Semiconductor Fundamentals

Presented to

EE2187 class in Semester 1 2019/20

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Lecture 3

Course information

❖ Semiconductors Materials - Types of Solids, Space lattice, Atomic Bonding,

❖ Introduction to quantum theory, Schrodinger wave equation, Electron in free space, Infinite well, and step potentials, Allowed and forbidden bands

❖ Electrical conduction in solids, Density of states functions, Fermi-Dirac distribution in Equilibrium,

❖ Valence band and Energy band models of intrinsic and extrinsic Semiconductors. Degenerate and non degenerate doping

❖ Thermal equilibrium carrier concentration, charge neutrality

❖ Carrier transport – Mobility, drift, diffusion, Continuity equation.

Reference

Text Book:

1. Physics of Semiconductor Devices, *S. M. Sze*, John Wiley & Sons (1981).

2. Solid State Electronics by *Ben G. Streetman and Sanjay Banerjee*, Prentice Hall International, Inc.

3. Semiconductor Physics and Devices, Donald A. Neamen, Tata Mcgraw-Hill Publishing company Limited.

4. Advanced Semiconductor Fundamentals by Pirret

Reference Book:

1. Fundamentals of Solid-State Electronic Devices, *C. T. Sah*, Allied Publisher and World Scientific, 1991.

2. Complete Guide to Semiconductor Devices, *K. K. Ng*, McGraw Hill, 1995.

3. Solid state physics, Ashcroft & Mermins.

4. Introduction to Solid State Electronics, *E. F. Y. Waug*, North Holland, 1980.

Directions and planes in crystals: Miller indices

Procedures for indexing

1. Invert the intercept values- i.e. form [1/intercept]s.

2. Use an appropriate multiplier, convert 1/intercept set to the smallest possible set of whole numbers.

3. Enclosed the whole number set in curvilinear brackets.

Some Special facts

If the plane to be indexed has an intercept along the negative portion of coordinate axis then bar sign is placed over corresponding index number.

All planes which fold into other application of crystal-symmetry operation can not be distinguished from each other by any physical measurement said to equivalent can be represented with braces { }.

Miller indices Example
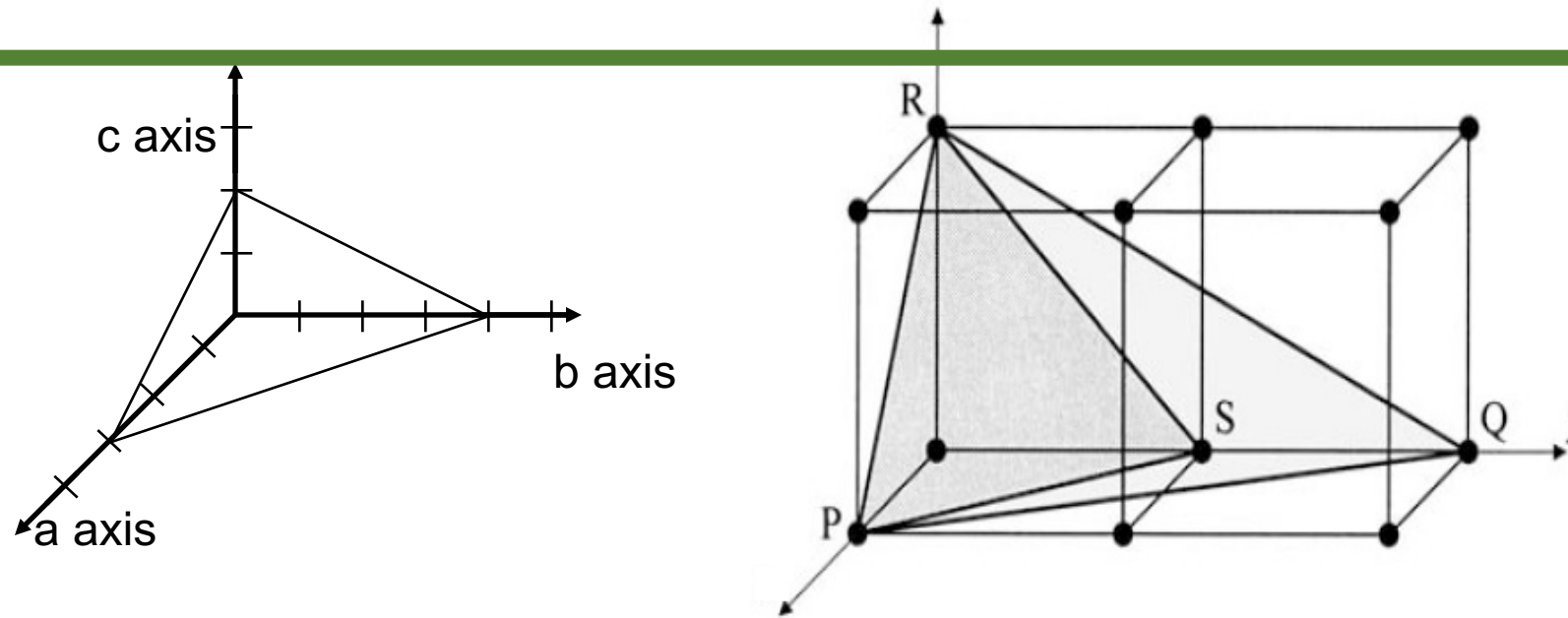
Inter-planar spacing $d_{hkl}=a/(h^2+k^2+l^2)^{1/2}$

