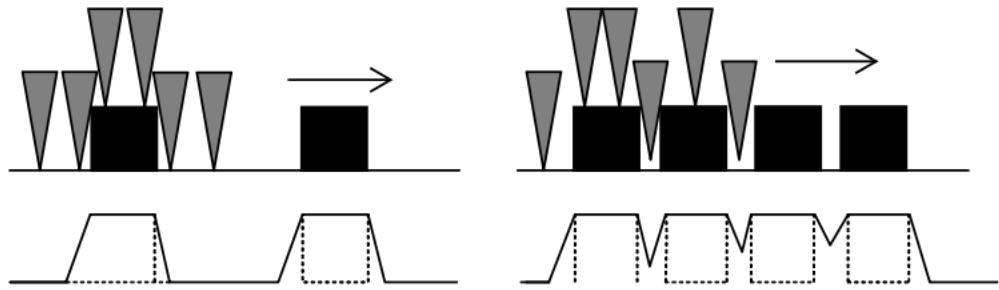


(b)

Tip Based distance/height measurements



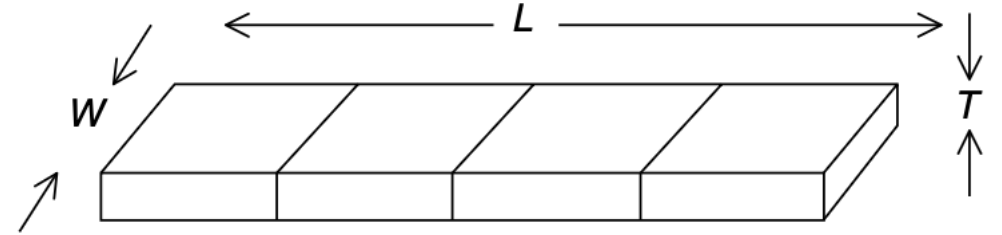
Scanning Tip Microscopes



Courtesy: Asylum research

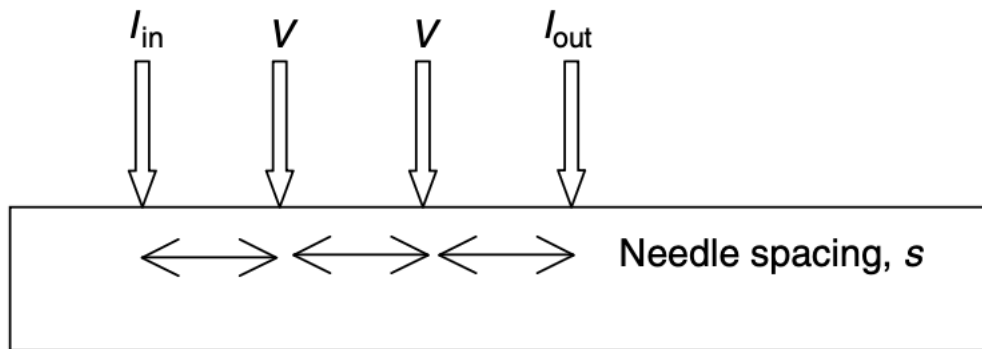
Electrical Characterization

$$\text{Resistance } R = \rho l / A$$



We define a quantity when $L = W$, $R = R_S$ (Sheet Resistance)

