Semiconductor Fundamentals

Presented to

EE2187 class in Semester 1 2019/20

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Lecture 13

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.

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.

Recap

Equilibrium Band Diagram

If $N_d < n_i$,

doping irrelevant (intrinsic semiconductor) $\rightarrow$

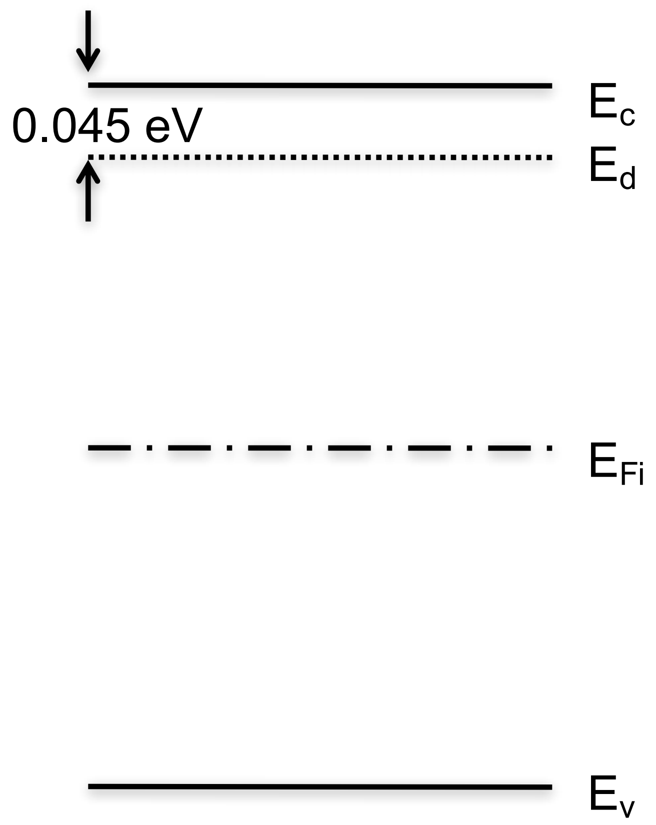
$n_{no} = p_{no} = n_i$

If $N_d > n_i$ and Donor atom completely ionized

doping controls carrier concentrations

(extrinsic semiconductor) $\rightarrow n_{no} = N_d^+ \quad p_{no} = n_i^2/N_d^+$

Note: n-type semiconductor: $n_{no} >> p_{no}$



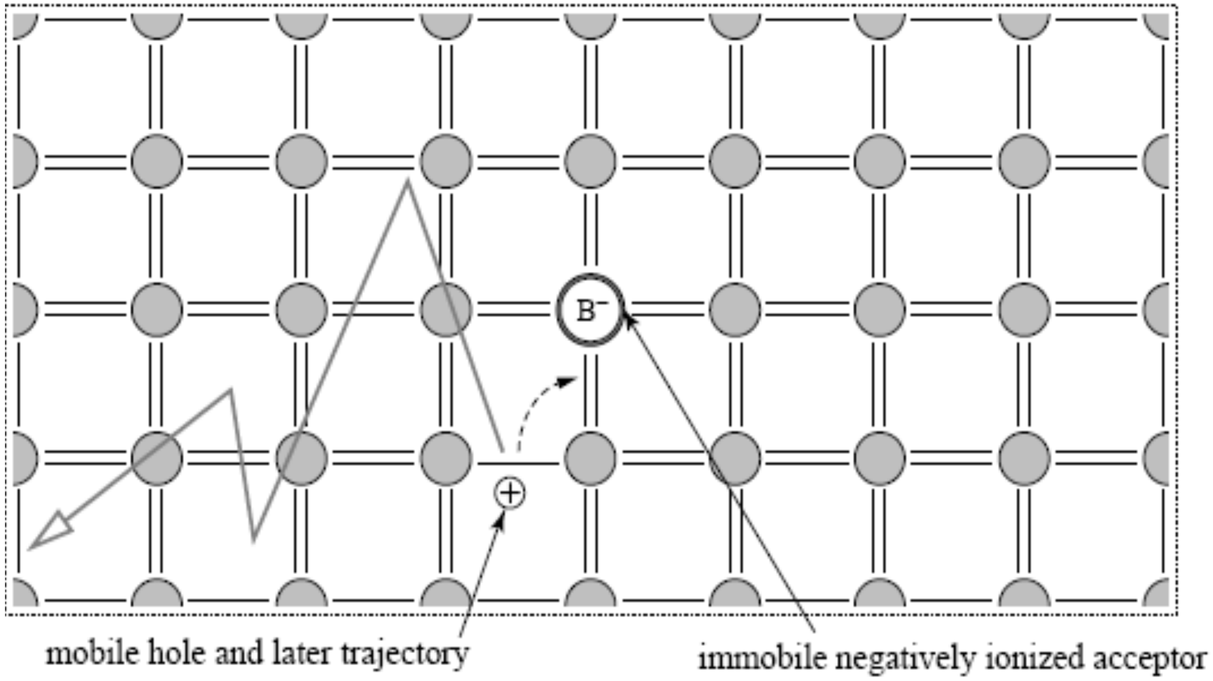
Example:

$Nd = 10^{17}\ cm^{-3} \rightarrow n_{no} = 10^{17}\ cm^{-3}$, $p_{no} = 10^3 cm^{-3}$.

In general: $N_d \;\; 10^{15} - 10^{20}\ cm^{-3}$

Acceptors: Introduce holes to the semiconductor (but not electrons)

IIB	IIIA	IVA	VA	VIA
	5 B	6 C	7 N	8 O
	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



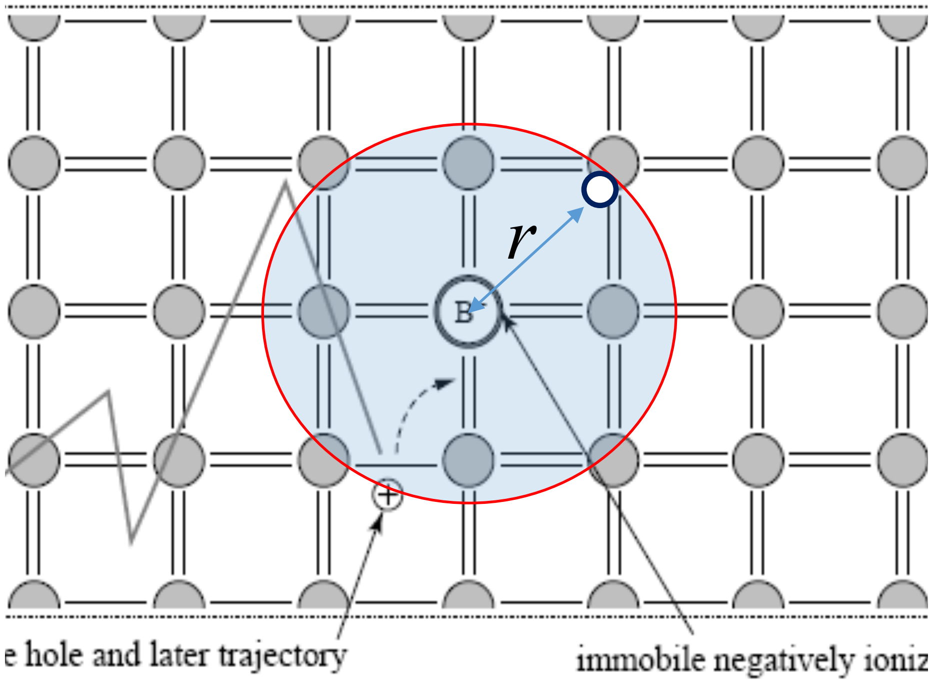
- 3 electrons used in bonding to neighboring Si atoms
- 1 bonding site "unsatisfied": – **easy to "accept" neighboring bonding electron to** complete all bonds – **at room temperature, each acceptor releases 1 hole** that is available to conduction
- acceptor site become negatively charged (fixed charge)

Question to ask

Can we have electrons?

Can we get hole by some other mechanism

More Insight (Bond Model)



$$F = \frac{-q^2}{4\pi \in 0 \in {}_r r^2}$$

Dielectric constant of Si which is ~12.