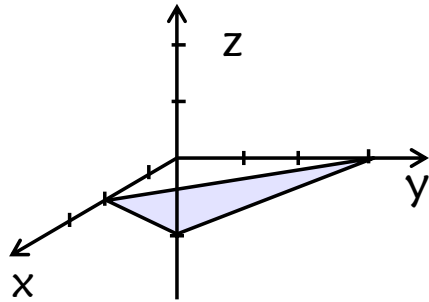And angle between two planes $(h_1 k_1 l_1)$ and $(h_2 k_2 l_2)$

$$\text{Cos}\theta = h_1 h_2 + k_1 k_2 + l_1 l_2 / \left(h_1^2+k_1^2+l_1^2\right)^{1/2}((h_2^2+k_2^2+l_2^2)^{1/2}$$

Some More example

If the plane to be indexed has an intercept along the negative portion of coordinate axis then bar sign is placed over corresponding index number.
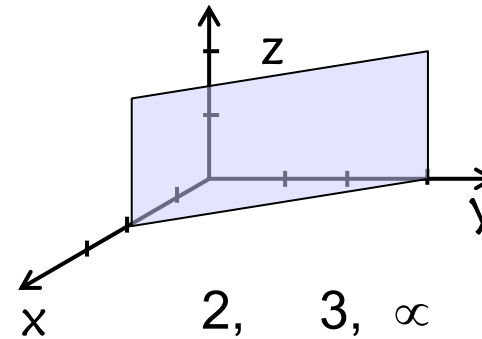
2, 3, -2

