Module 2 Unit 1
Semiconductors

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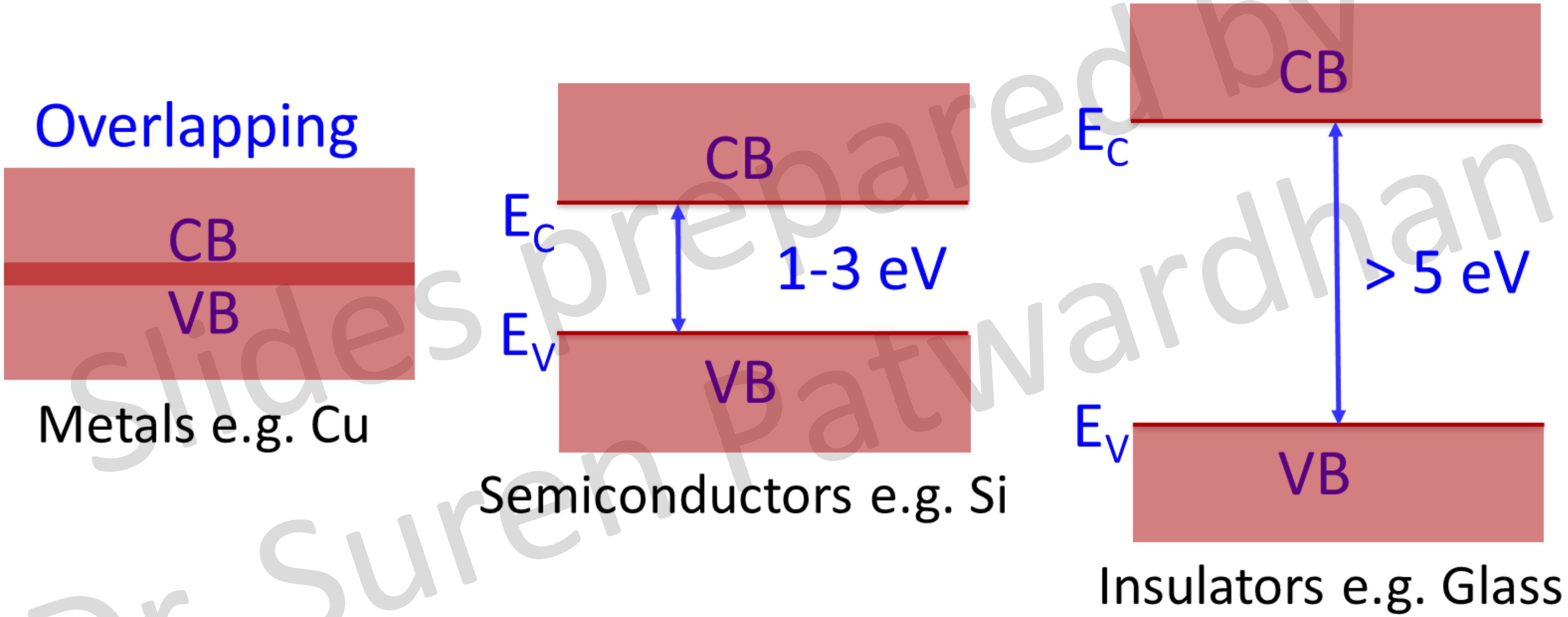
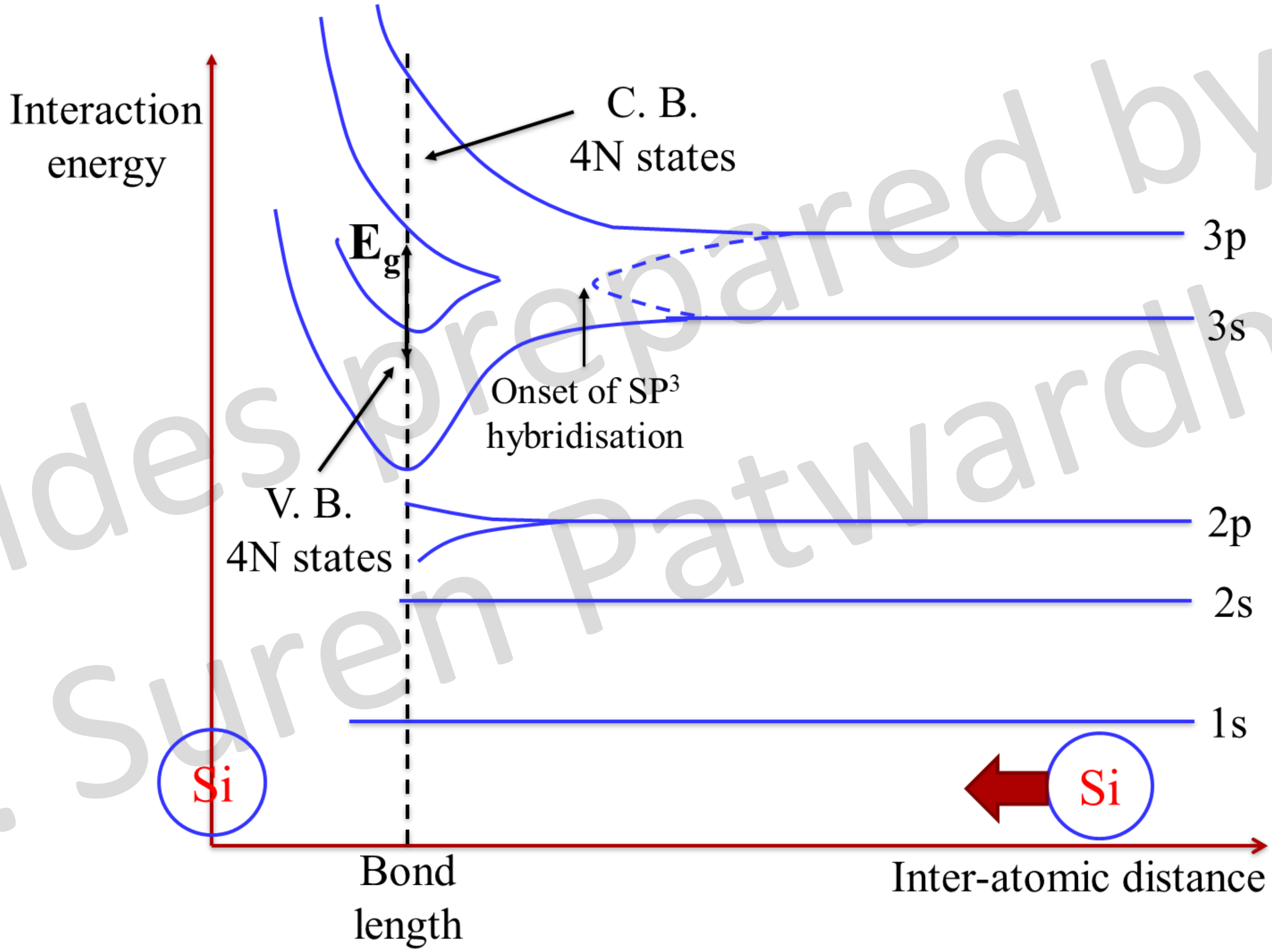
Semiconductors: Outline

0. Formation of energy bands in solids
1. Intrinsic and extrinsic semiconductors
    a) Doping, creation of additional charge carriers
    b) Energy band diagrams
    c) Charge carrier concentration and its temperature dependence
    d) Conductivity, resistivity and its temperature dependence
2. Important concepts in semiconductor
    a) Concept of holes
    b) concept of effective mass
    c) E-k diagrams
    d) Direct and indirect semiconductors
3. Charge carrier transport in semiconductors:
    a) Carrier drift, mobility and drift current
    b) Carrier diffusion, diffusivity and diffusion current
4. Fermi-Dirac statistics
    a) Fermi level – concept
    b) Temperature dependence Fermi-Dirac function
    c) Carrier concentration formulae
    d) Temperature dependence of Fermi level
    e) Doping density dependence of Fermi level

