Energy Conversion by Semiconductor Devices

Jun-Ho YUM
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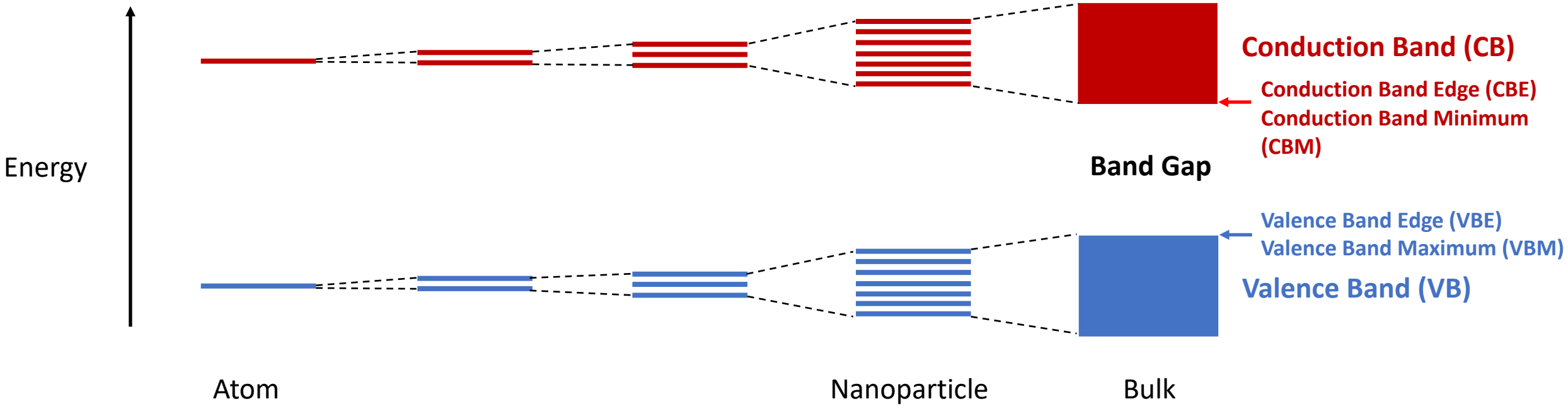
Description of Semiconductor



A **band gap** is the distance between the VB and the CB and the band gap represents the minimum energy that is required to excite an electron up to a state in the CB where it can participate in conduction.

It represents a set of forbidden energies that do not correspond to any allowed combinations of atomic orbitals.

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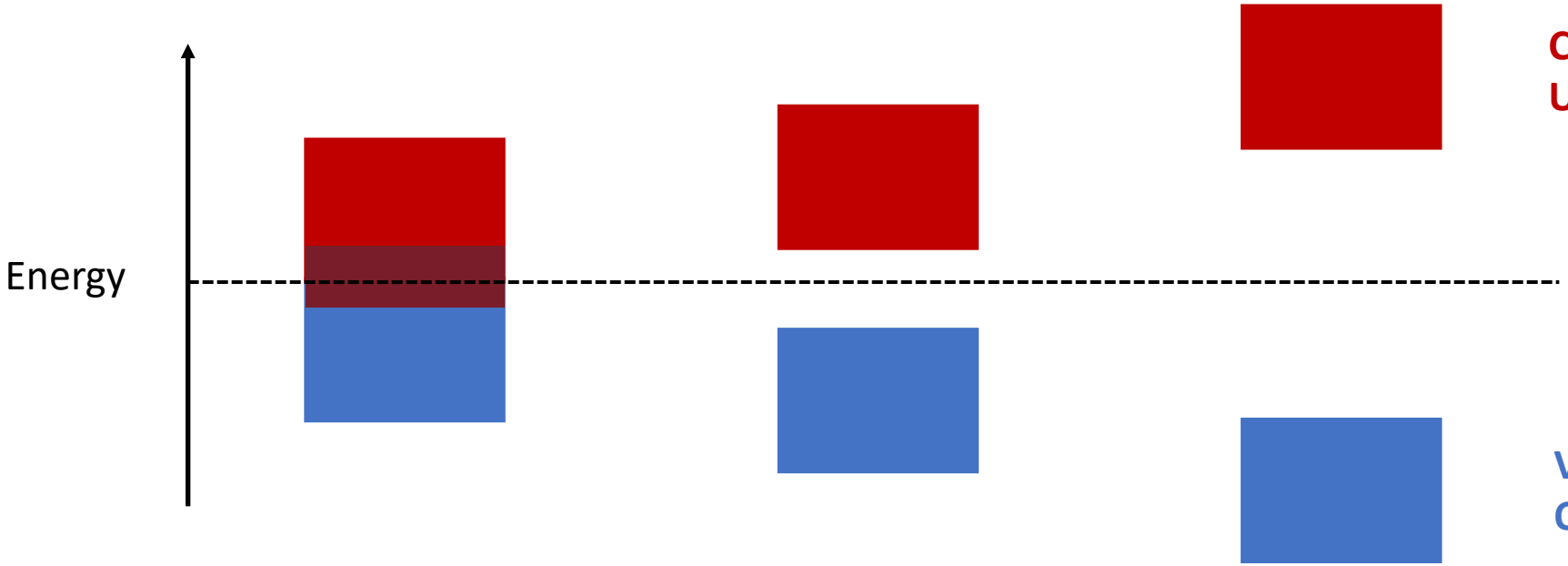