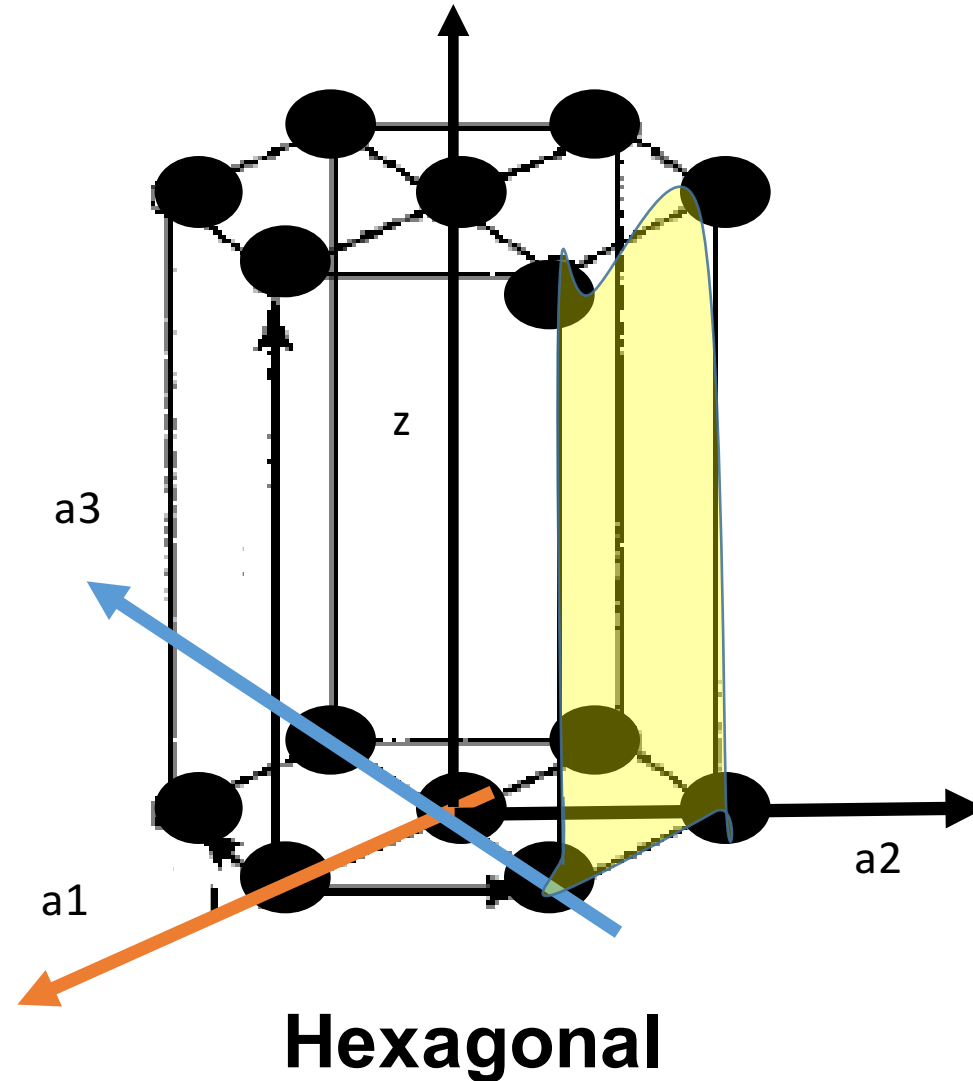1/2, 1/3, -1/2

3, 2, -3

$(3\,2\,\bar{3})$

2, 3, ∞

1/2, 1/3, 0

3, 2, 0
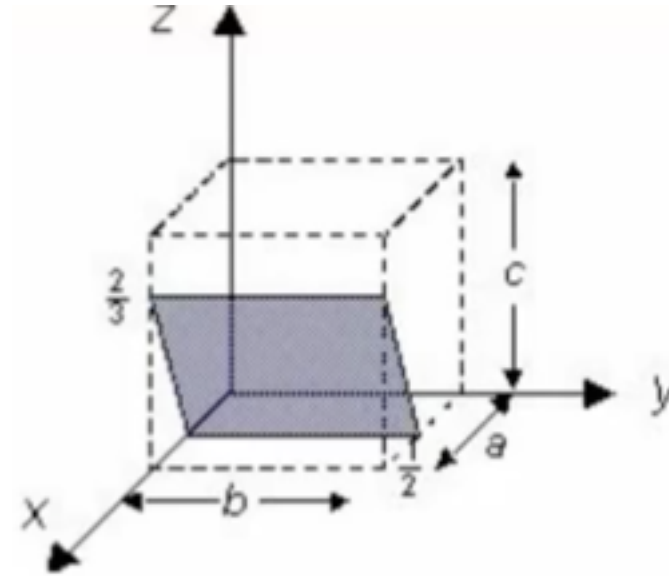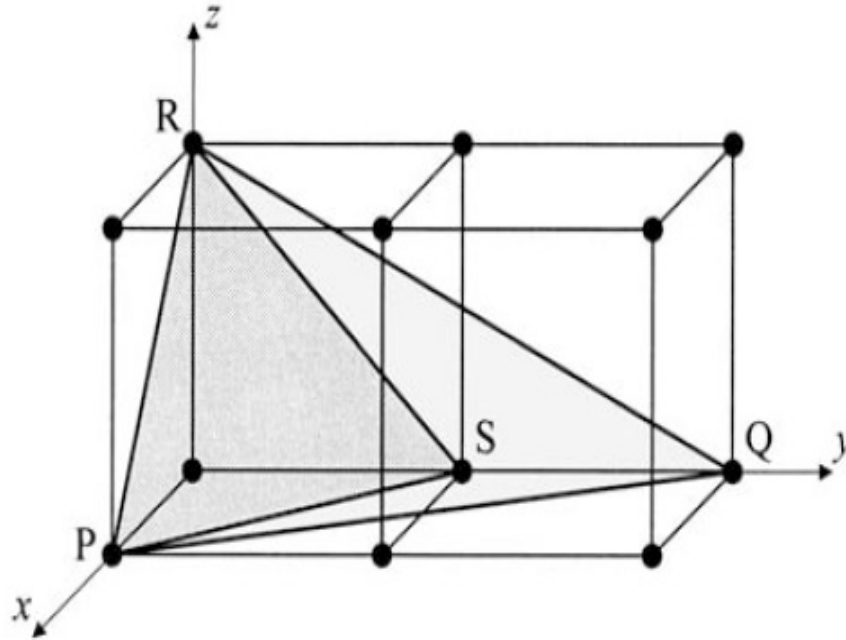
$(3\,2\,0)$

All planes which fold into other application of crystal-symmetry operation can not be distinguished from each other by any physical measurement said to equivalent can be represented with braces { }.