$$R_S = \frac{\rho}{T} \left(\frac{\Omega}{\square} \right)$$

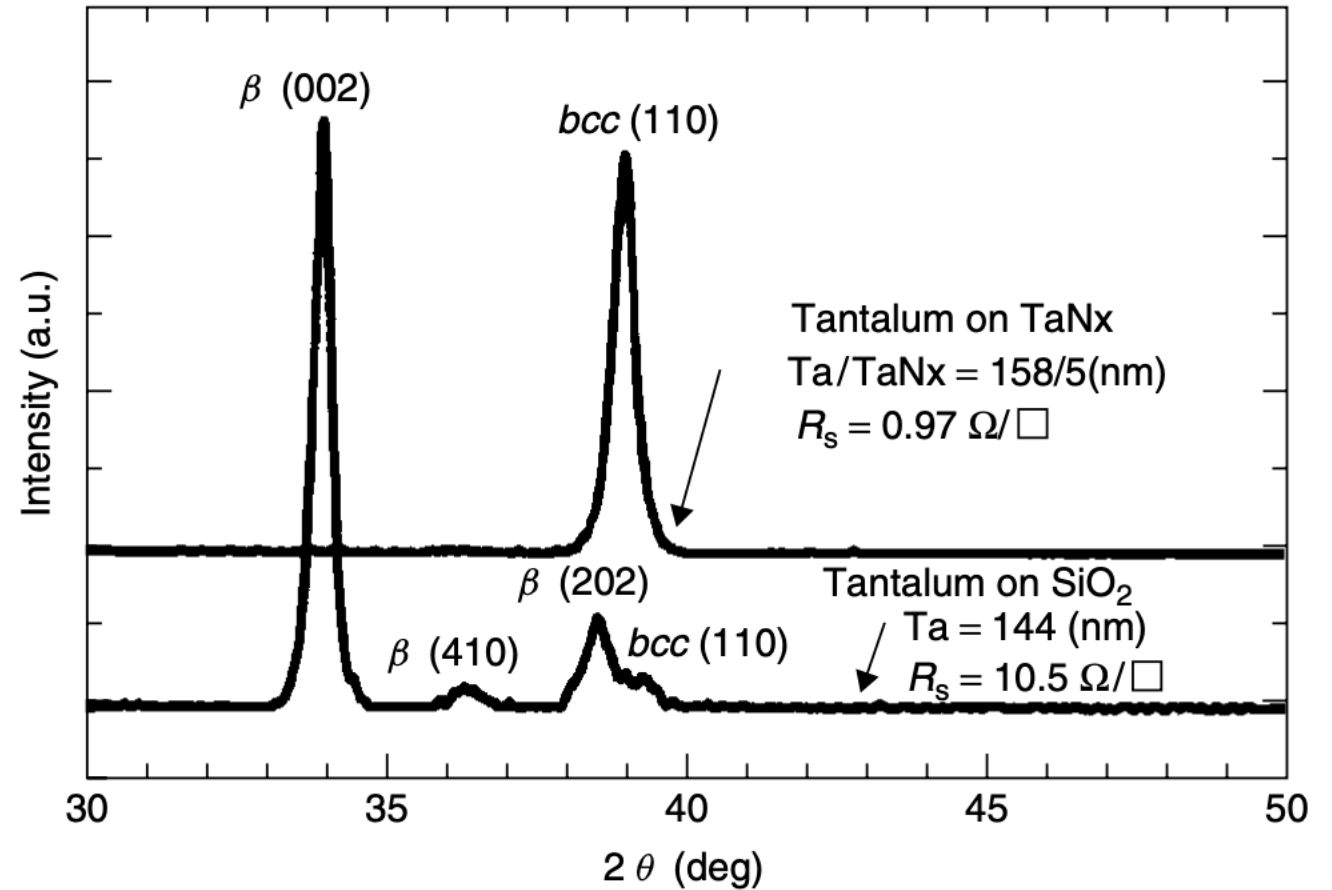


When a thin film is measured with four probes,

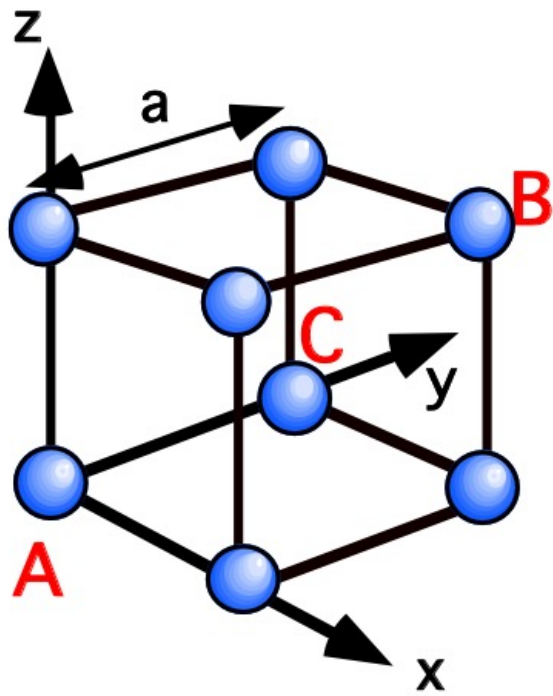
$$R_S = \frac{\pi}{\ln(2)} \frac{V}{I}$$