Conduction Band (CB)
Unoccupied (empty) by electrons

Valence Band (VB)
Occupied (filled) by electrons

Metal	**Semiconductor**	**Insulator**
Partially filled band	0.1 eV < E_g < 3.5 eV	E_g > 3.5 eV
Cu, Ag, Au, Al	**Si, Ge, GaAs, CdS**	**Diamond, SiO_2, MgO**

vs The energy ≈ 26 meV at 298 K

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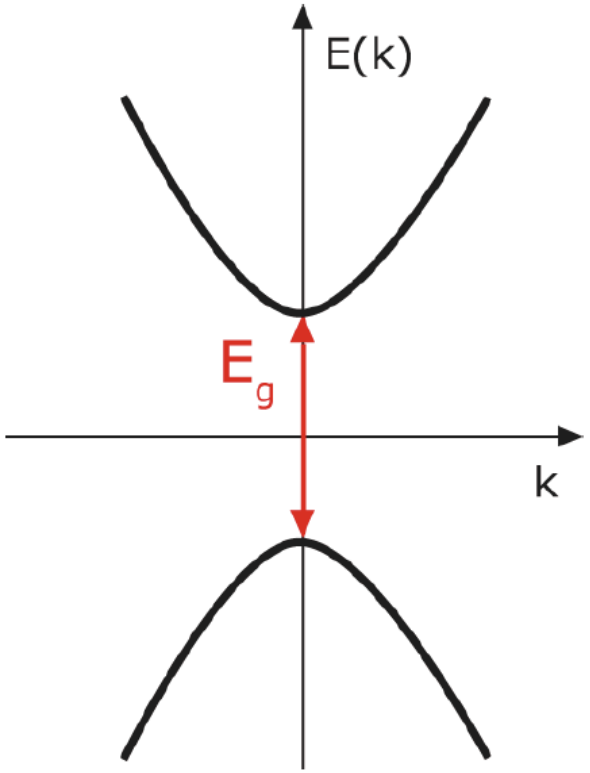
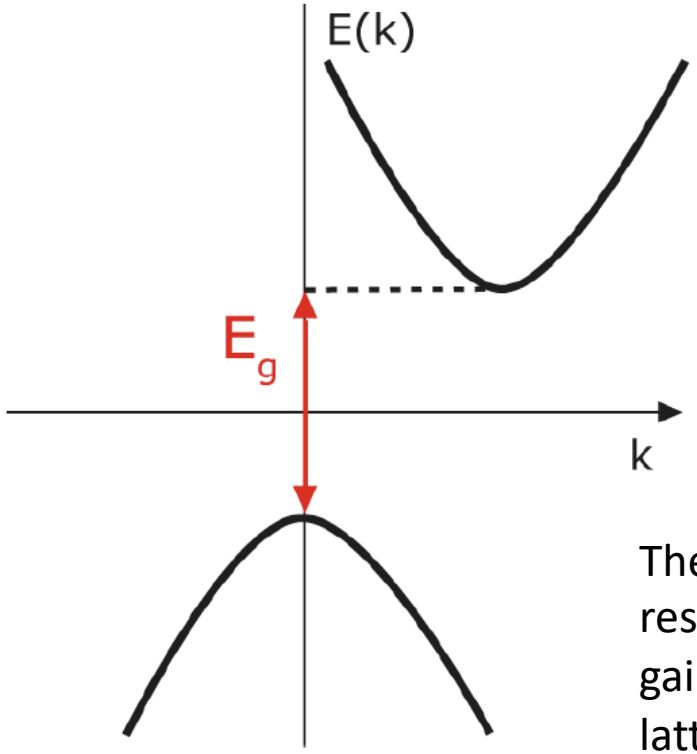
Direct and Indirect Band Gaps

Electron can make a smallest energy transition from the CB to the VB without a change in crystal momentum k value.