Miller indices for Hexagonal Lattice

Hexagonal

Miller Indices More….

Inter-planar spacing $d_{hkl}=a/(h^2+k^2+l^2)^{1/2}$

And angle between two planes $(h_1 k_1 l_1)$ and $(h_2 k_2 l_2)$

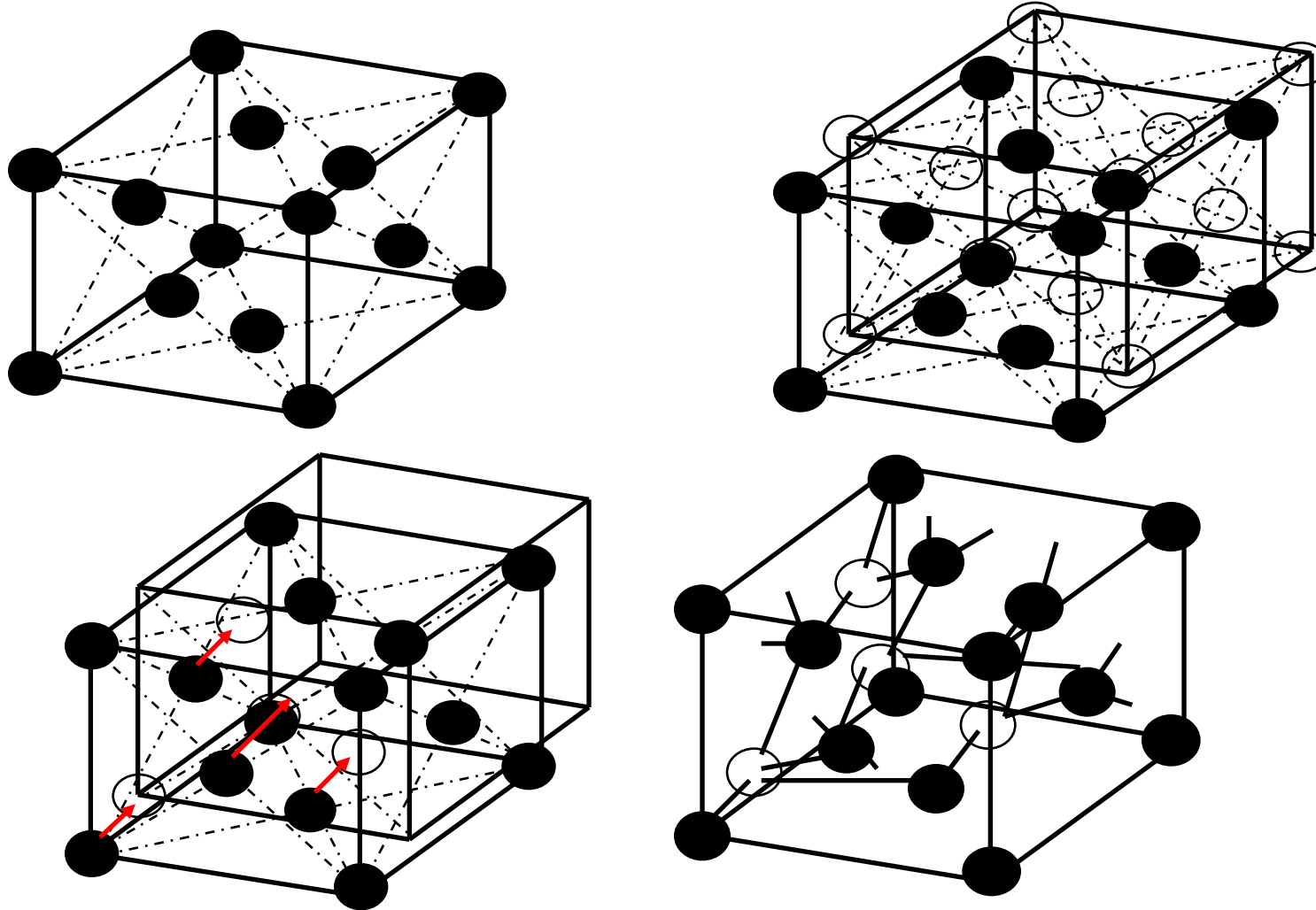$Cos\theta=h_1 h_2 + k_1 k_2 + l_1 l_2 / \left(h_1^2+k_1^2+l_1^2\right)^{1/2}((h_2^2+k_2^2+l_2^2)^{1/2}$