Classification of Solids

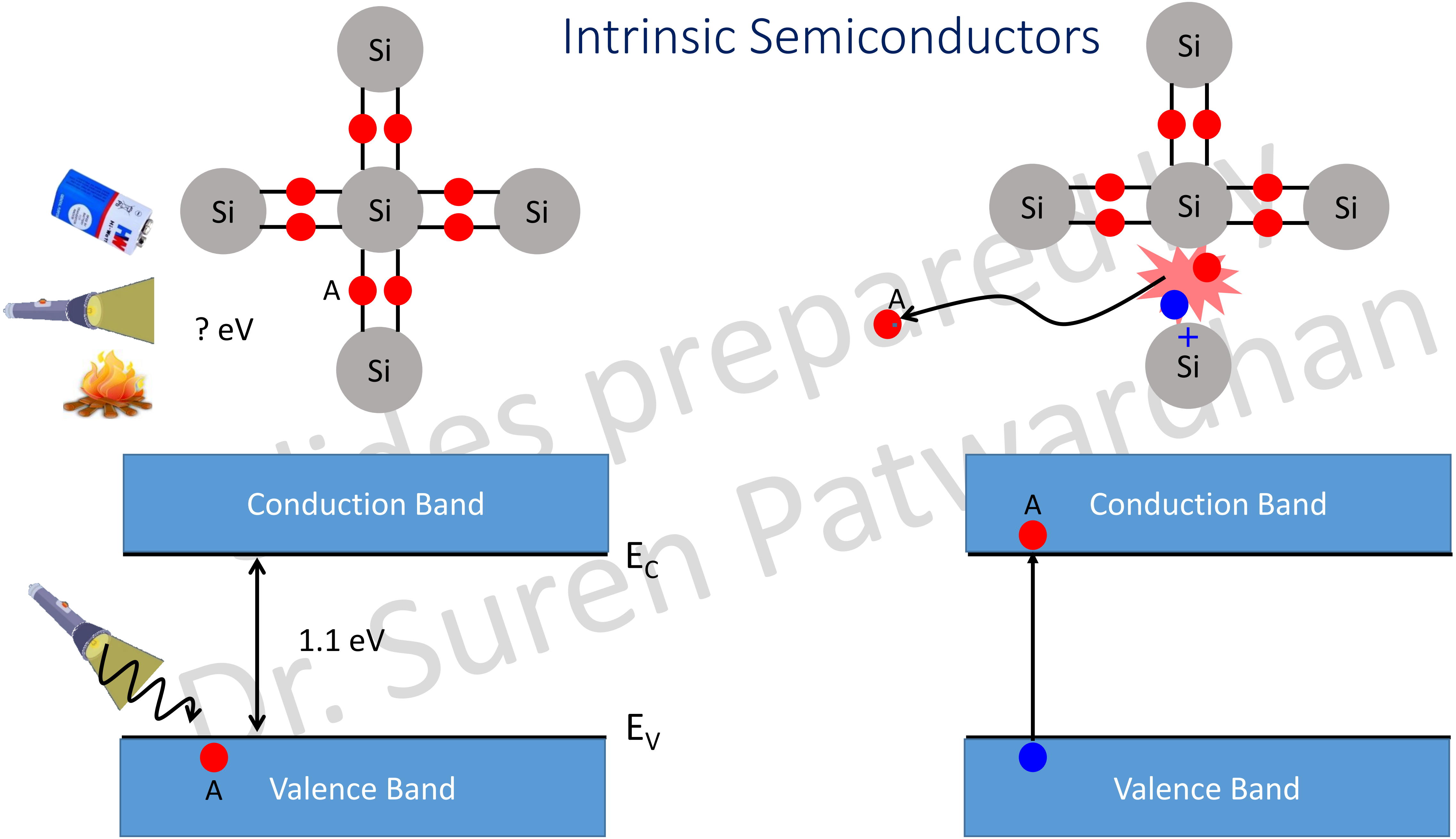


Formation of Energy Bands

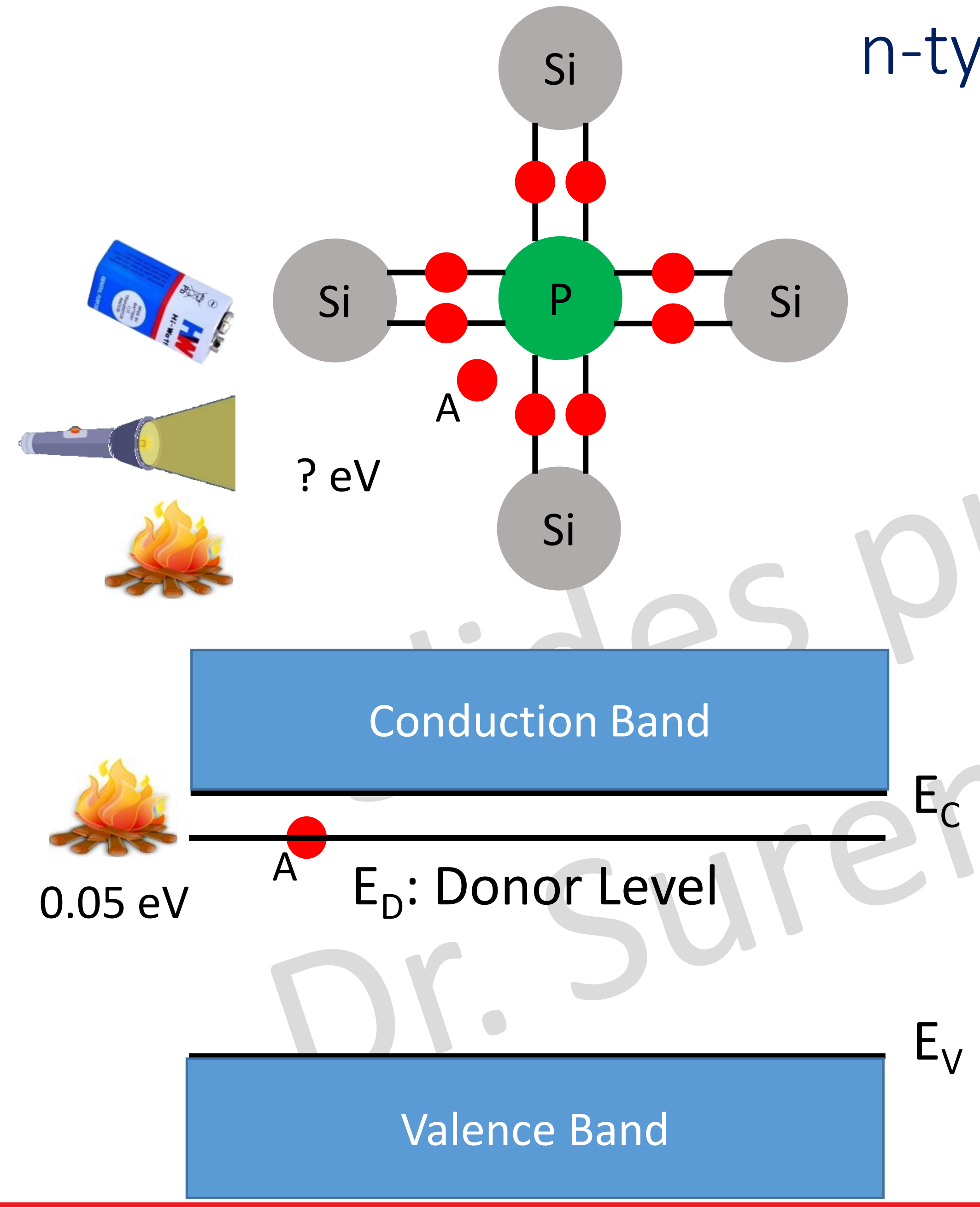


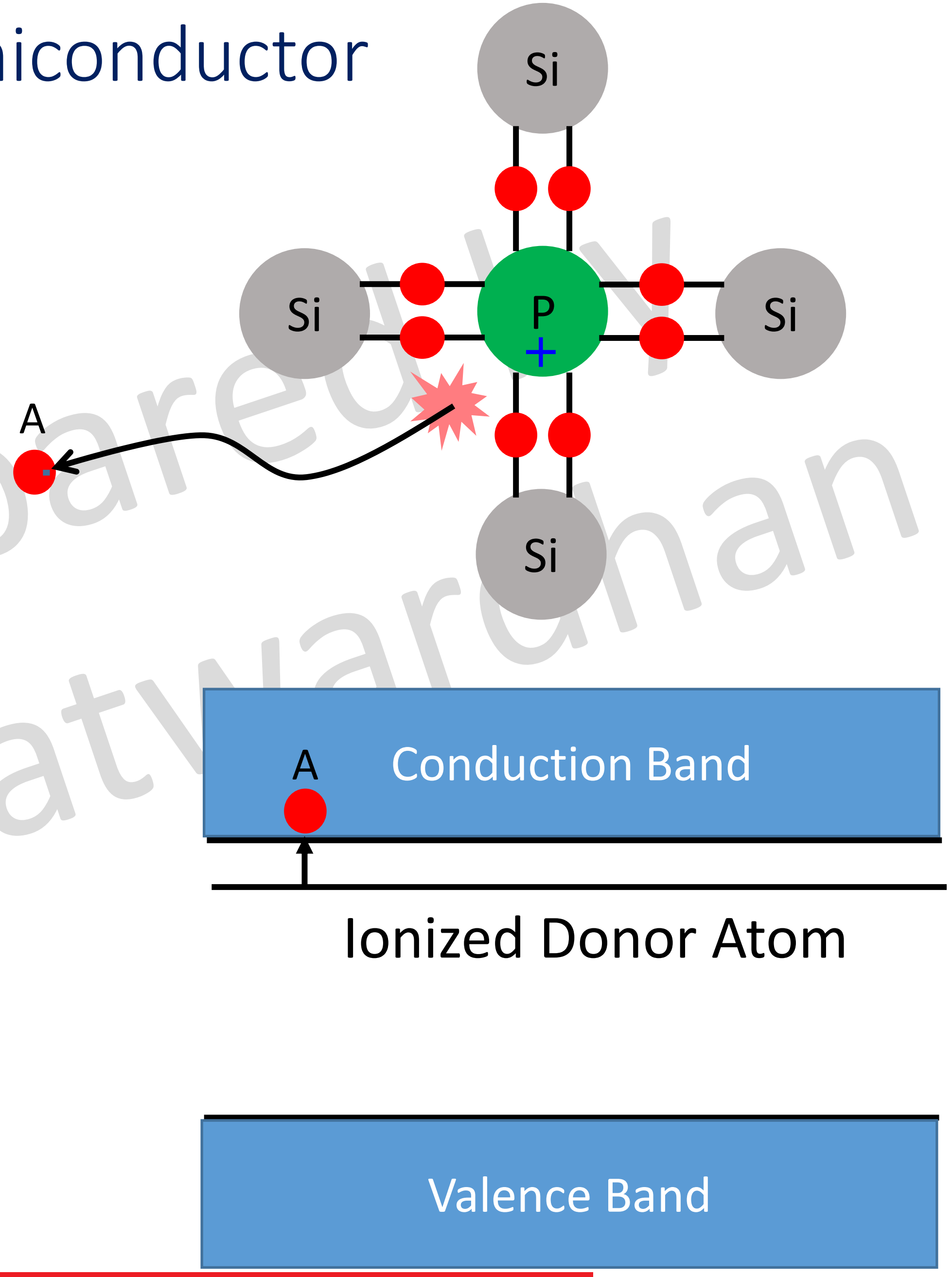
Intrinsic and Extrinsic Semiconductors

Intrinsic Semiconductors

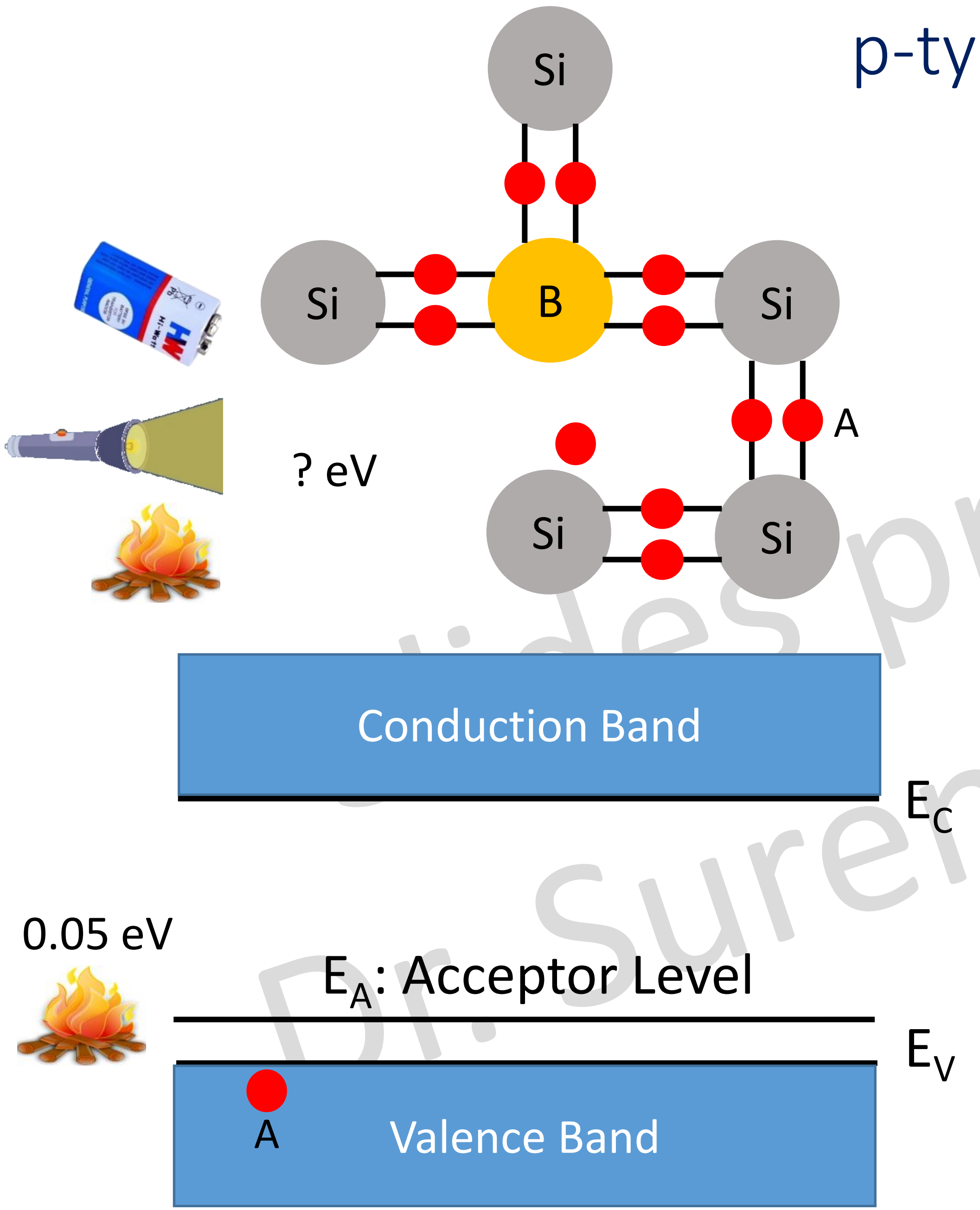


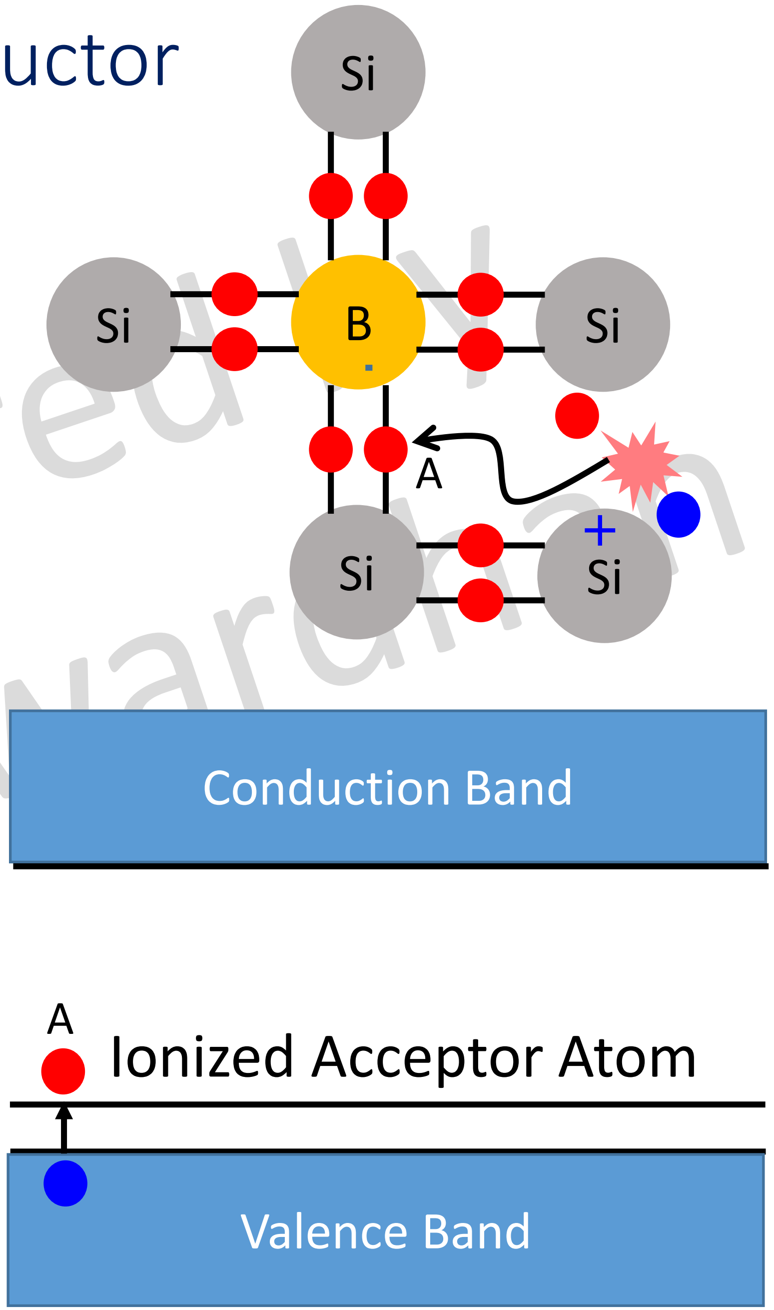
n-type Semiconductor





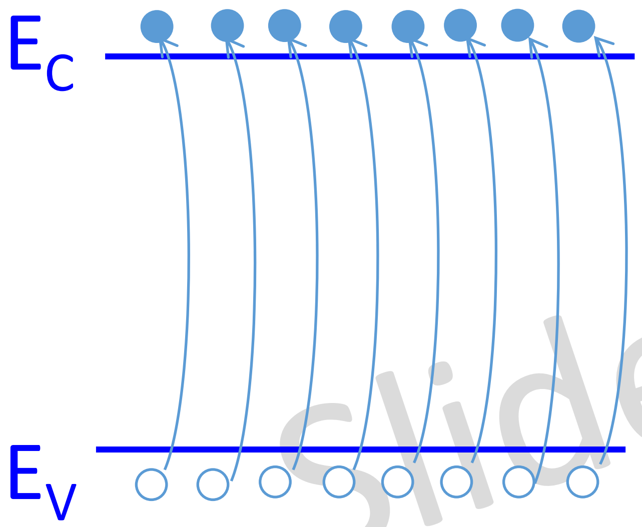
p-type Semiconductor



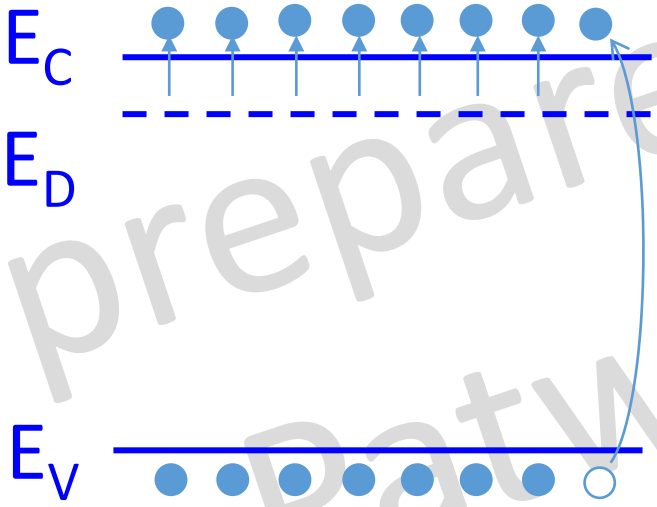


Generation of Charge Carriers in Semiconductors

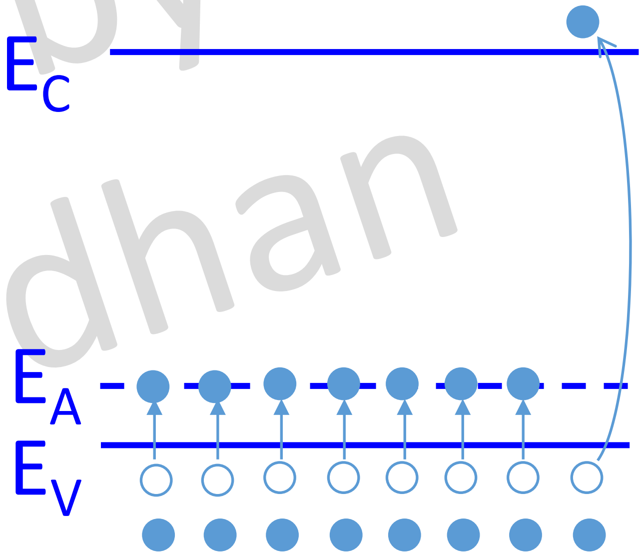
Intrinsic



n-type



p-type



Intrinsic carrier concentration:

$$n = p = n_i = \sqrt{N_C N_V}\exp\left(-\frac{E_g}{2kT}\right)$$

Extrinsic carrier concentration:

$n \approx N_D$ (majority charge carriers)

$p \approx \frac{n_i^2}{N_D}$ (minority charge carriers)

Extrinsic carrier concentration:

$p \approx N_A$ (majority charge carriers)

$n \approx \frac{n_i^2}{N_A}$ (minority charge carriers)

Conductivity and Resistivity

μ: mobility
(unit: m^2/V-sec)

The term $qn\mu_n$ or $qp\mu_p$ is defined as *conductivity*. Thus,

For n-type material $\sigma_n = qn\mu_n$