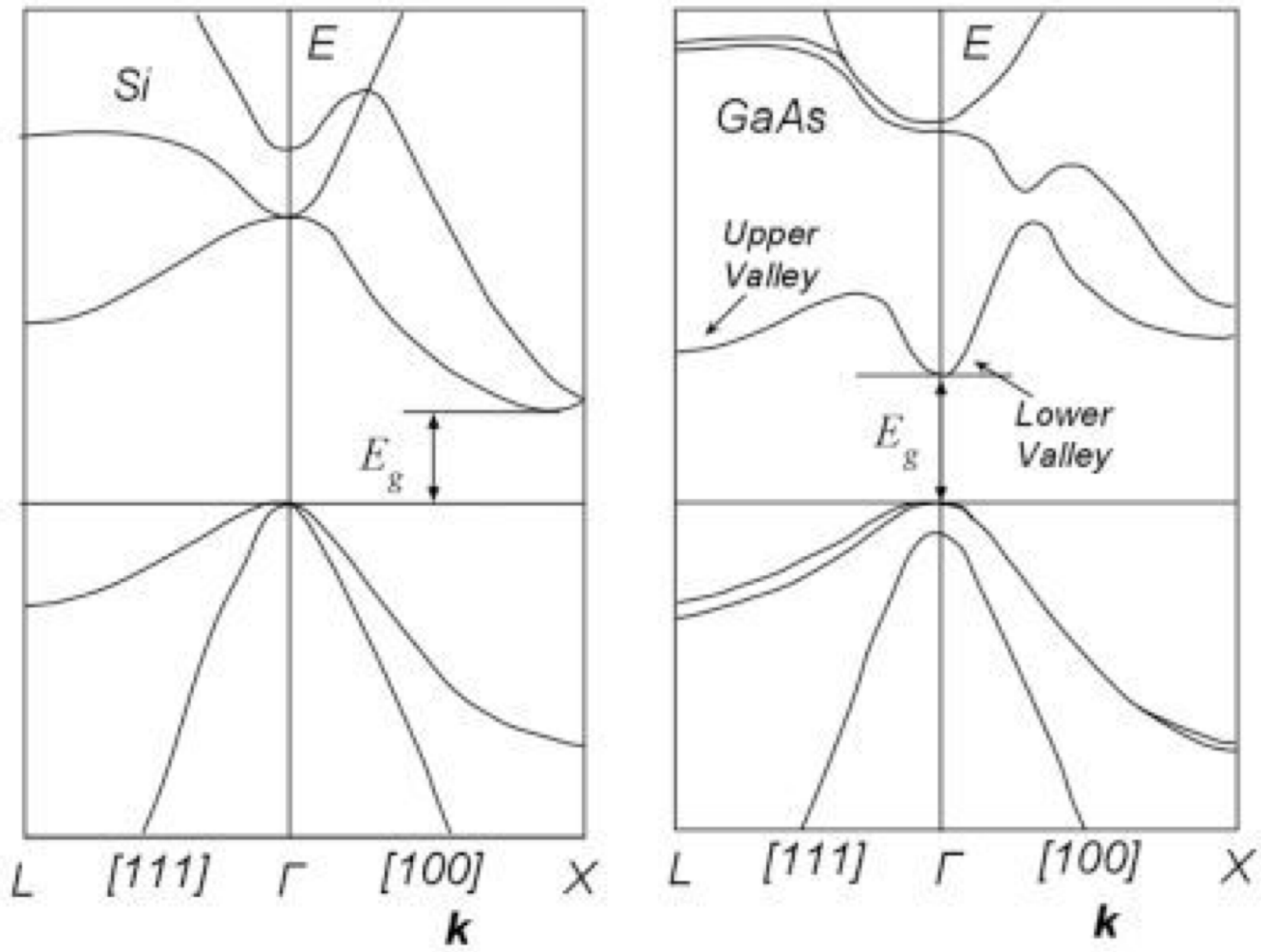
GaAs, CdS, ZnS, InSb, HgTe, GaN



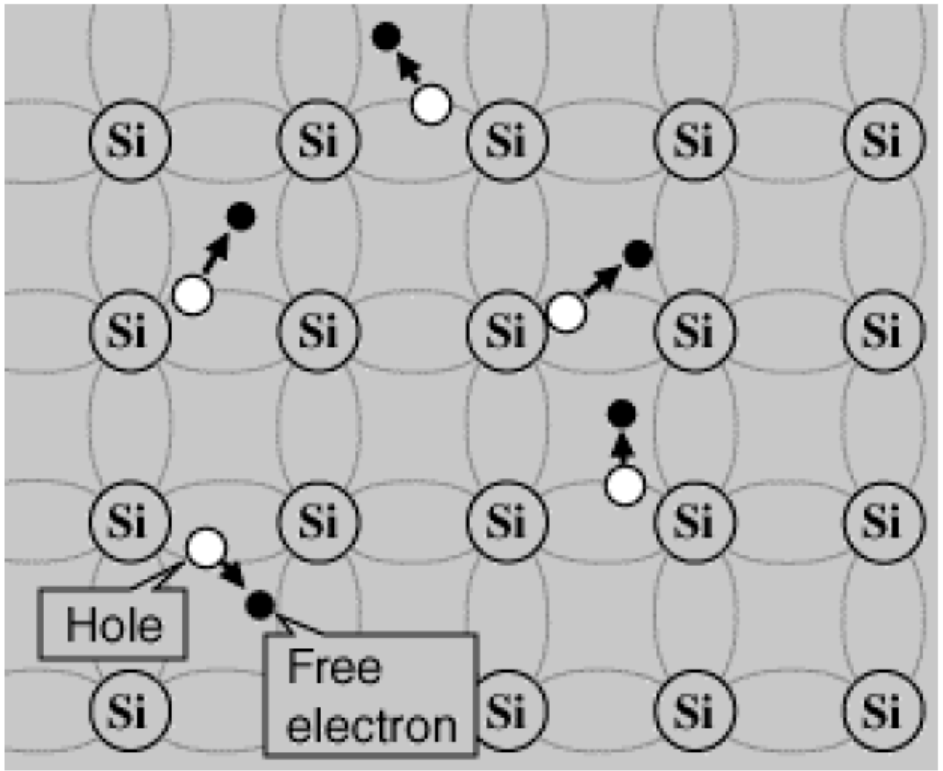
Si, Ge, GaP, AlAs

The change of k value will result from either losing or gaining energy from the lattice vibration (phonons).