Notation Used in Crystallography

Notation	Designation
(hkl)	Plane
$\{hkl\}$	Equivalent plane
$[uvw]$	Direction
$\langle uvw \rangle$	Equivalent direction
$(hkil)$	Plane in hexagonal systems
$[uvtw]$	Direction in hexagonal systems

Si and Ge Crystal structure

Si and Ge have diamond cubic lattice structure

Two merged FCC lattice with offset from a/4 in all direction

Elemental and Compound Semiconductors

	II	III	IV	V	VI
	4 Be	5 B	6 C	7 N	8 O
	12 Mg	13 **Al**	14 **Si**	15 **P**	16 S
	30 **Zn**	31 **Ga**	32 Ge	33 **As**	34 **Se**
	48 Cd	49 In	50 Sn	51 Sb	52 Te
	80 Hg	81 Tl	82 Pb	83 Bi	84 Po

Elemental(e.g., Si, C)

III-V: InP, GaAs, (InxGa 1-x)(AsyP 1-y)
II-VI: CdTe
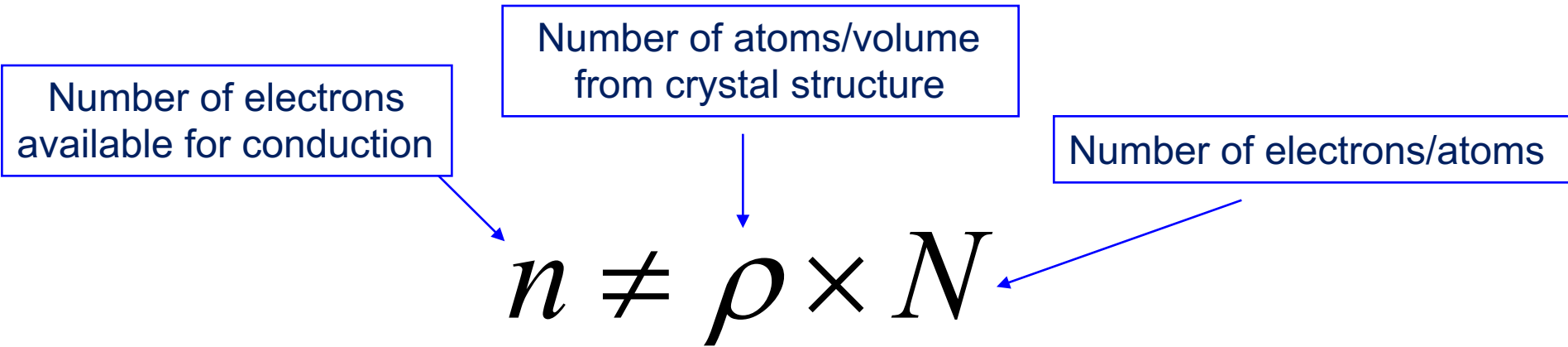IV-VI: PbS

Not all combinations possible:

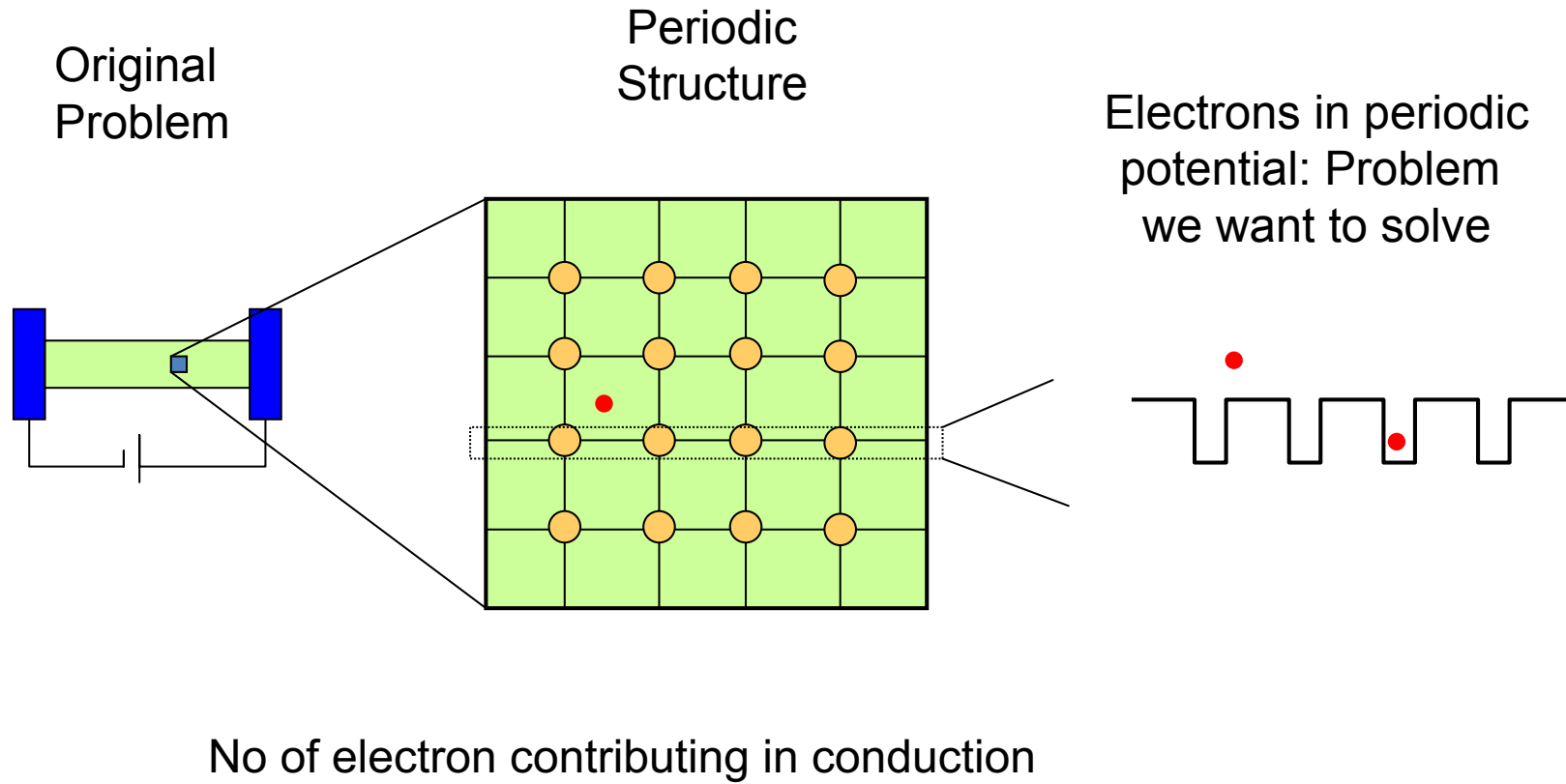Lattice mismatch, room temp. instability, etc. are concerns

Need of Quantum Mechanics

Number of atoms/volume
from crystal structure

Number of electrons
available for conduction

Number of electrons/atoms

$$n \neq \rho \times N$$

All electrons may be indistinguishable ,
but they appear do not behave identically!

Cont.

Original
Problem

Periodic
Structure

Electrons in periodic
potential: Problem
we want to solve

No of electron contributing in conduction

Challenge to Classical Physics

- Blackbody Radiation

Amount of energy per unit Surface area per unit time per unit solid angle per unit wavelength emitted at a frequency v.

Rayleigh and Jeans:
$$u(v, T) = \frac{8\pi v^2}{C^3} k_b T$$

A *continuous* spectrum of vibrational mode frequencies
ν = ω /2π = c/λ

Weins :
$$u(v, T) = \frac{2\pi v^3}{C^3} e^{(-hv)/kbT}$$

Plank fitting formula
$$u(v, T) = \frac{8\pi v2}{C^3} \frac{hv}{e^{(-hv)/kbT} - 1}$$

- Plank hypothesis

The atoms vibrating at a frequency *n* in a material could only radiate or absorb energy in discrete or *quantized* packages proportional to the frequency