Binding Energy of Electron of ground state

$$E = \frac{-mq^4}{8\pi \in 20 \in 2_r h^2}$$

$m * \sim 0.4 m_n$ $\in {}_r \sim 12$

At T>0K

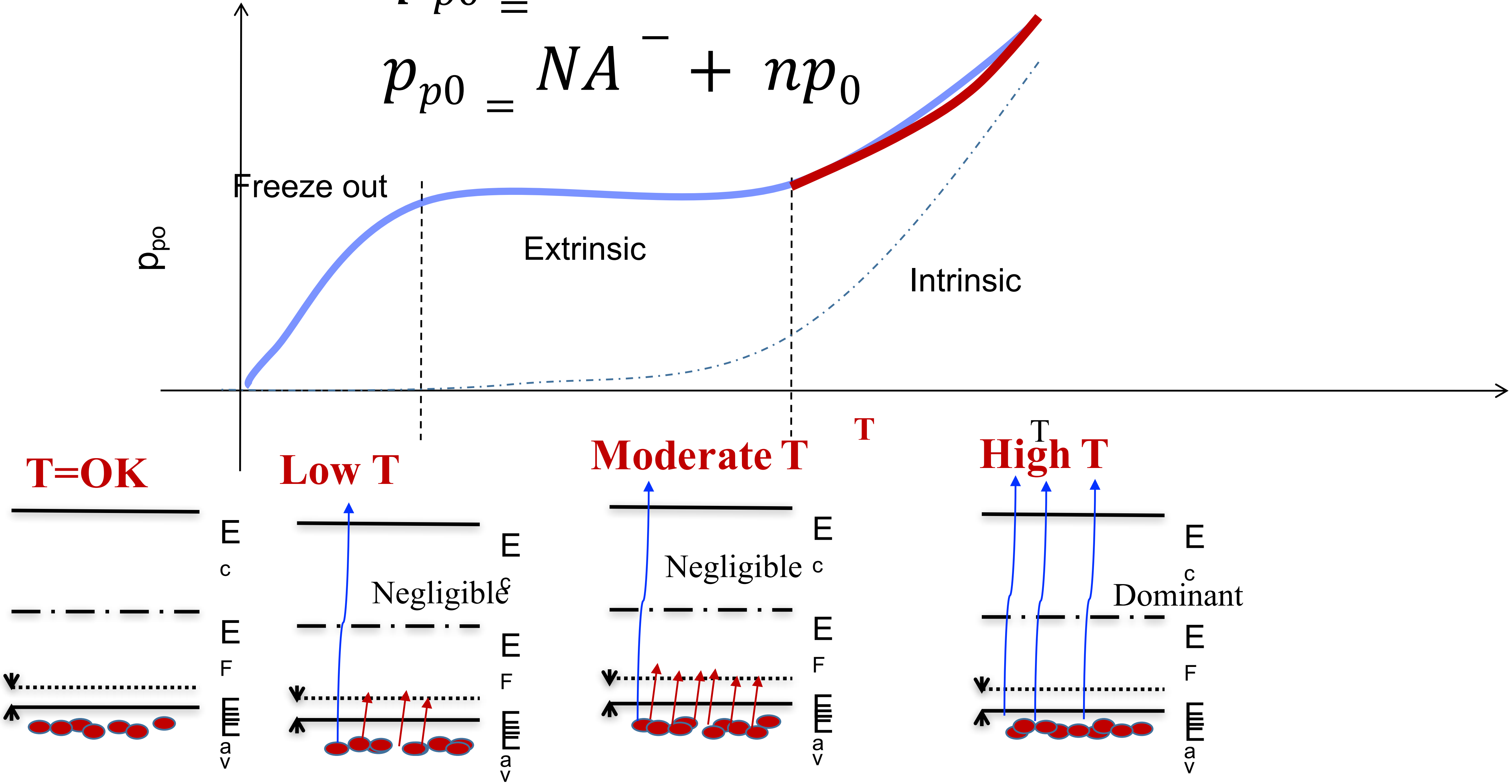
This is very small also known as ionization energy, so effectively this empty state level lying just above E_v

This is called Acceptor state

Holes Concentration and Band Diagram

$$p_{p0} = NA^{-}$$

$$p_{p0} = NA^{-} + np_{0}$$



Equilibrium Band Diagram

If $N_a < n_i$, doping irrelevant (intrinsic semiconductor)

$n_{po} = p_{po} = n_i$

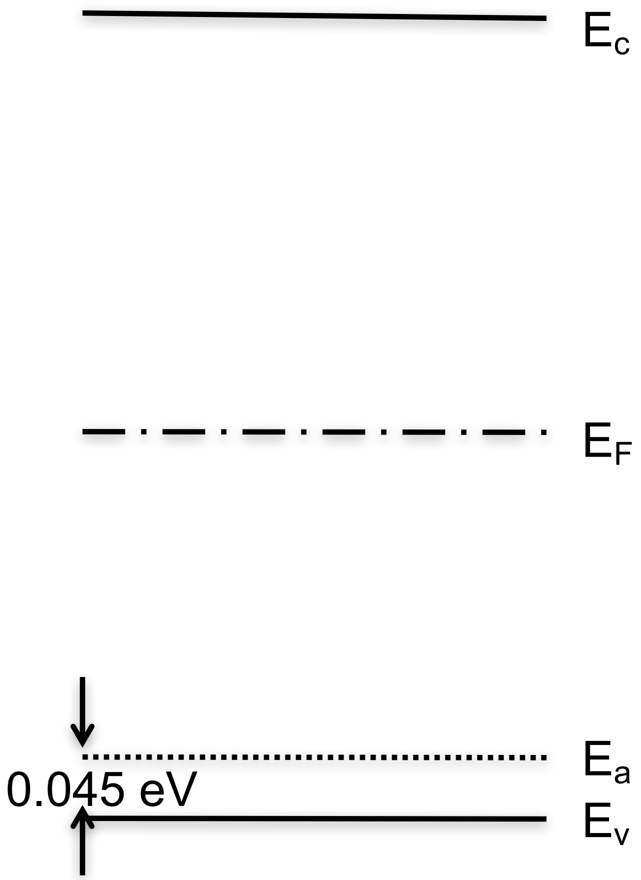
If $N_a > n_i$, doping controls carrier concentrations (extrinsic semiconductor) $\rightarrow p_{po} = N_{a^-}$ (if Na completely ionized $n_{po} = n^2_i/N_a^-$