For p-type material $\sigma_p = qp\mu_p$

Reciprocal of conductivity is the *resistivity*. Thus,

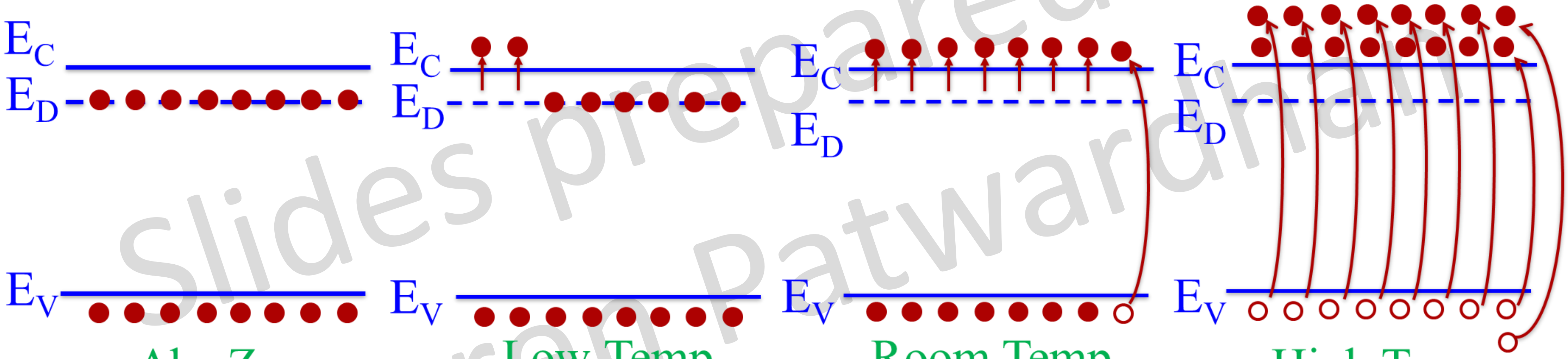
$$\rho_n = \frac{1}{qn\mu_n}$$ for n-type

$$\rho_p = \frac{1}{qp\mu_p}$$ for p-type

$$\rho_i = \frac{1}{qn_i(\mu_n+\mu_p)}$$ for intrinsic

Charge Carrier generation: Temperature dependence

n-type semiconductor



Freeze-out regime — Abs Zero (0 K)

$n = 0$

Ionization regime — Low Temp (10-100 K)

$n = N_D^+$

$N_D^+ << N_D$

$n_i \rightarrow 0$

Extrinsic regime — Room Temp (300 K)

$n \approx N_D$

$N_D^+ = N_D$

$n_i << N_D$

Intrinsic regime — High Temp ($\geq$ 500 K)

$n \approx n_i$

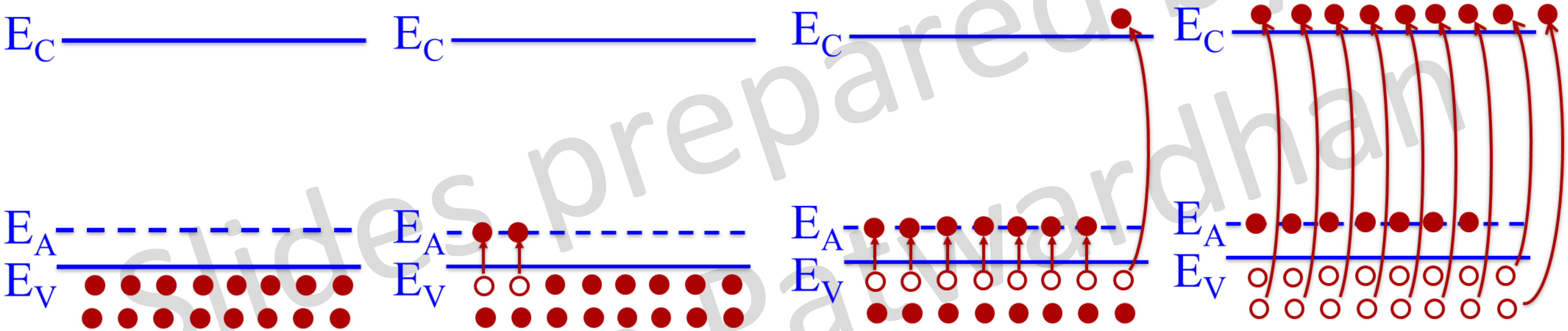
$N_D^+ = N_D$

$n_i >> N_D$

Charge Carrier generation: Temperature dependence

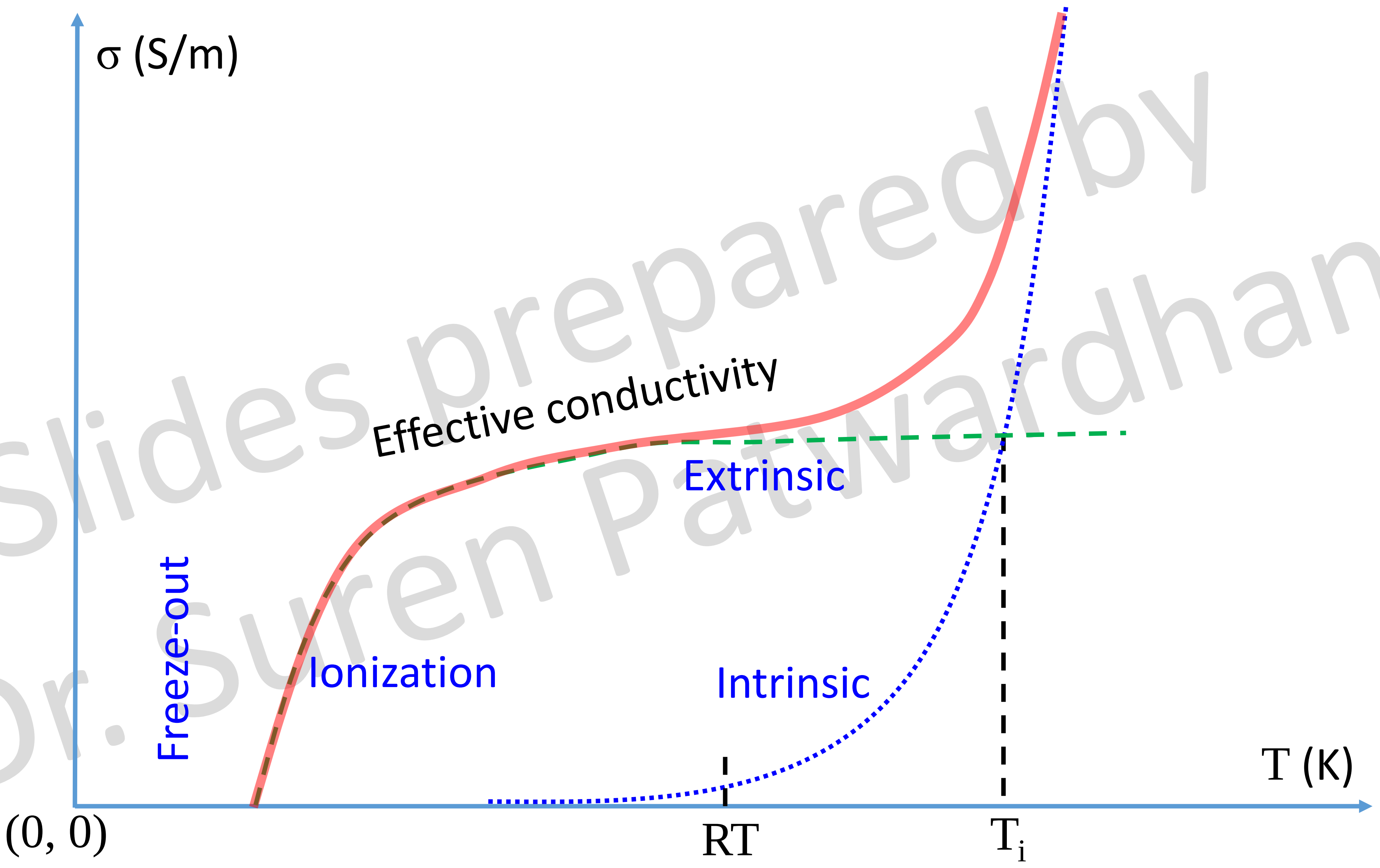
p-type semiconductor

Freeze-out regime	Ionization regime	Extrinsic regime	Intrinsic regime



Abs Zero (0 K)	Low Temp (10-100 K)	Room Temp (300 K)	High Temp (> 500 K)
$p = 0$	$p = N_A^-$ $N_A^- << N_A$ $n_i \rightarrow 0$	$p \approx N_A$ $N_A^- = N_A$ $n_i << N_A$	$p \approx n_i$ $N_A^- = N_A$ $n_i >> N_A$