Other Physico-Chemical Characterizations

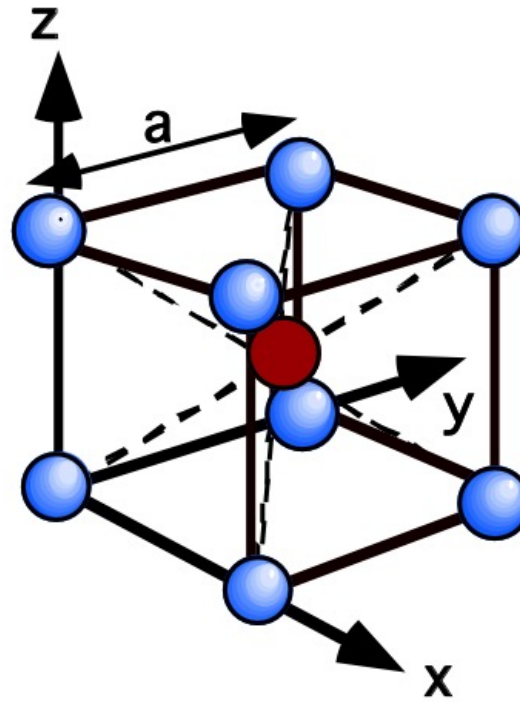
- X-Ray Diffraction
 - Crystal Orientation, texture
 - Strain
 - Grain size
- X-ray Photo-electron spectro
- Auger Electron spectroscopy