Note: $p_o >> n_o$: p-type semiconductor

Example:

$Na = 10^{16}\ cm^{-3} \rightarrow p_{po} = 10^{16}\ cm^{-3}$, $n_{po} = 10^4$ cm−3.

In general: N_a $10^{15} - 10^{20}\ cm^{-3}$



Thermal Equilibrium Concentration of Electrons and Holes in Extrinsic Semiconductor

$$n_{n0} = \int_{E_c}^{E_{Top}} f(E)g(E)dE$$

$$n_{n0} = \int_{E_c}^{E_{Top}} \frac{\frac{m_n{}^*}{2\pi^2\hbar^3}\sqrt{2mn*(E-Ec)}}{1+\exp(E-EF)/KT} dE, \quad May\ not\ integrable$$

However we can apply MB

$$\boxed{n_{n0} = \int_{E_c}^{E_{Top}} \frac{\frac{m_n{}^*}{2\pi^2\hbar^3}\sqrt{2mn*(E-Ec)}}{\exp(E-EF)/KT} dE = N_C \exp -\frac{(E_C-EF)}{KT}}$$

$$\boxed{p_{n0} = N_V \exp -\frac{(E_F - EV)}{KT}}$$

$$N_V = 2\left(\frac{m_V^*}{\pi\hbar^2}KT\right)^{3/2} \qquad N_C = 2\left(\frac{m_C^*}{\pi\hbar^2}KT\right)^{3/2}$$

.... More Insight

$$n_{n0} = NC\, e^{-\frac{(E_C - EF)}{KT}}$$

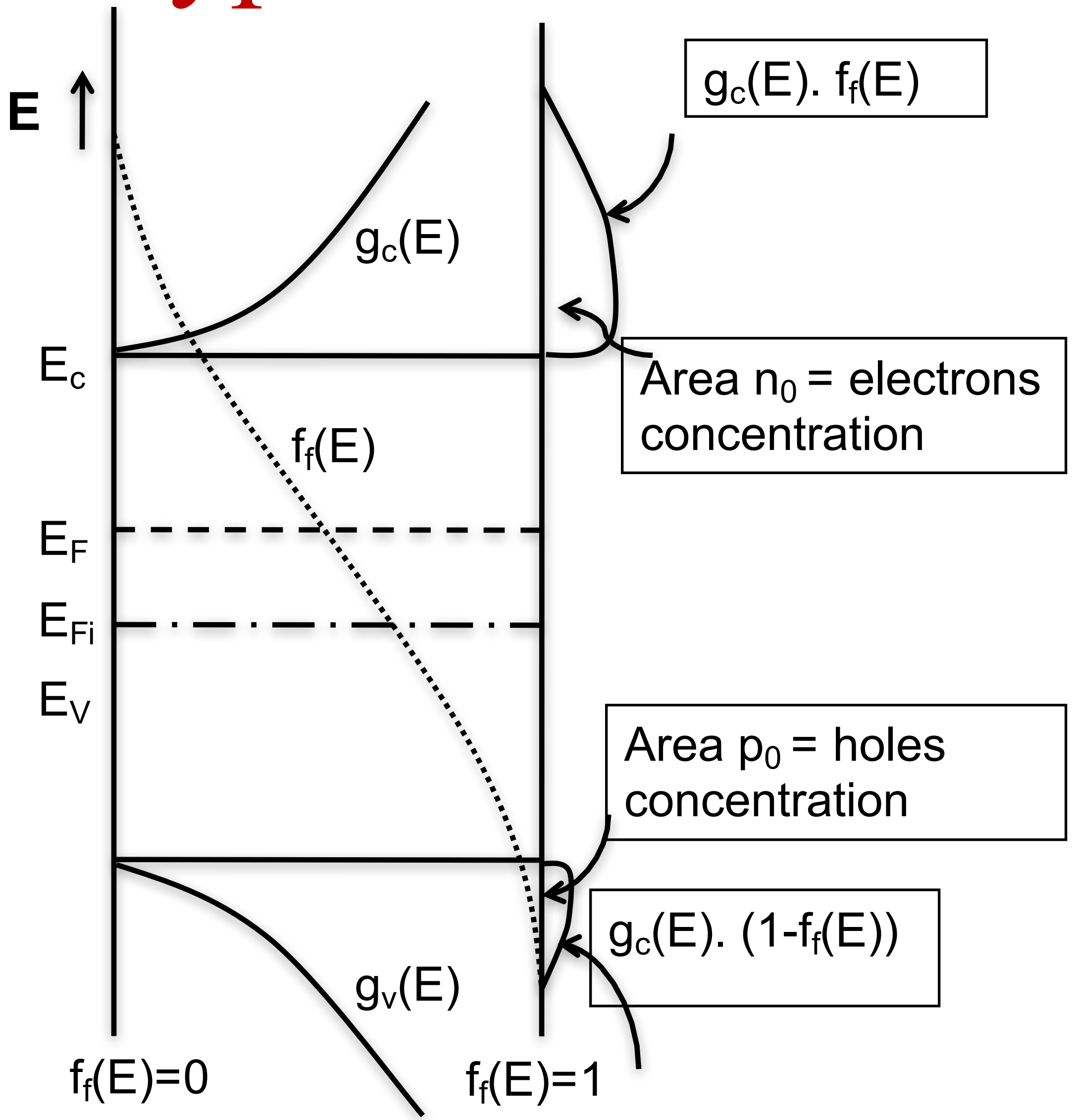
$$n_{n0} = NC\, e^{-\frac{(E_c - EF_i) + (EFi - EF)}{KT}}$$