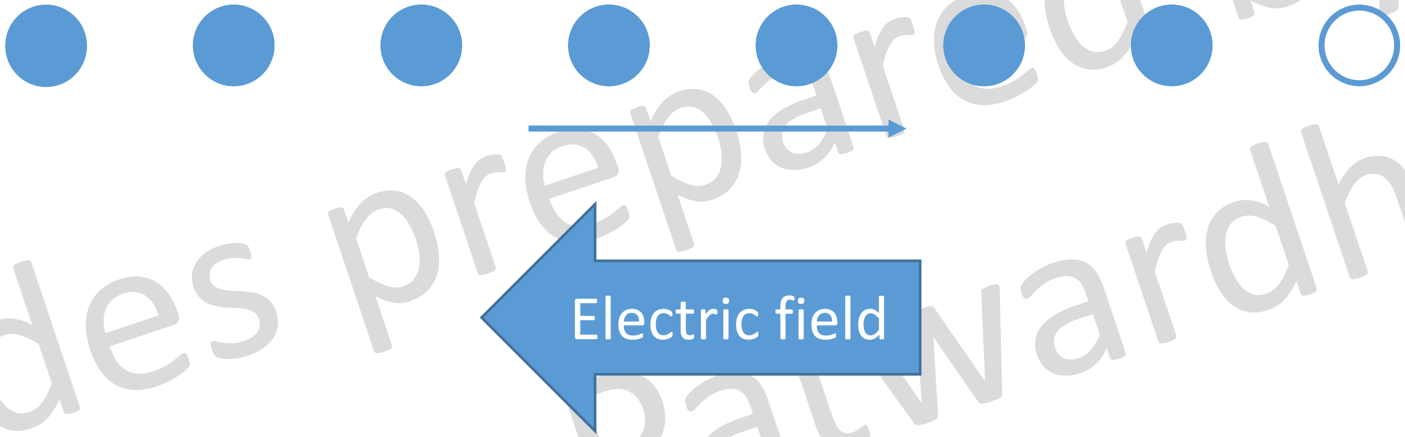
Temperature dependence of conductivity



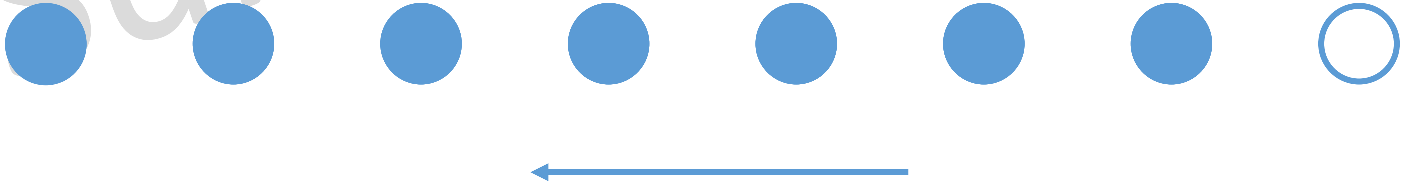
Important Concepts in Semiconductors

Concept of Holes

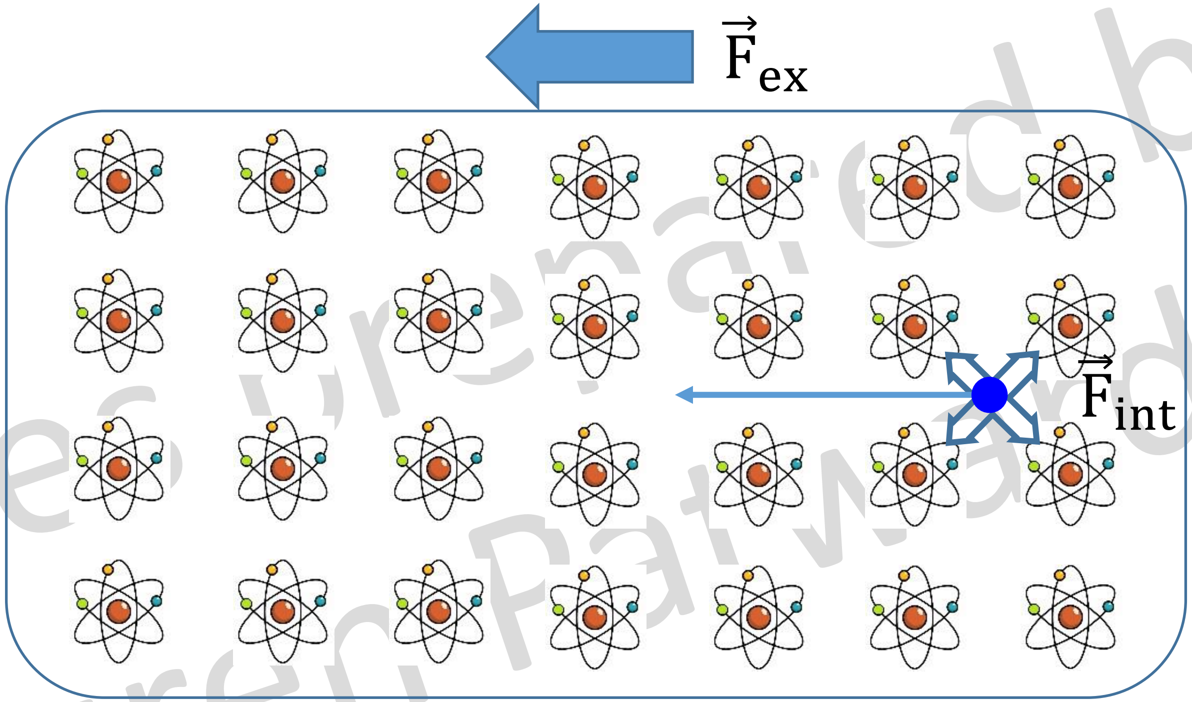
Movements of valence electrons



Apparent movement of a hole

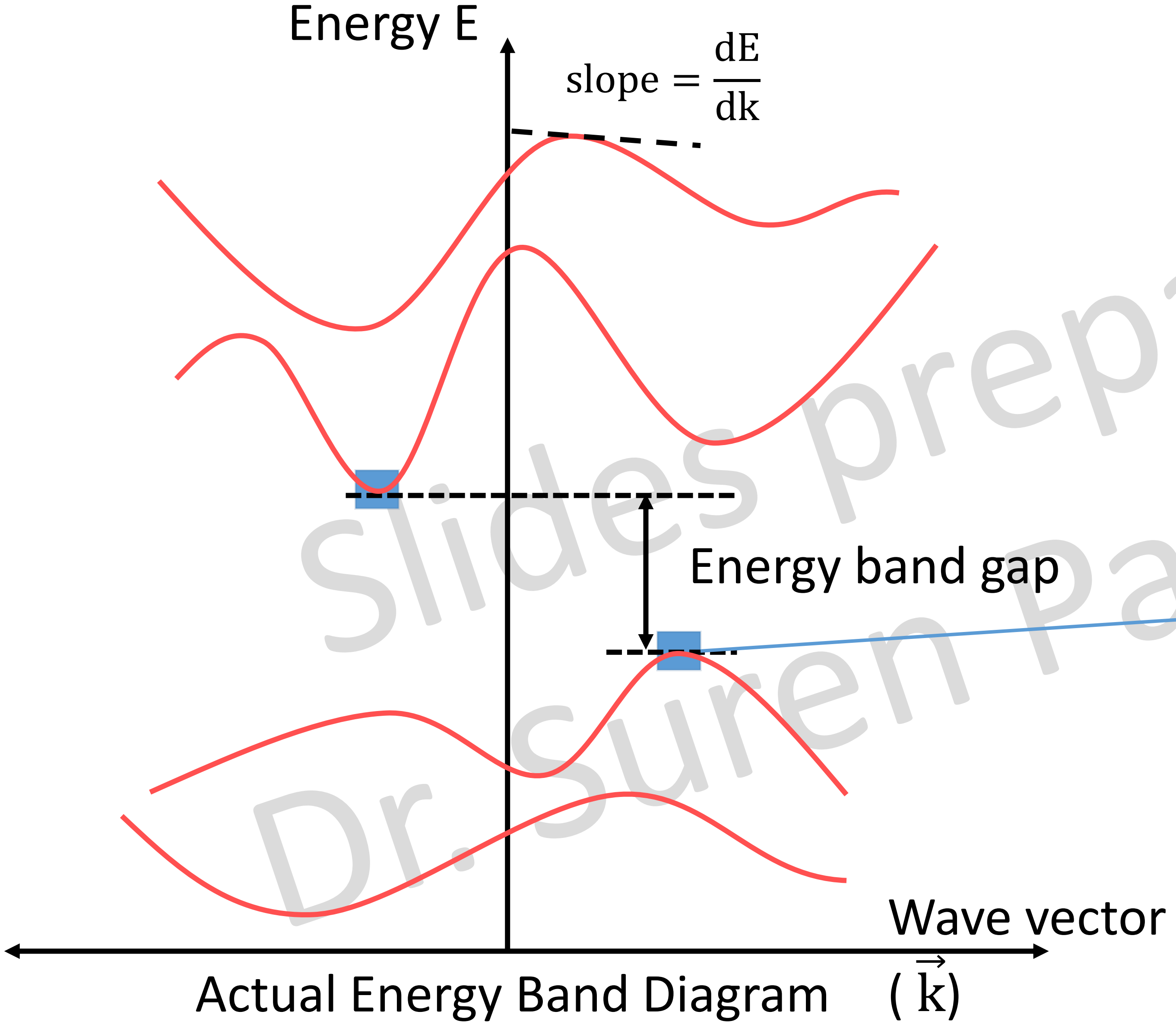


Concept of Effective Mass

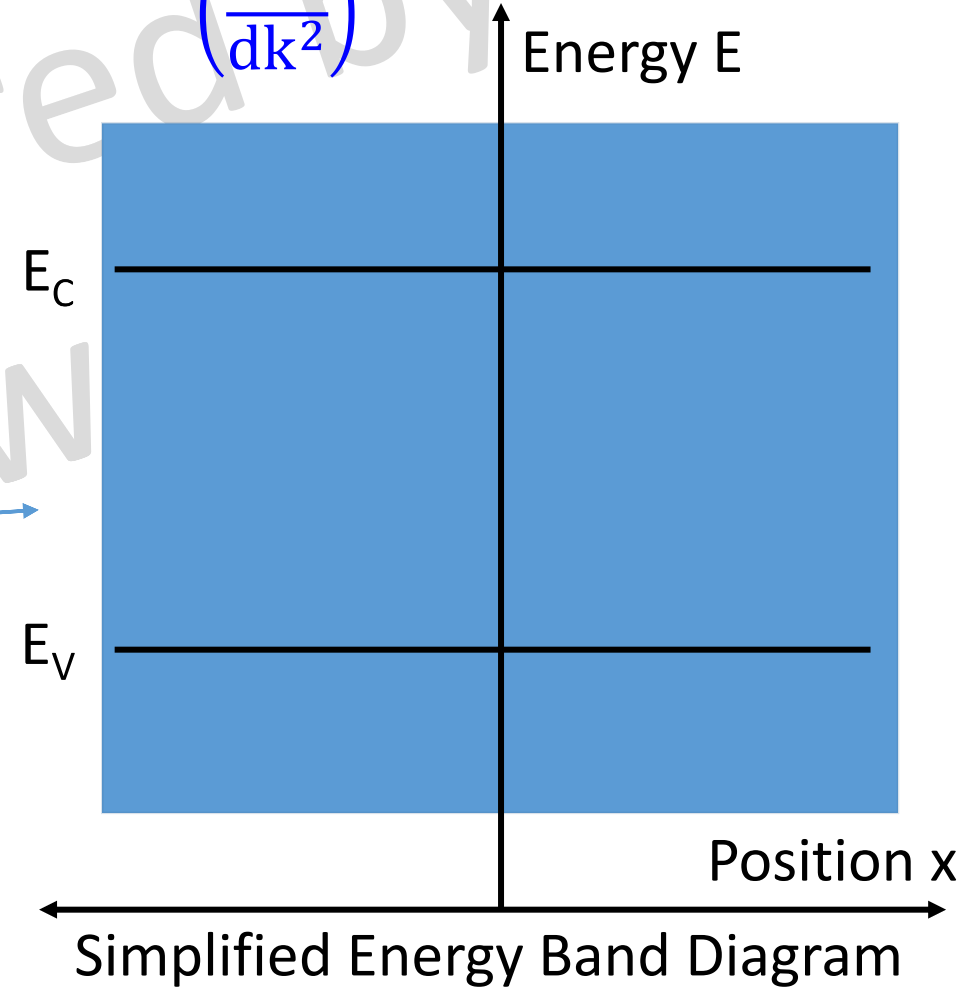


$$\vec{F} = \vec{F}_{ex} + \vec{F}_{int}$$

Concept of Effective mass: E-k Diagrams