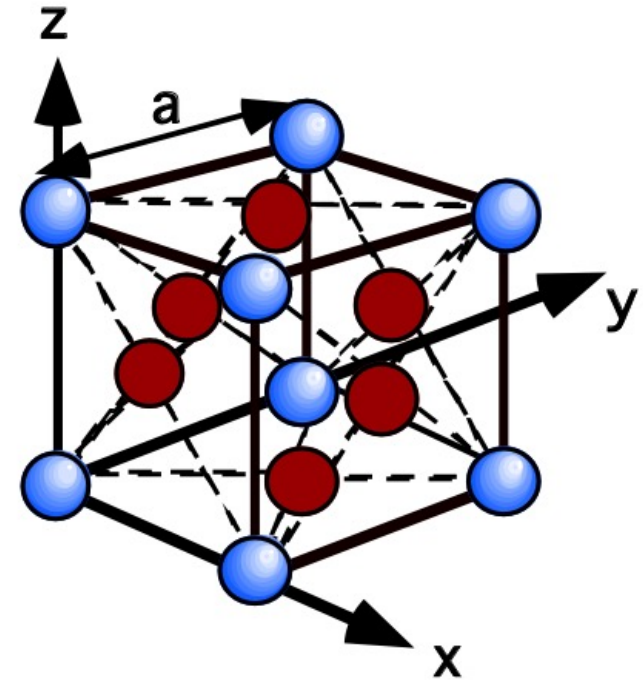
Basic Properties of Si Wafers



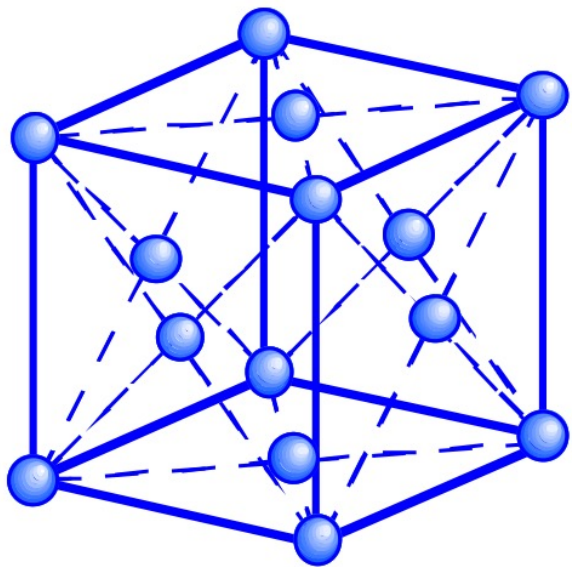
Cubic



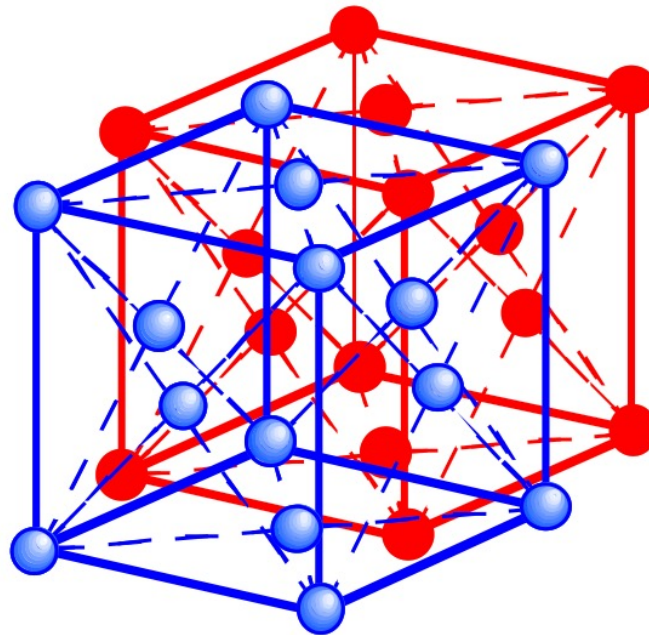
BCC



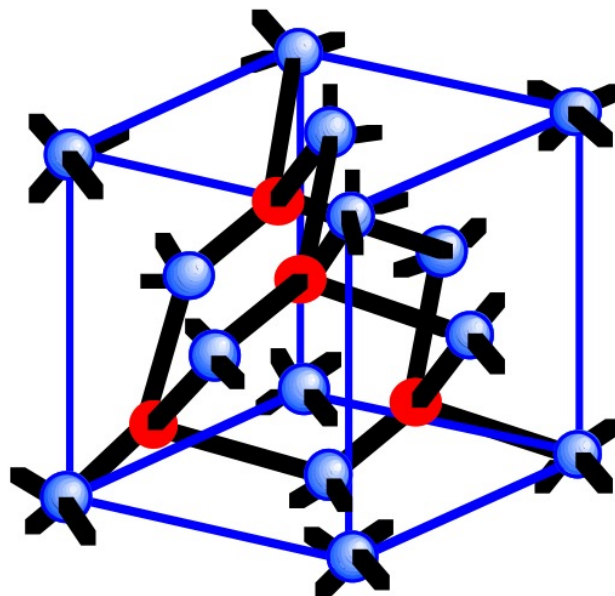
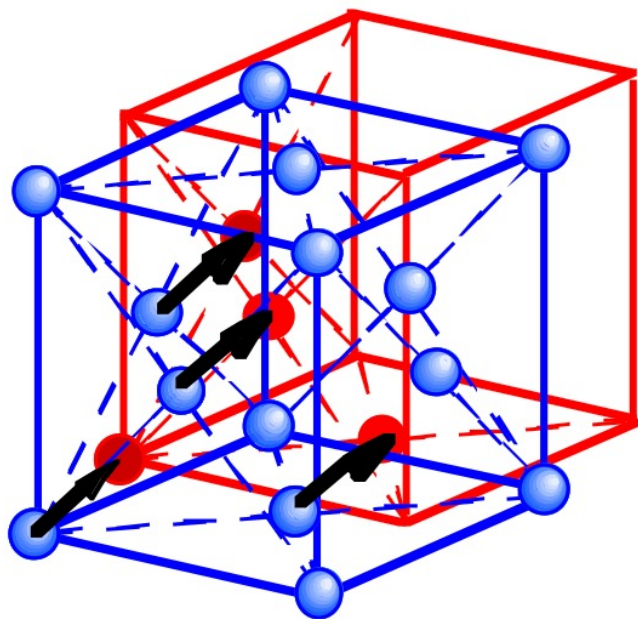
FCC



a)



b)



Visualization of Diamond lattice

Two inter-penetrating FCC lattices!

If both the lattice has the same atom, you have diamond!

Else you have the Zinc Blende