$$n_{n0} = N_C\, e^{-\frac{(E_c - EF_i)}{KT}} * e^{-\frac{(E_{Fi} - EF)}{KT}}$$

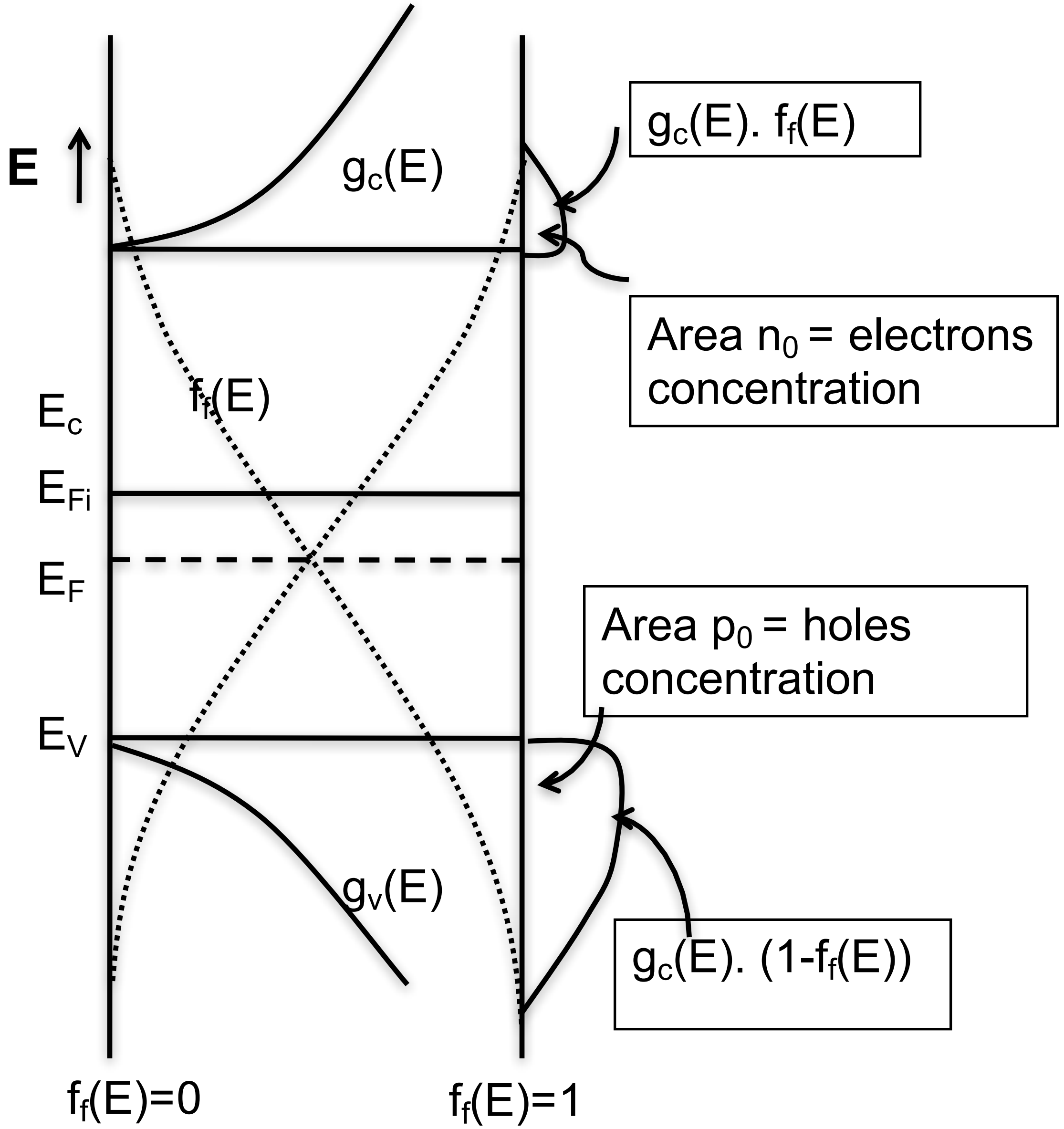
$$n_{n0} = n_i\, exp\, \frac{(E_F - EF_i)}{KT}$$