$$m^* = \frac{\hbar^2}{\left(\frac{d^2E}{dk^2}\right)}$$

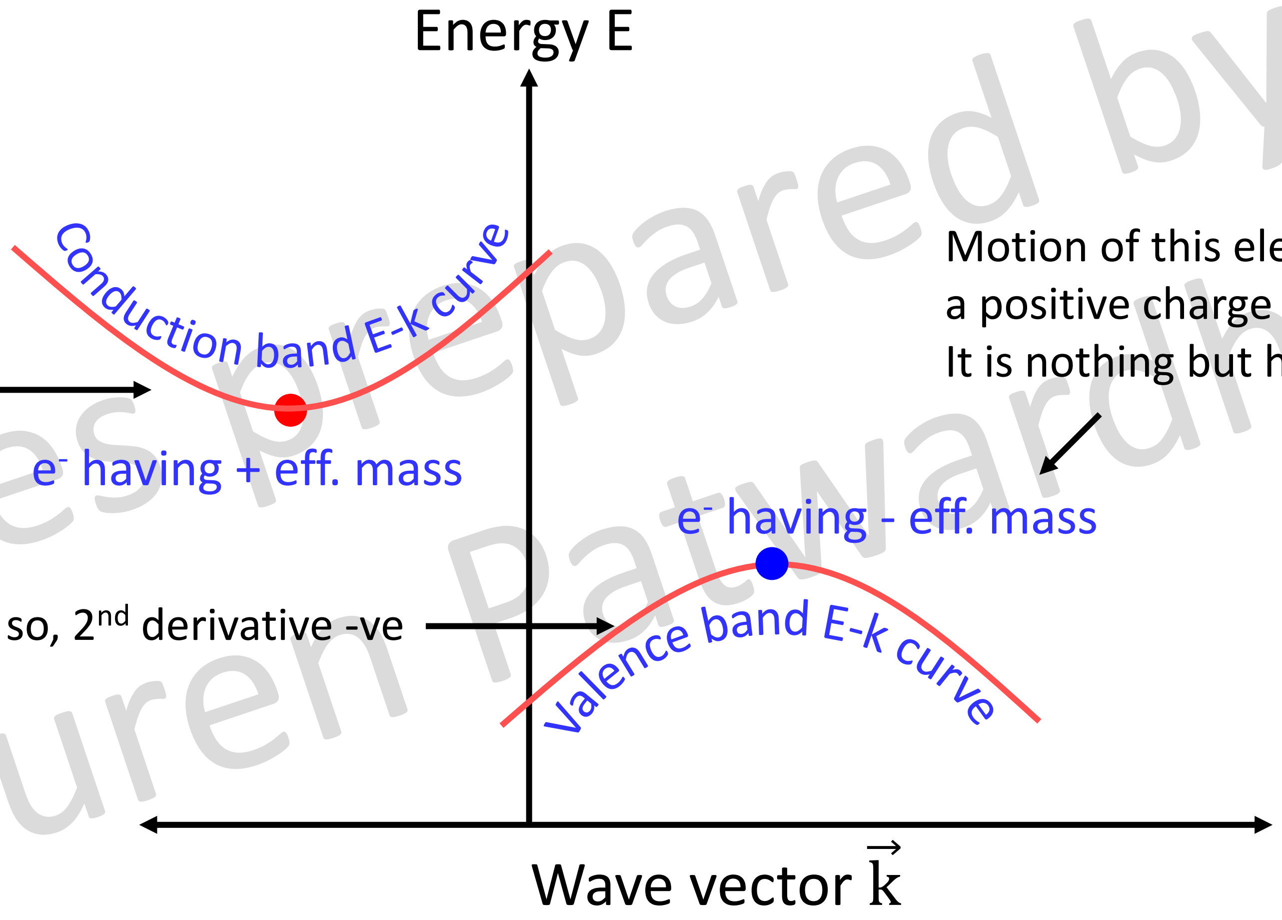


Concept of holes Revisited

$$m^* = \frac{\hbar^2}{\left(\frac{d^2E}{dk^2}\right)}$$

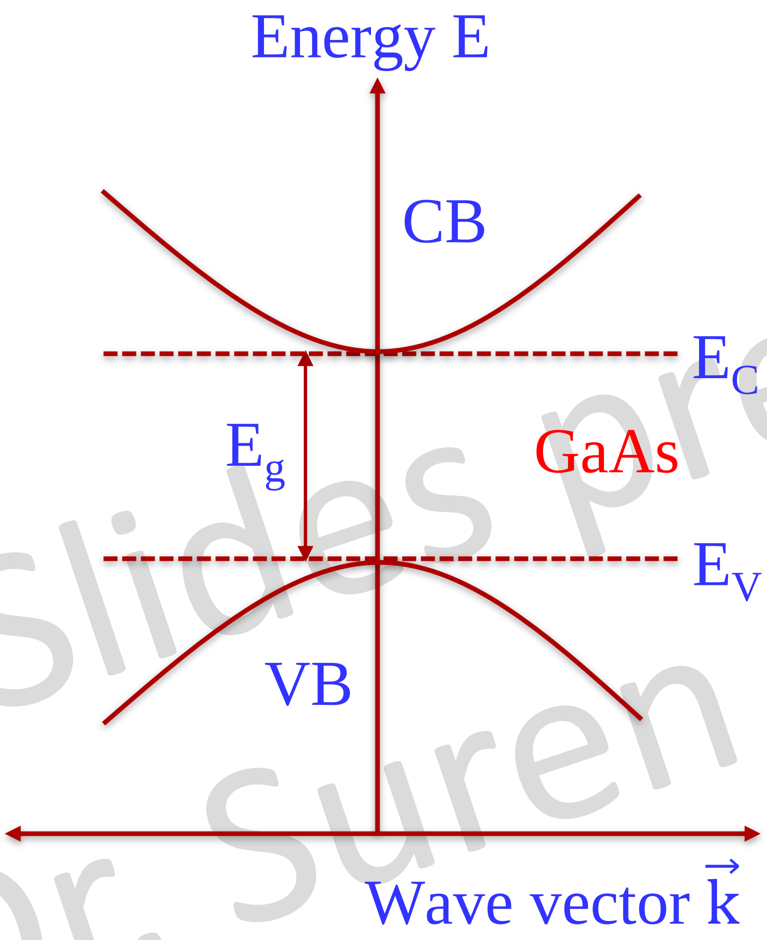
Has minima, 2^{nd} derivative +ve

But this has maxima so, 2^{nd} derivative -ve

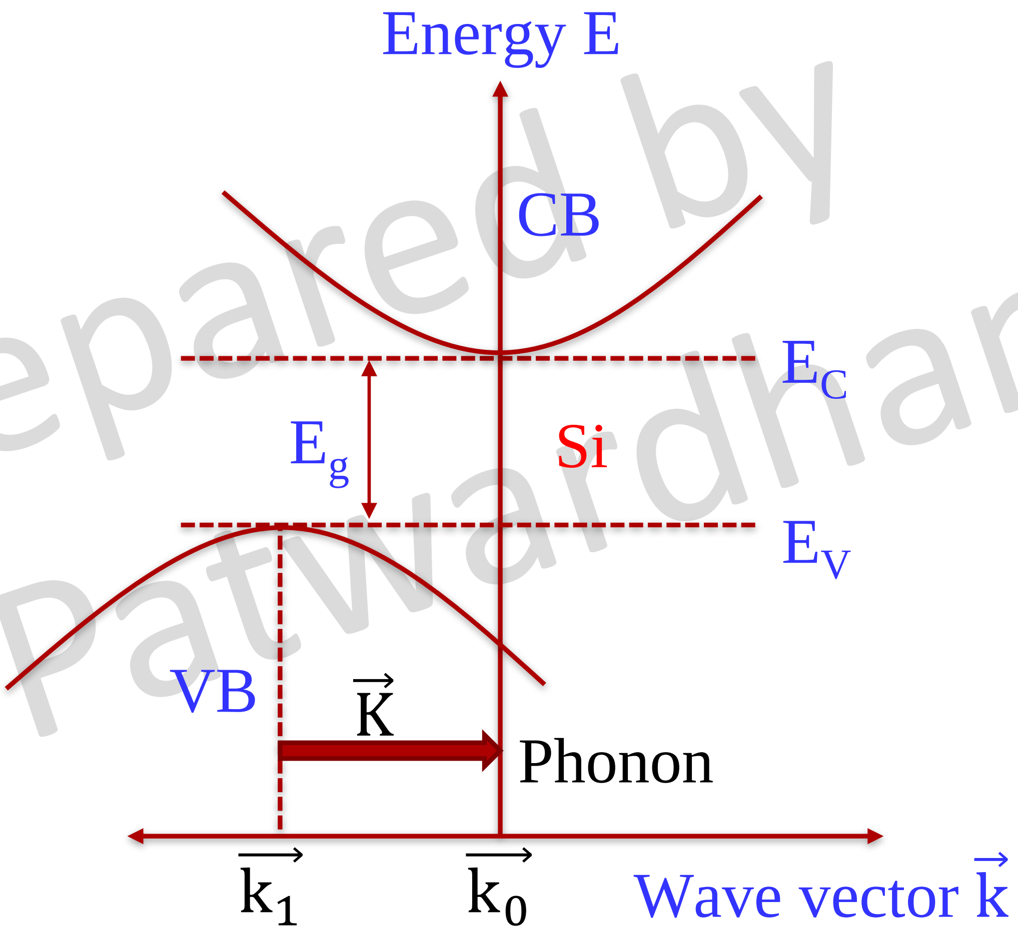


Motion of this electron is analogous to a positive charge having positive mass
It is nothing but hole