Interpretation

$$\lambda$$

$$f$$

$$=$$

$$u(v,T) = \frac{8\pi v2}{c^3} \frac{hv}{e^{(-hv)/kbT} - 1}$$

nos. of modes

Energy of mode

Occupation Probability

EM emission occurs in discrete quanta of

$$E = hf \qquad n=1,2, \ldots\ldots. N$$

Photoelectric Effect
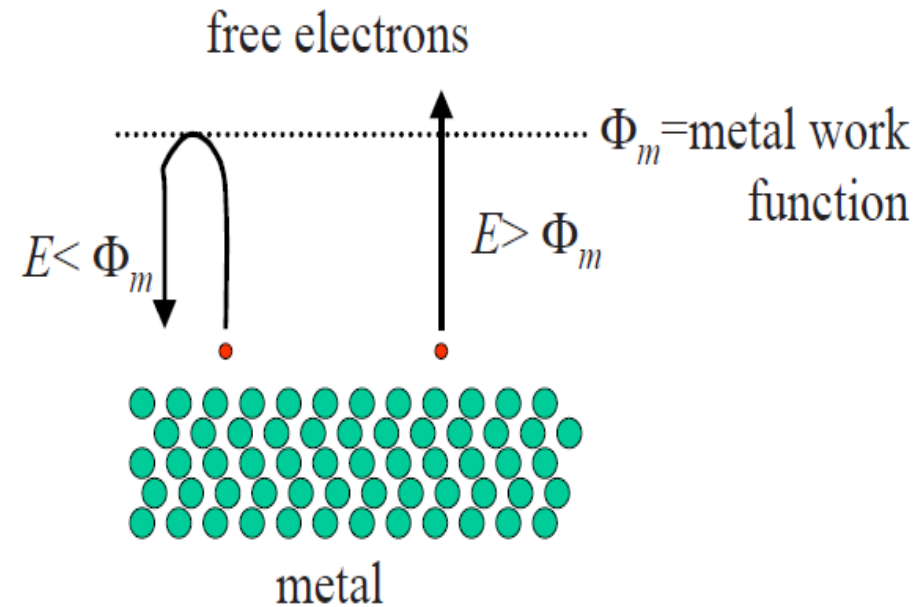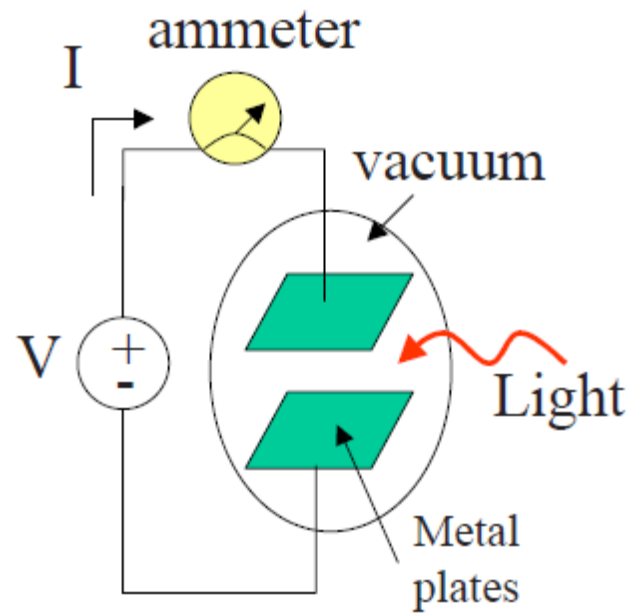
Bohr Model:

Electron in atom are restricted to to certain well defined orbit

Assume that angular momentum is quantized:

$$r_n = \frac{4\pi\varepsilon_0(n\hbar)^2}{m_0 q^2}$$

$$E_n = -\frac{m_0 q^4}{2(4\pi\varepsilon_0 n\hbar)^2} = -\frac{13.6}{n^2} eV$$

Wave Particle Duality

Louis de Broglie conjectured that, since the electromagnetic radiation had particle-like properties, particles (e.g. electrons) should have wave-like properties as well. This was called the wave-particle duality.