$$Simlerly\ pp_0 = n_i\, exp\, \frac{(E_{Fi} - EF)}{KT}$$

Equilibrium Distribution of Electrons in n type Semiconductor



Equilibrium Distribution of Electrons in p type Semiconductor

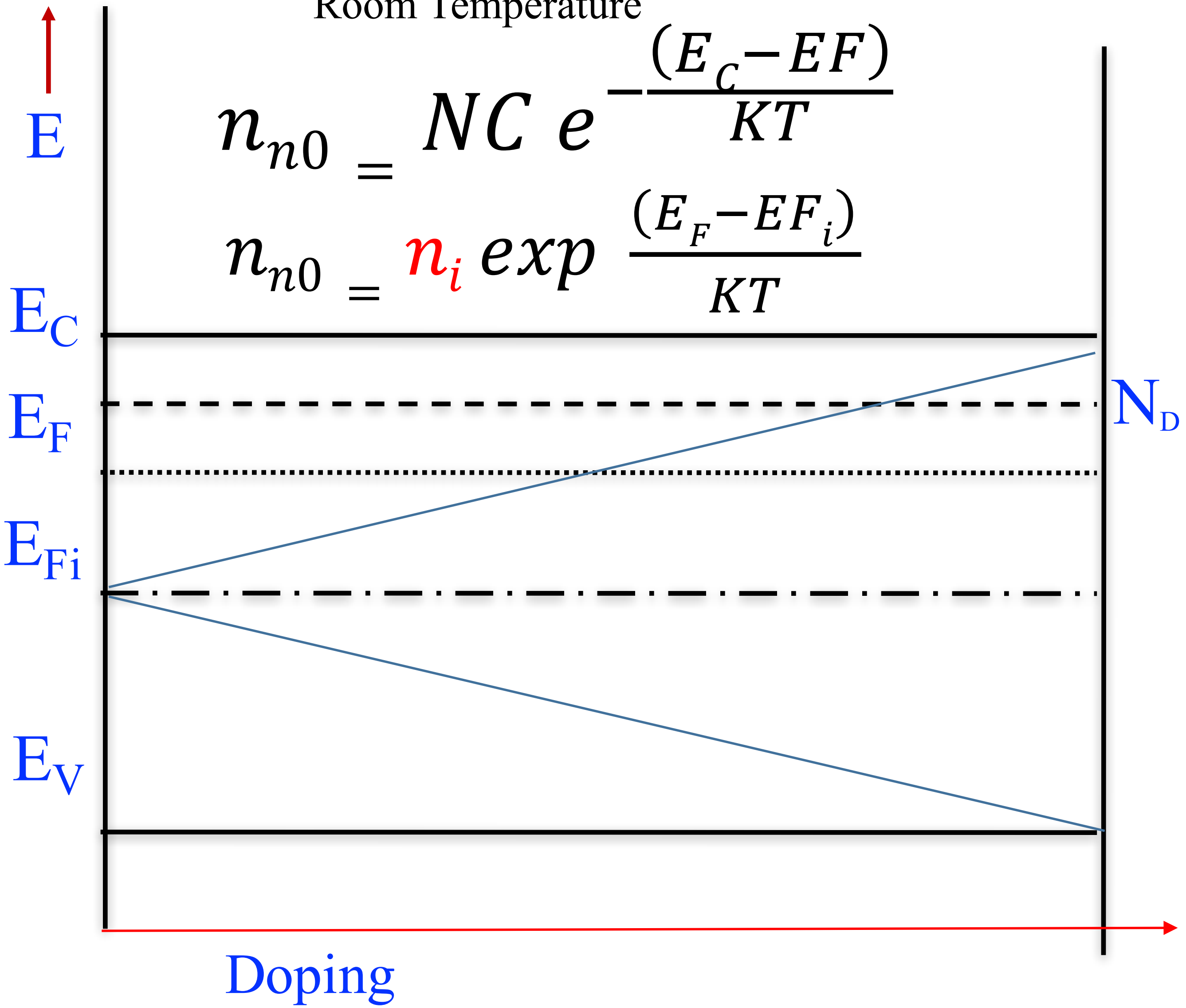


Fermi Level Variation with Doping

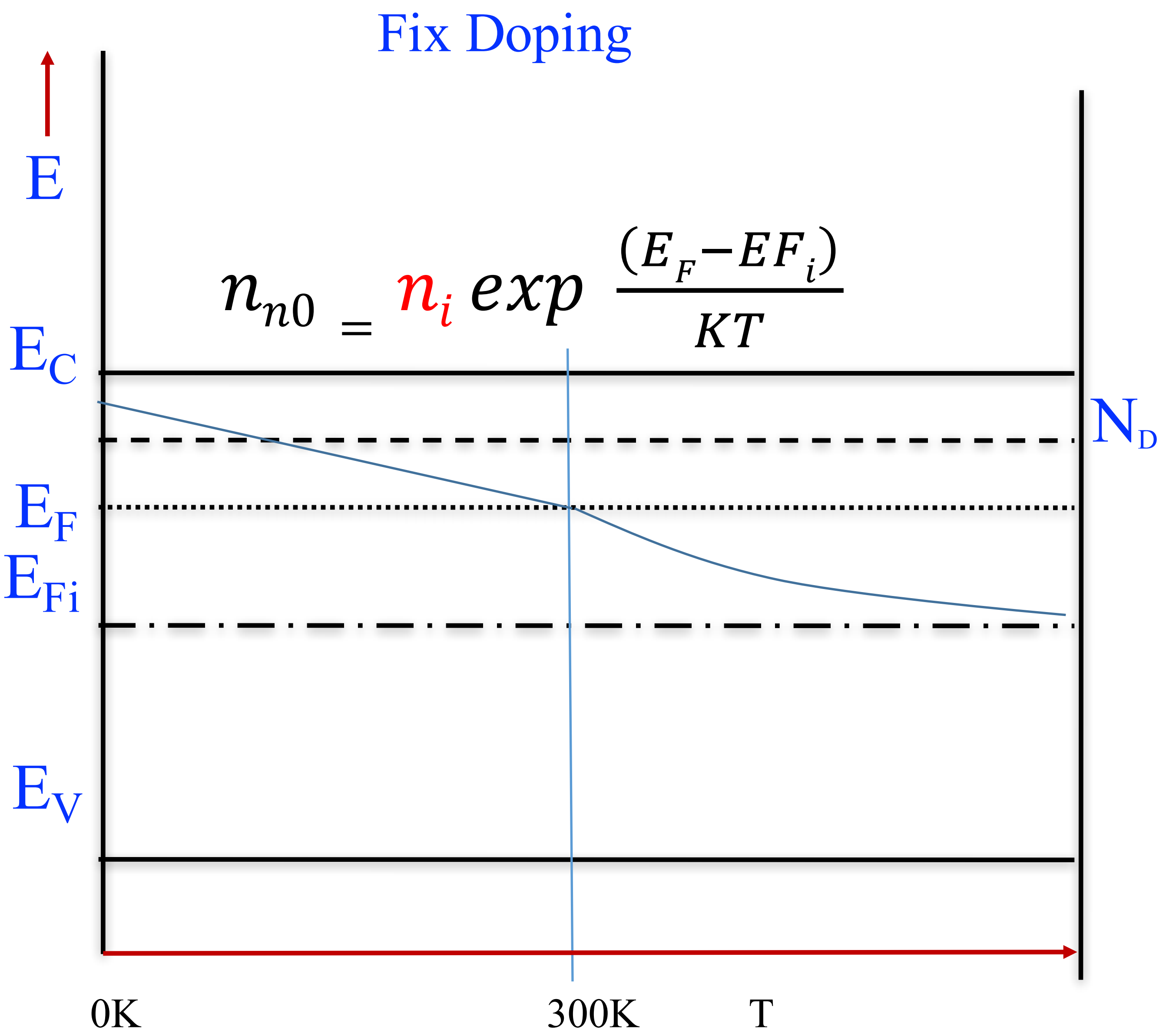
Room Temperature

$$n_{n0} = NC\, e^{-\frac{(E_C - EF)}{KT}}$$

$$n_{n0} = n_i \, exp \, \frac{(E_F - EF_i)}{KT}$$



Fermi Level Variation with Temperature

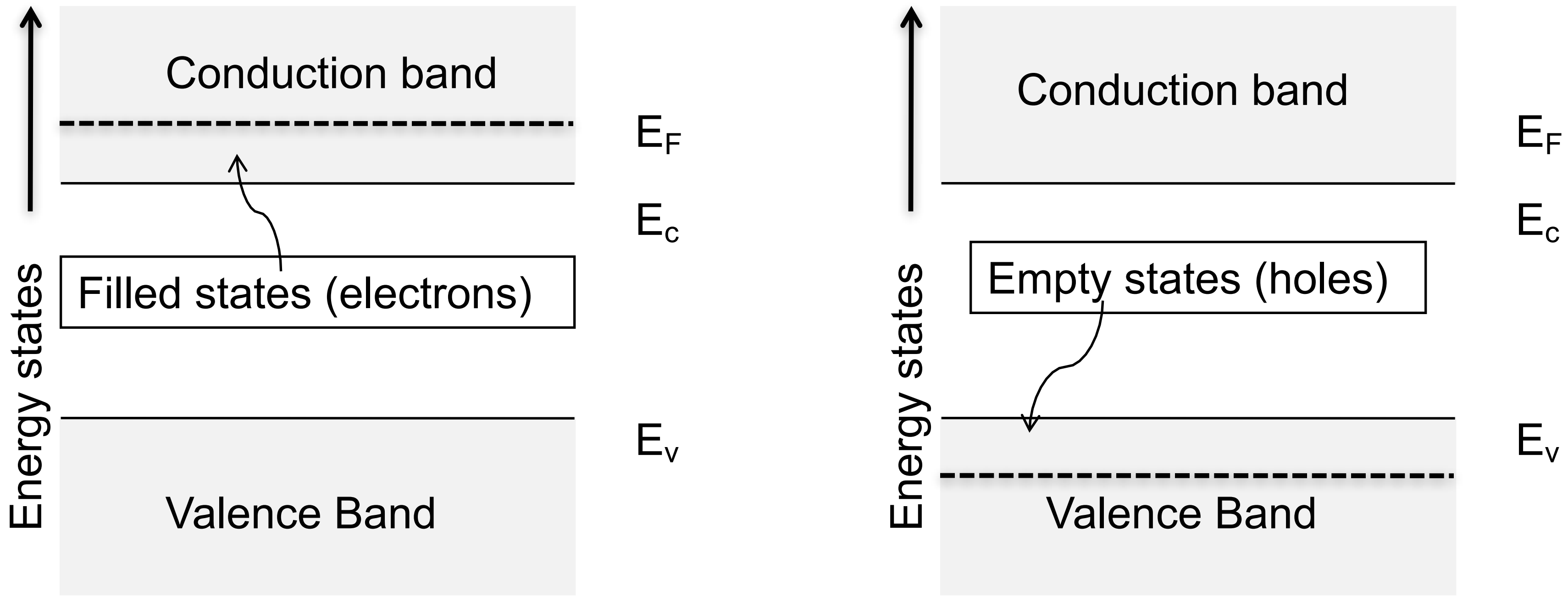


Degenerate and Nondegenerate Semiconductors

If the added dopant atoms is small then there is no interaction between them. It will introduced non interacting discreet donar/accepter energy state in n/p type semiconductor. Known as nondegenerate semiconductor.

If the added dopant atoms is large then there is interaction between them. It will introduced band of energies. This further widen and may overlap with bottom of conduction/and top of valence band. When the concentration electrons/holes in conduction/valence band exceeds to the density of states N_c/N_vt, the fermi level lies in conduction/valence band known as degenerate semiconductor.

Band diagram for degenerate n-type and p-type semiconductor



Probability Function of Donors and Accepters

Pauli exclusive principle still holds donors and accepters states

Suppose we have N_i= Electrons, and g_i= Quantum sates.

Probability function of electron empty the donor states is-

$$f_{nd}(E) = \frac{1}{1+g\ \exp(ED-EF)/KT}$$

Similarly Probability function of holes occupying the accepters states is-

$$f_{pa}(E) = \frac{1}{1+g\ \exp(EF-Ea)/KT}$$