Direct and Indirect Bandgap Semiconductors



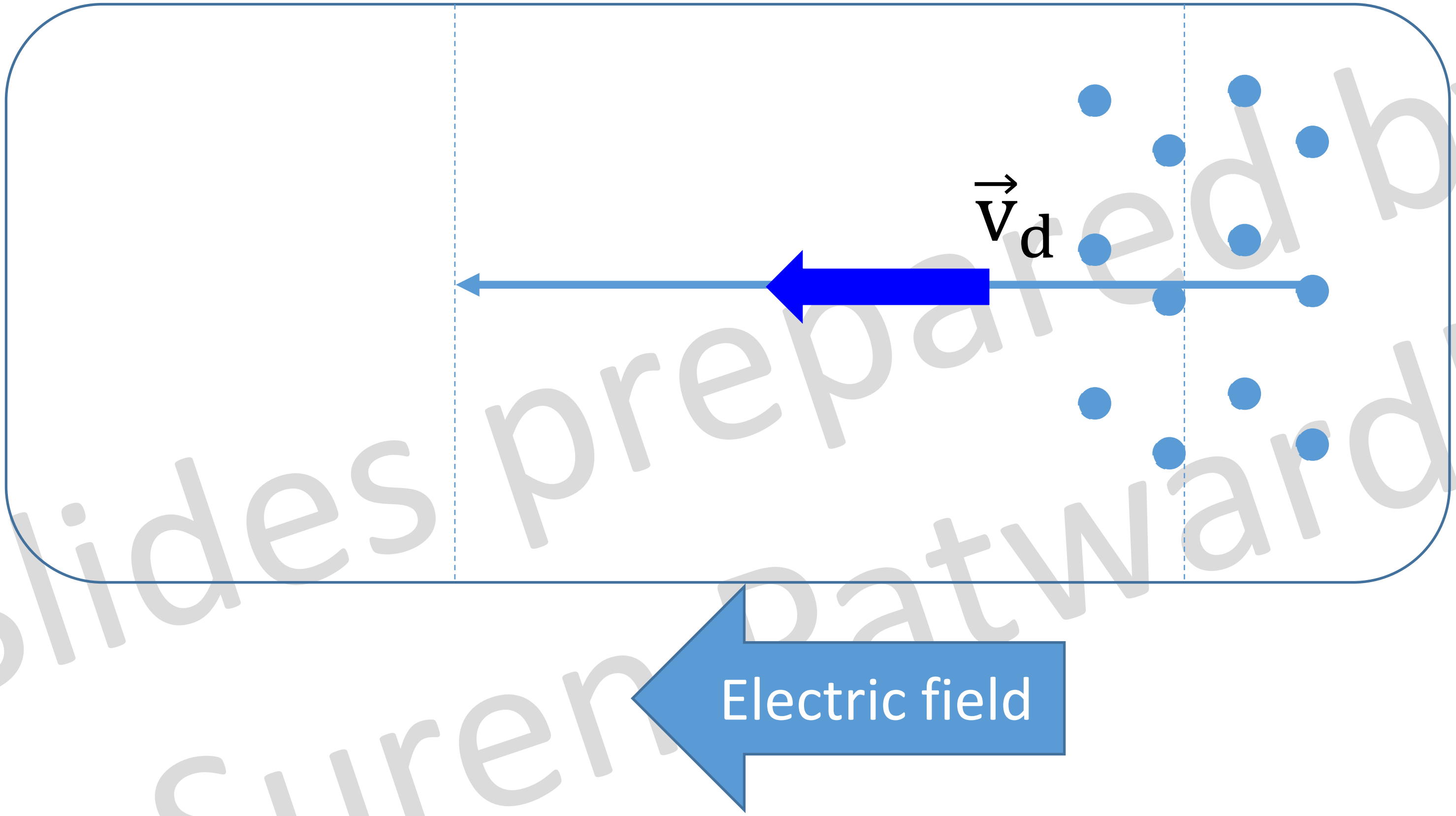
Direct band gap semiconductor



Indirect band gap semiconductor

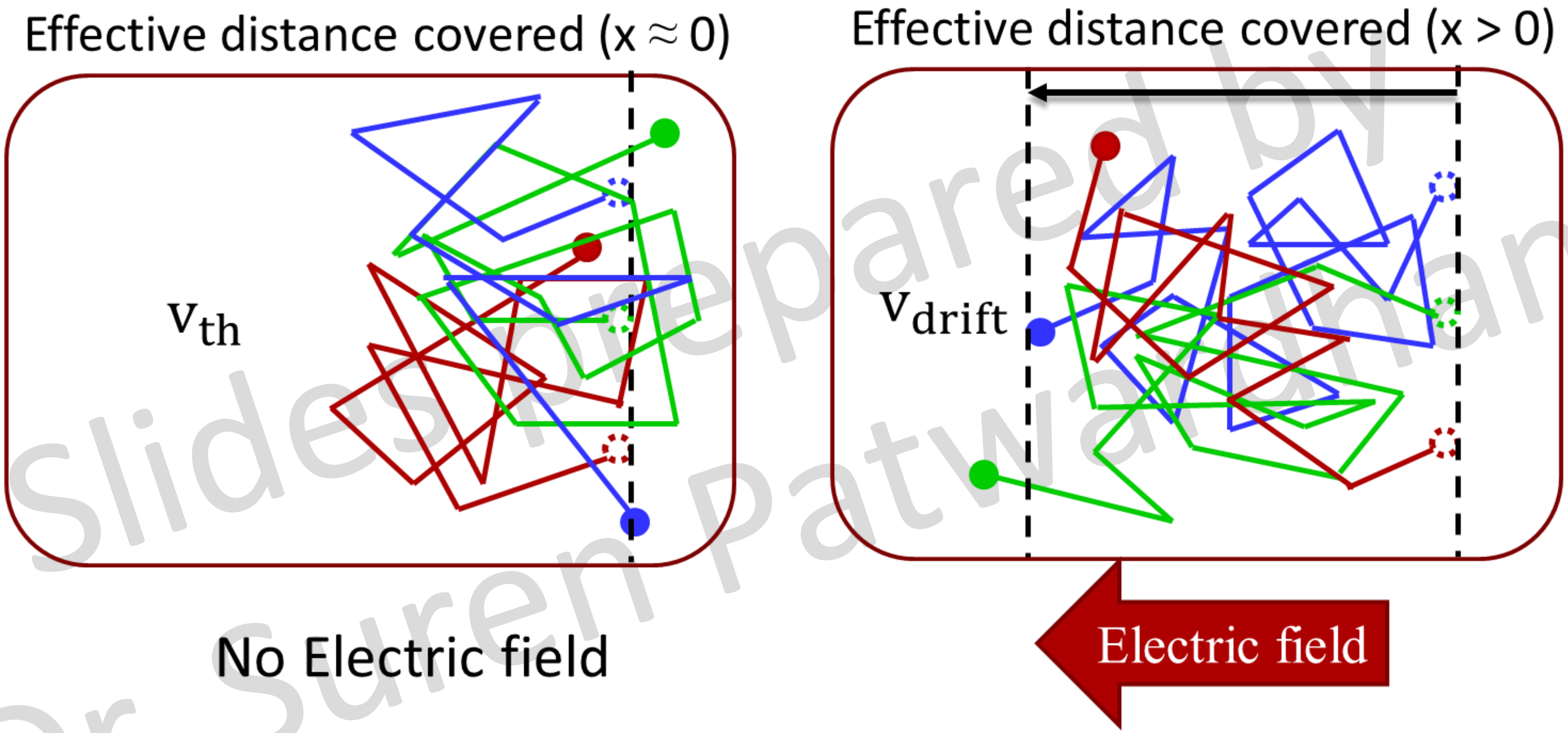
Charge Carrier Transport in Semiconductors

Thermal Velocity v_{th} and Drift Velocity v_d

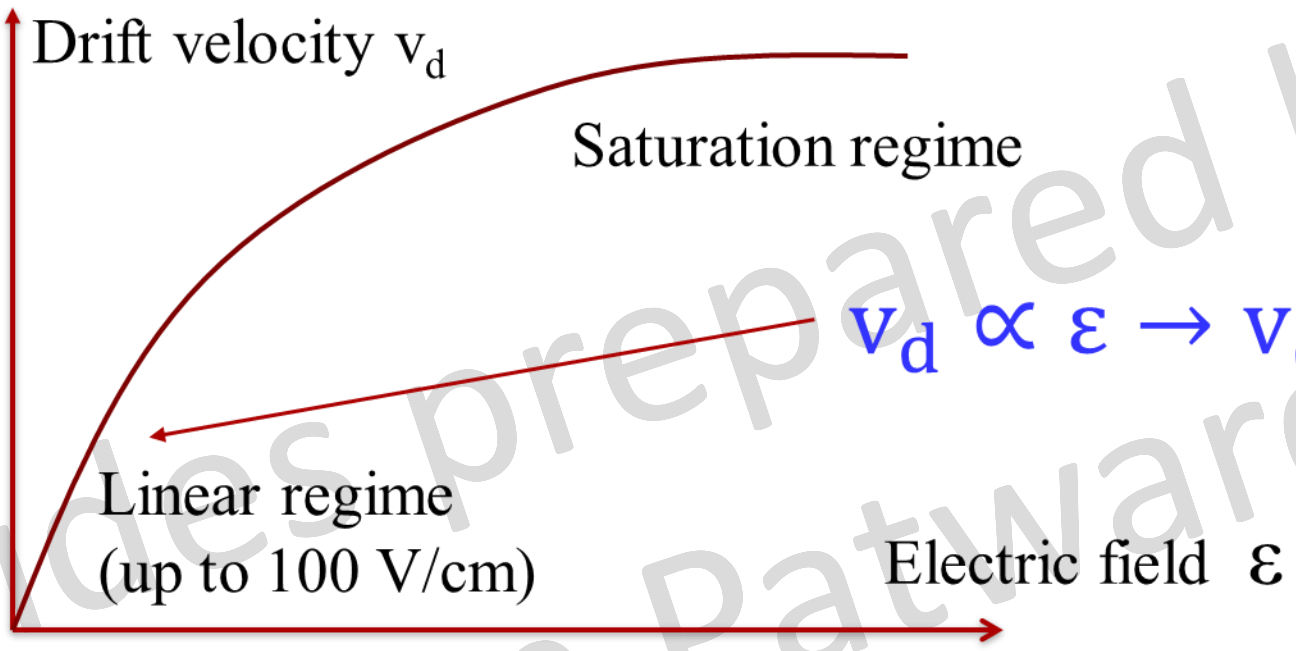


$\vec{J}_{drift} \propto \vec{v}_d$ and p;
p: particle density

Thermal Velocity v_{th} and Drift Velocity v_d



Carrier Mobility



$$v_d \propto \varepsilon \rightarrow v_d = \mu\varepsilon$$

μ: mobility (unit: $cm^2/V\text{-}sec$ or $m^2/V\text{-}sec$)

$$\vec{J}_{drift} = qn\mu\vec{\varepsilon}$$

Drift Current Density

For electrons,

$$\vec{J}_{drift}(\text{electrons}) = \vec{J}_n\ (\text{drift}) = (-q) \times n \times (-\vec{v}_d)$$

$$= qnv_d \text{ numerically}$$

$$= qn\mu_n\vec{\varepsilon} = \sigma_n\vec{\varepsilon}$$

For holes,

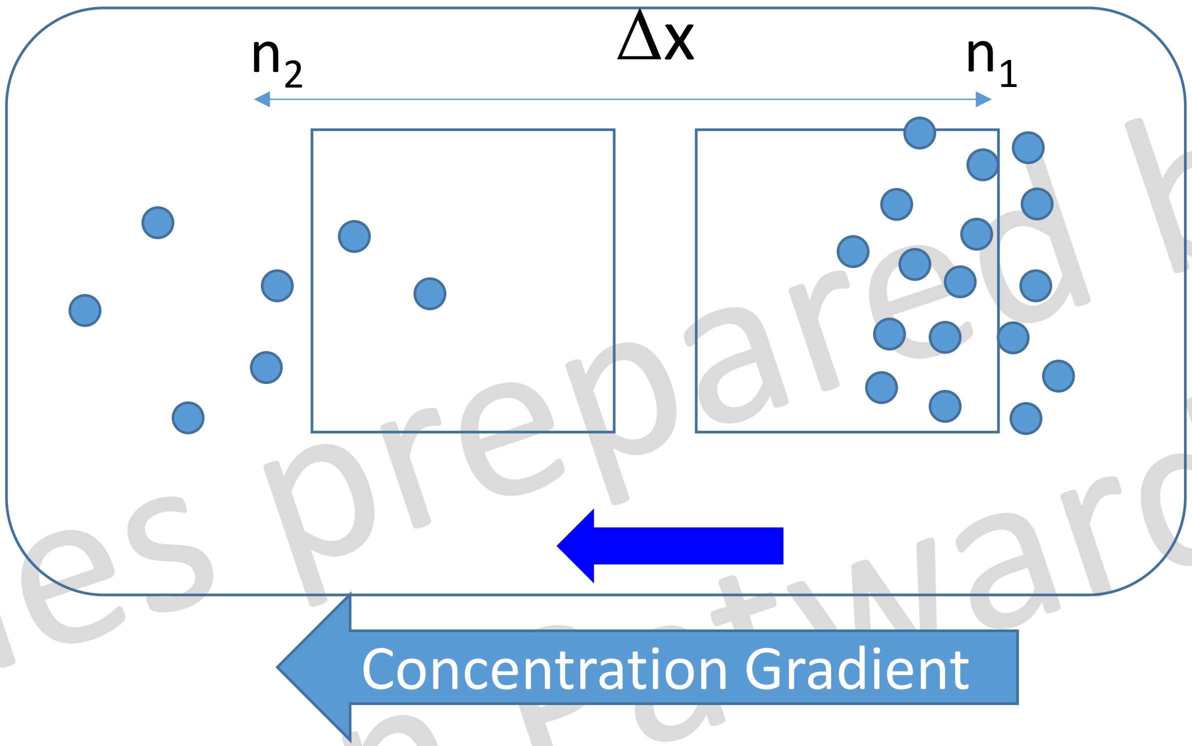
$$\vec{J}_{drift}(\text{holes}) = \vec{J}_p\ (\text{drift}) = (+q) \times p \times (+\vec{v}_d)$$

$$= qpv_d \text{ numerically}$$

$$= qp\mu_p\vec{\varepsilon} = \sigma_p\vec{\varepsilon}$$

The equation $J = \sigma E$ is nothing but "Ohm's law"