He postulated that a particle with a momentum p can be viewed as a wave with a wavelength given by

$$\lambda = \frac{h}{P}$$

Substantiated by Davission and Germer Experiment
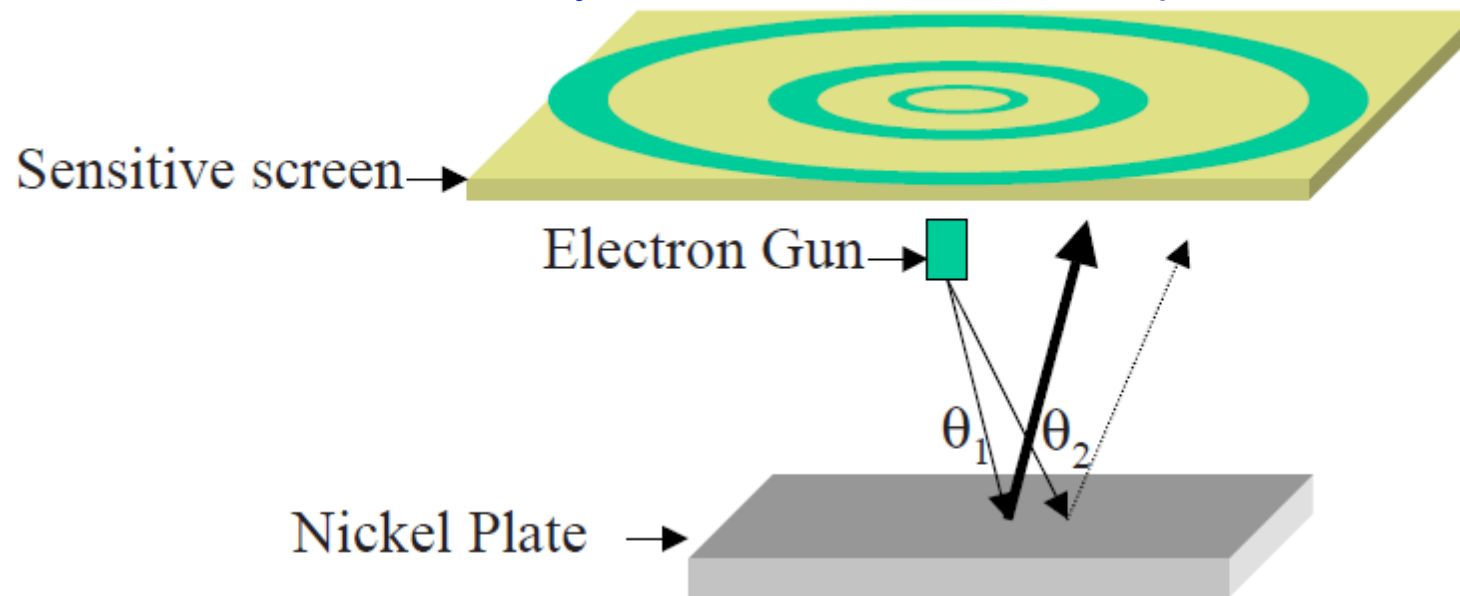
Basic formalism of Quantum Mechanics

(1) **The state of a system can be described by a definite (in general complex) mathematical function $\Psi(x, y, z, t)$, called the wavefunction of the system, which depends on the set of coordinates of the quantum system and time t.**

(2) **The wavefunction is a solution of the time dependent Schrödinger equation (SE)**

$$i\hbar \frac{\partial \psi(x,y,z,t)}{\partial t} = H\,\psi(x,y,z,t)$$

Operator H is called the "Hamiltonian" total energy of the system in the form of mathematical operators.

The sum of the kinetic and potential energy operator which make up the Hamiltonian are given by

$$H = -\frac{\hbar^2}{2m}\nabla^2 + U(x,y,z,t)$$

.

Kinetic energy of the particle and Is a differential operator which acts on the wavefunction.,

The potential energy, keeps its classical form.

One can think of the action of H on the wavefunction to be one of "measurement" of the total energy of the system

Cont.

(3). Ψ and derivative of Ψ * must be finite, single valued, for all value of x,y,z and t.

(4). The probability that a physical measurement will result in values of the system coordinates in a volume around at a time *t* is given by Ψ (xyz *t*)² *dxdydz*. The sum of the probabilities of all possible values of spatial coordinates of the system must be, by definition, equal to unity

$$\iiint_{-\infty}^{\infty} \Psi\ (x\ y\ z\ t)\ \Psi*(x\ y\ z\ t)\ dxdydz=1$$

This equation is the normalization condition for the wavefunction

(5). One can associate with a unique mathematical operator with each dynamic system variable such as position and momentum. The value or more precisely, the expectation value is obtained by operating on the wavefunction.

$$<\alpha>= \iiint_{-\infty}^{\infty} \Psi\ (x\ y\ z\ t)\ aop\ \Psi*(x\ y\ z\ t)\ dxdydz$$