Carrier Diffusion



$$\text{Concentration gradient} = \frac{n_1 - n_2}{\Delta x} = \frac{\Delta n}{\Delta x}$$

$$\vec{J}_{\text{diffusion}} \propto \frac{\Delta n}{\Delta x}$$

Diffusion Coefficient and Einstein's Ratio

$$\lim_{\Delta x \to 0} \frac{\Delta \mathrm{n}}{\Delta \mathrm{x}} = \frac{\mathrm{dn}}{\mathrm{dx}}$$

$$\vec{\mathrm{J}}_{\mathrm{diffusion}} \propto -\frac{\mathrm{dn}}{\mathrm{dx}}$$

$$\vec{\mathrm{J}}_{\mathrm{diffusion}} = -\mathrm{qD}\frac{\mathrm{dn}}{\mathrm{dx}}$$

D: diffusion coefficient (unit: cm^2/sec or m^2/sec)

At any given temperature, $\frac{\mathrm{D}}{\mu} = \frac{\mathrm{kT}}{\mathrm{q}} = \mathrm{constant}$

- Known as "Einstein's relations"

Diffusion Current Density

For electrons,

$$\vec{J}_{diffusion}(\text{electrons}) = \vec{J}_n\ (\text{diff}) \propto -\frac{dn}{dx}\hat{\imath}$$

$$= (-q) \times D_n \times (-\frac{dn}{dx})\hat{\imath}$$

$$= qD_n\frac{dn}{dx}\ \text{numerically}$$

For holes,

$$\vec{J}_{diffusion}(\text{holes}) = \vec{J}_p\ (\text{diff}) \propto -\frac{dp}{dx}\hat{\imath}$$

$$= (+q) \times D_p \times (-\frac{dp}{dx})\hat{\imath}$$

$$= -qD_p\frac{dp}{dx}\ \text{numerically}$$

Total Current Density

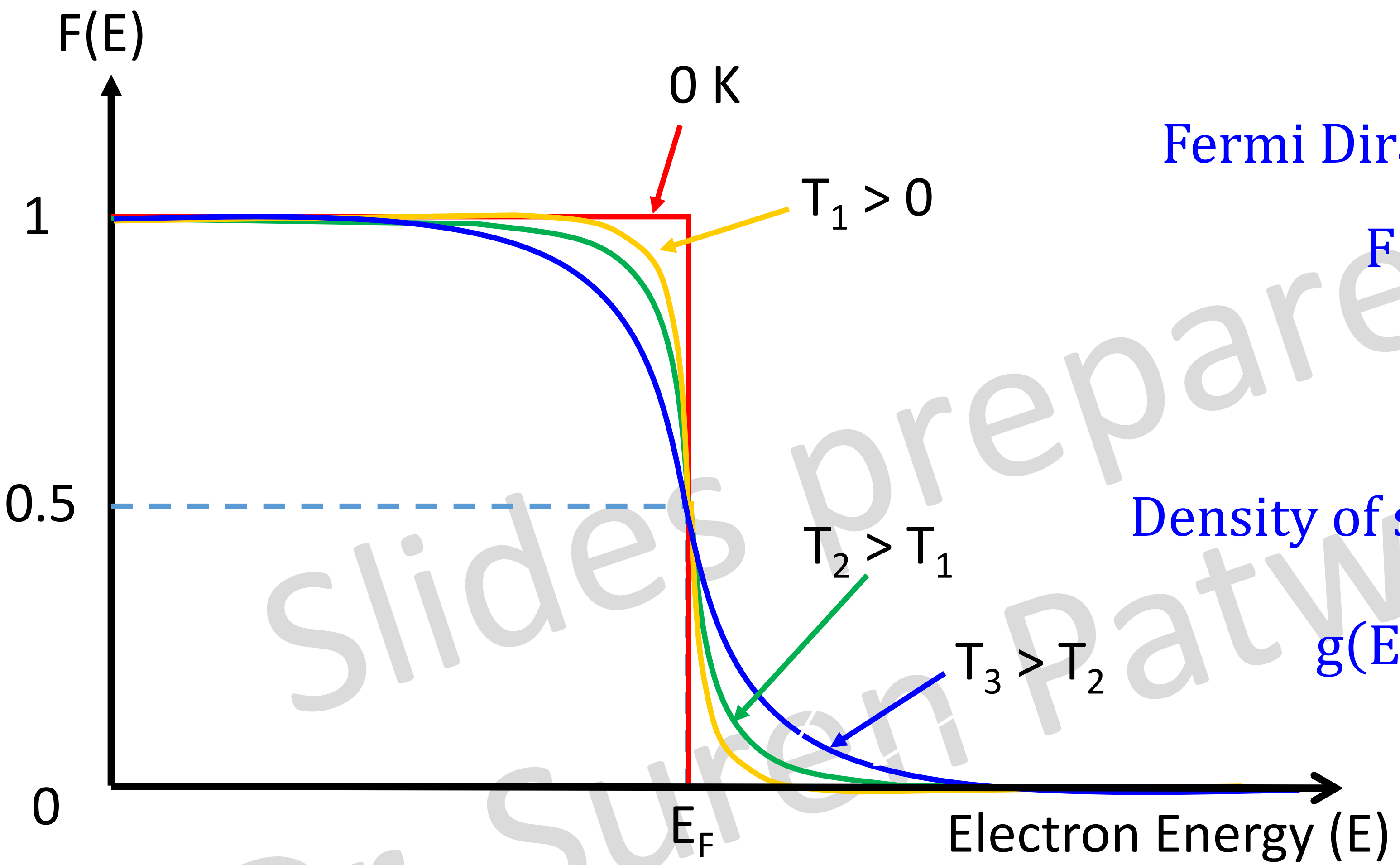
Total currents flowing in any semiconductor under external bias (voltage, light or heat)

$$\vec{J}(\text{total}) = \vec{J}(\text{drift}) + \vec{J}(\text{diffusion})$$

$$\vec{J}(\text{total}) = q\left[(n\mu_n + p\mu_p)\vec{\varepsilon} + \left(D_n\frac{dn}{dx} - D_p\frac{dp}{dx}\right)\hat{\imath}\right]$$

Fermi-Dirac Statistics

Fermi-Dirac Statistics



Fermi Dirac function (probability factor):

$$F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}$$

Density of state function (energy states):

$$g(E) = \frac{1}{2\pi^2}\left(\frac{2m^*}{\hbar^2}\right)^{3/2} E^{1/2}$$

Fermi energy is that energy for which, the probability of occupation is 50% at all temperatures except absolute zero

Estimation of charge densities

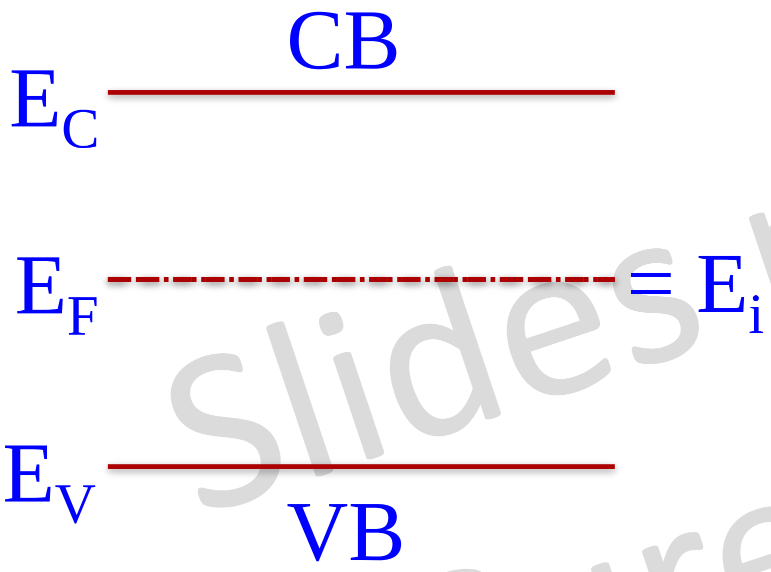
No. of electrons per unit vol. $n = \int_{E_C}^{\infty} F(E)\, g(E) dE = N_C \exp\left(-\frac{E_C - E_F}{kT}\right)$

No of holes per unit vol. $p = \int_{-\infty}^{E_V} [1 - F(E)]\, g(E) dE = N_V \exp\left(-\frac{E_F - E_V}{kT}\right)$

N_C and N_V are called "Effective densities of states" in C.B and V.B respectively

$$N_C = \frac{1}{4\pi^3}\left(\frac{2\pi kTm_n^*}{\hbar^2}\right)^{3/2}, N_V = \frac{1}{4\pi^3}\left(\frac{2\pi kTm_p^*}{\hbar^2}\right)^{3/2}$$

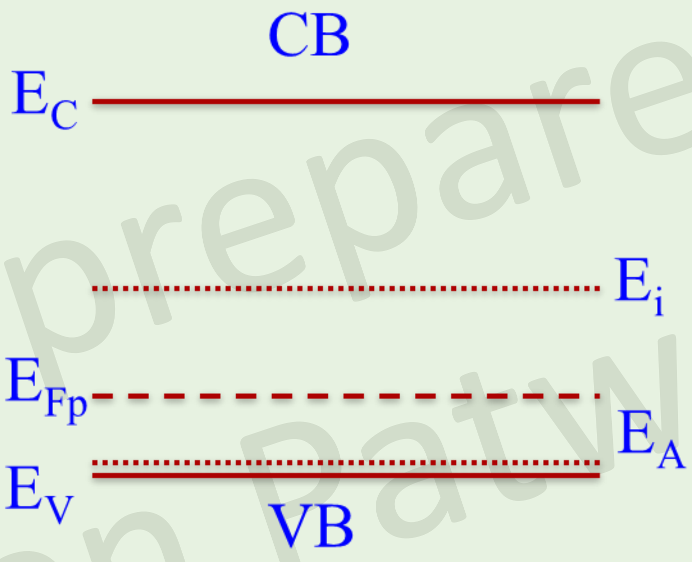
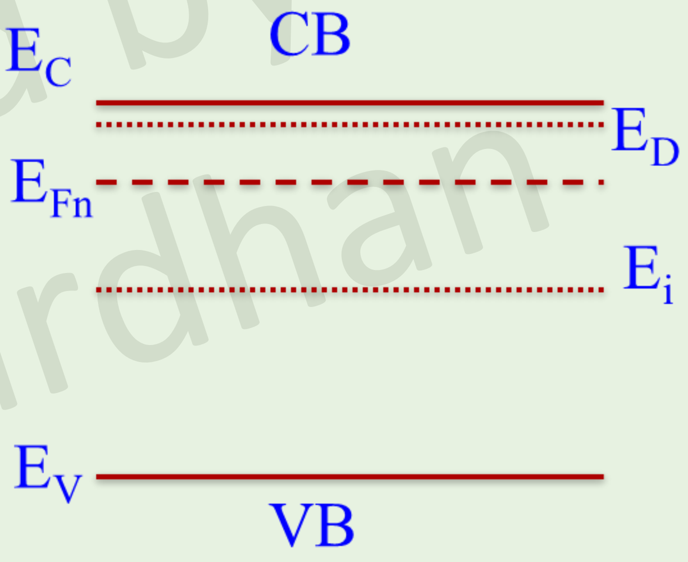
Fermi level in intrinsic semiconductors



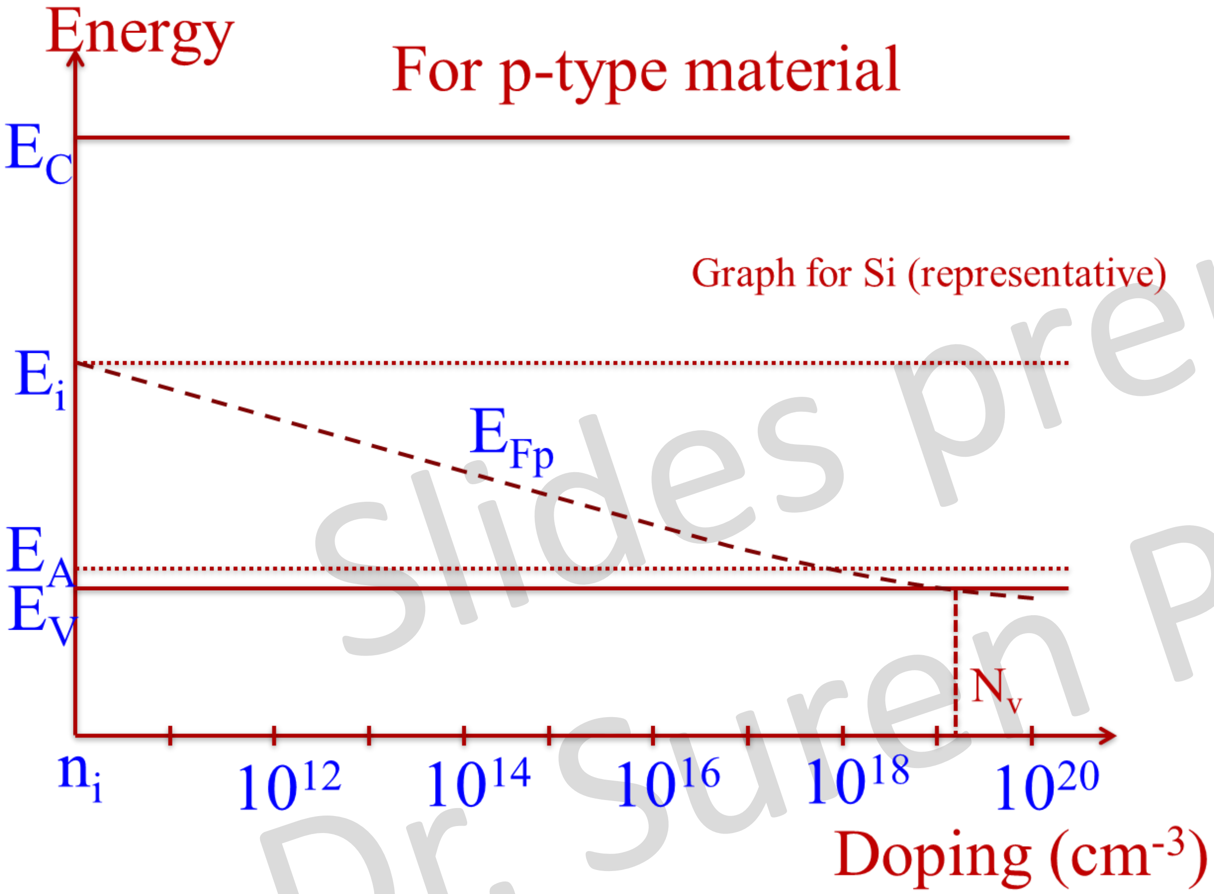
In intrinsic semiconductors, Fermi level is located near the centre of energy band gap

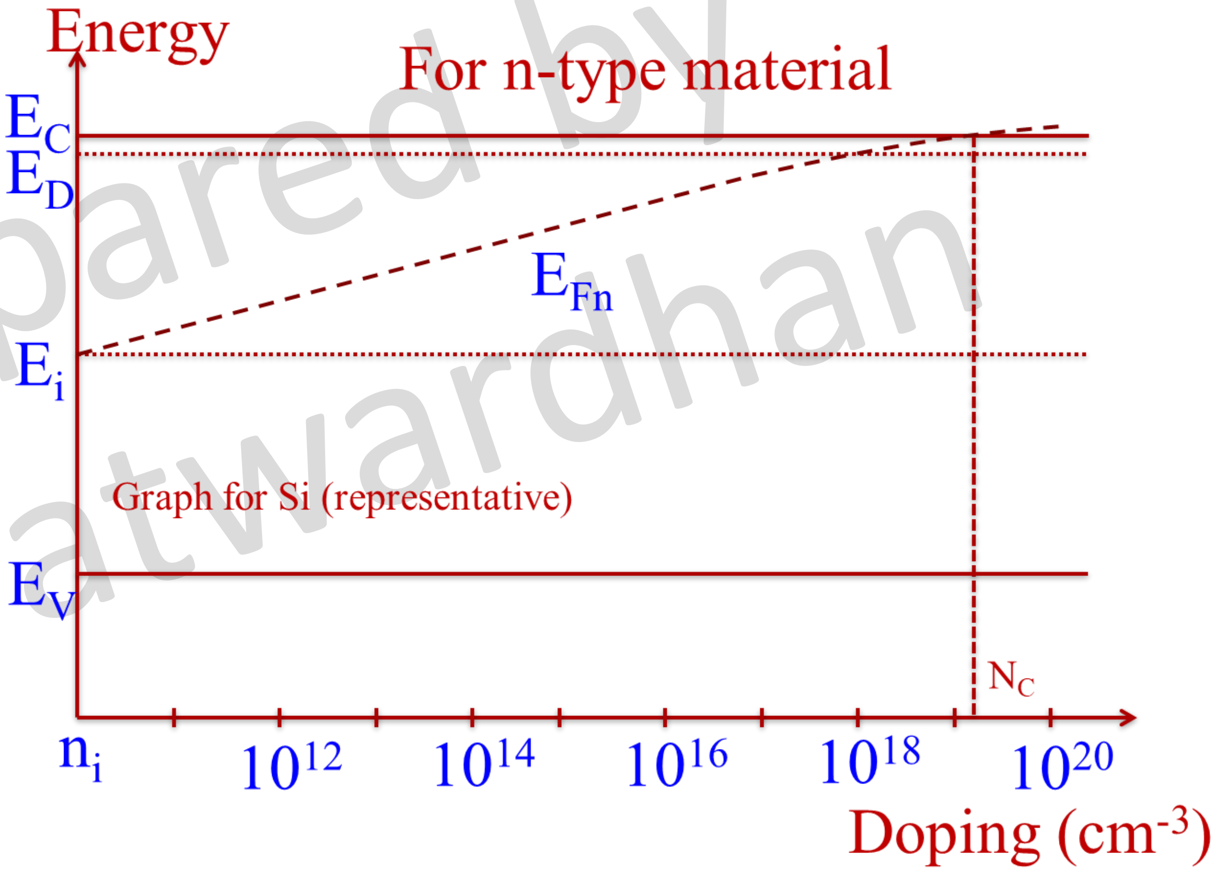
$$E_F = \frac{E_C + E_V}{2} + \frac{3kT}{4} \ln\left(\frac{m_p^*}{m_n^*}\right) \approx \frac{E_C + E_V}{2}$$

Effect of doping on Fermi Level

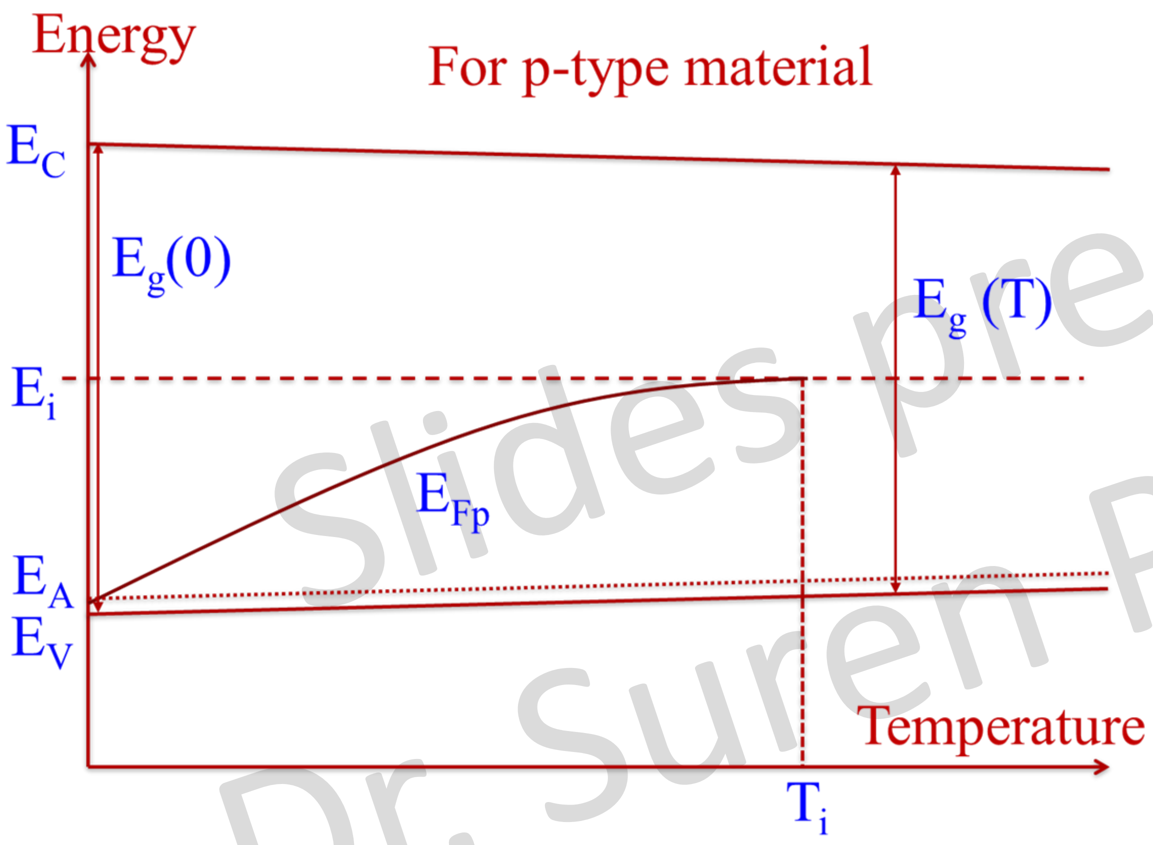
Material	P-type	N-type
Energy band diagram		
Shift in Fermi level	$E_F - E_i = -kT\ln\left(\frac{p}{n_i}\right)$	$E_F - E_i = kT\ln\left(\frac{n}{n_i}\right)$

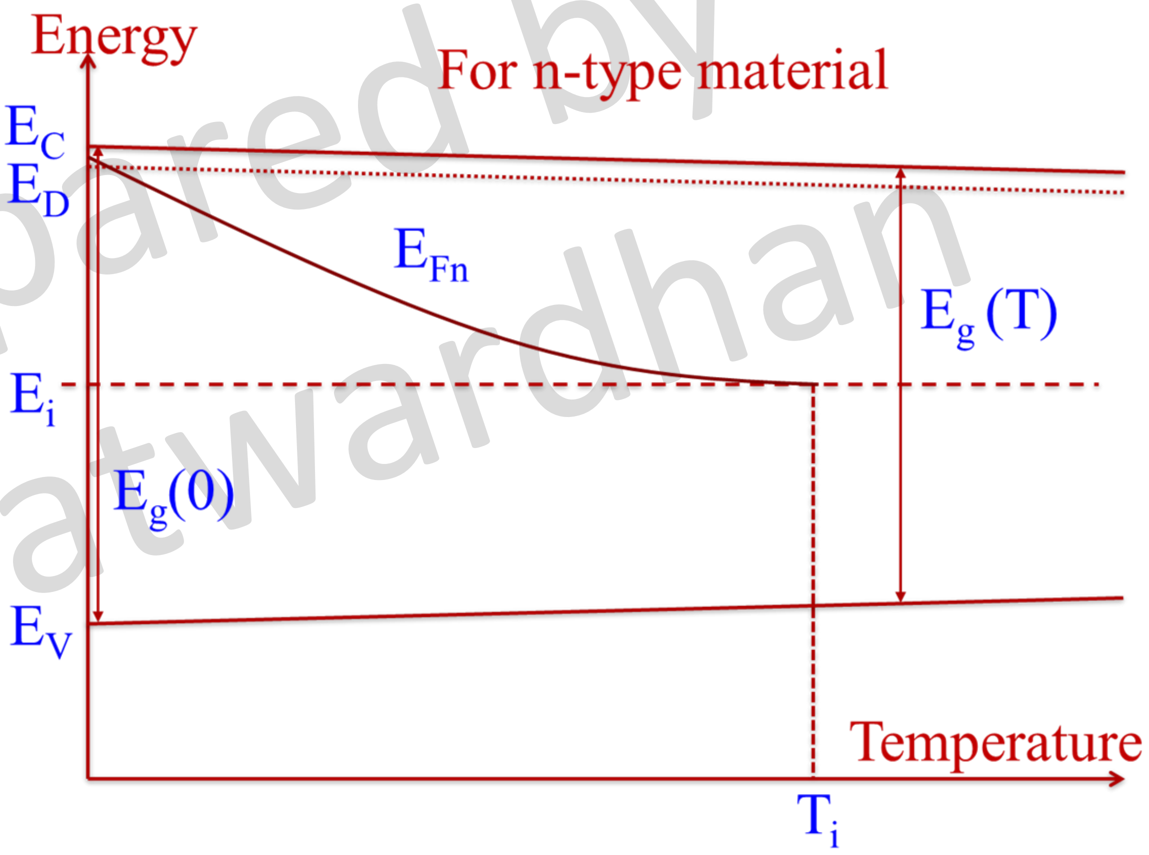
Effect of doping on Fermi Level





Effect of temperature on Fermi Level





Applications