E-k diagram of Si and GaAs

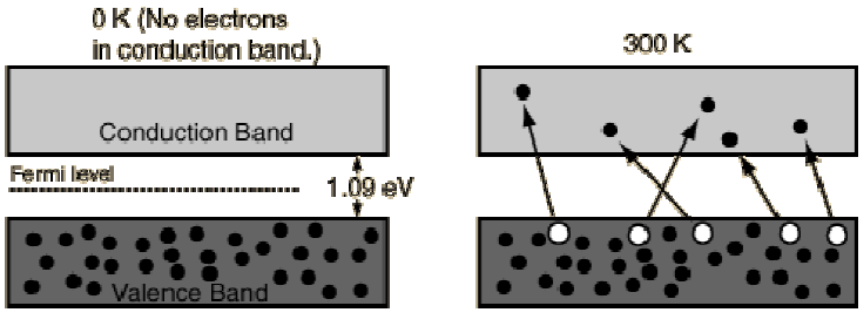


Charge Carrier Concentration

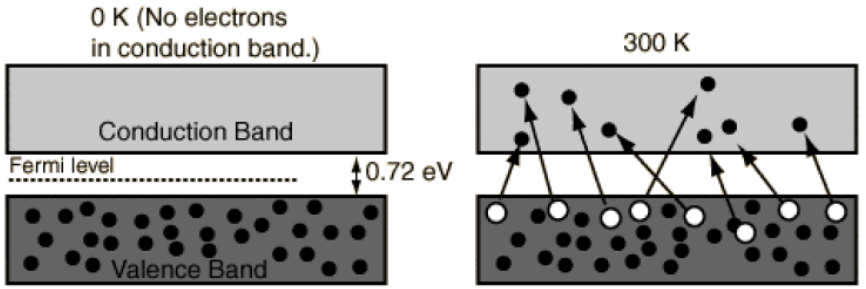


At RT

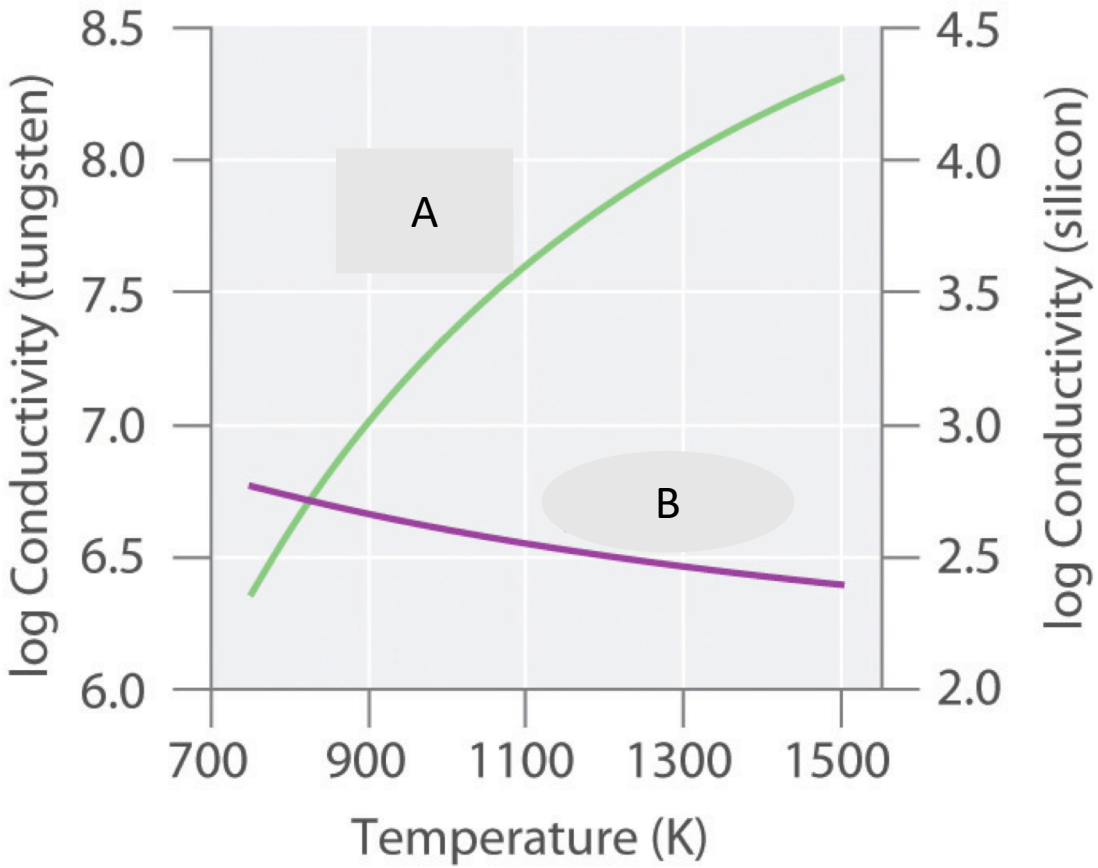
silicon: E_g=1.09 eV



germanium: E_g = 0.72 eV



Temperature and Conductivity



$$\sigma = qn\mu_n$$

Which one of A and B is silicon?

Semiconductor has a negative temperature coefficient: The electrical conductivity of a semiconductor increases with increasing temperature.

Metal has a positive temperature coefficient: The electrical conductivity of a metal decreases with increasing temperature.

At higher temperatures, the metal nuclei collide with the mobile electrons more frequently and with greater energy, thus decreasing the conductivity.
This effect is, however, substantially smaller than the increase in conductivity with temperature exhibited by semiconductors.

Charge Carrier Concentration

- **Charge carrier number = number of states multiplied by % of states occupied by electrons at a given energy.**

- **The density of states** in a semiconductor equals the number of electron states per unit volume per unit energy: energy of the number of solutions to Schrödinger's equation.

- **The Fermi-Dirac distribution** gives the number of electrons, or other fermions, per single-particle state for a macroscopic system at a nonzero temperature.

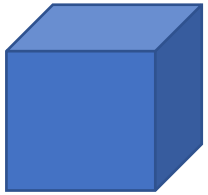
Density of States

Q. How many charge carriers? $\int g(E) \cdot f(E) dE$

$g(E) = Density\ of\ States$

$f(E) = Probability\ of\ occupied\ states$

3D (bulk)



$$g(E) = \frac{(2m)^{3/2}\sqrt{E - E_{min}}}{2\pi^2\hbar^3}$$

2D (slab)

$$g(E) = \frac{m}{\pi\hbar^2}$$

1D (wire)

$$g(E) = \frac{1}{\hbar\pi} \cdot \sqrt{\frac{m}{2E - E_{min}}}$$

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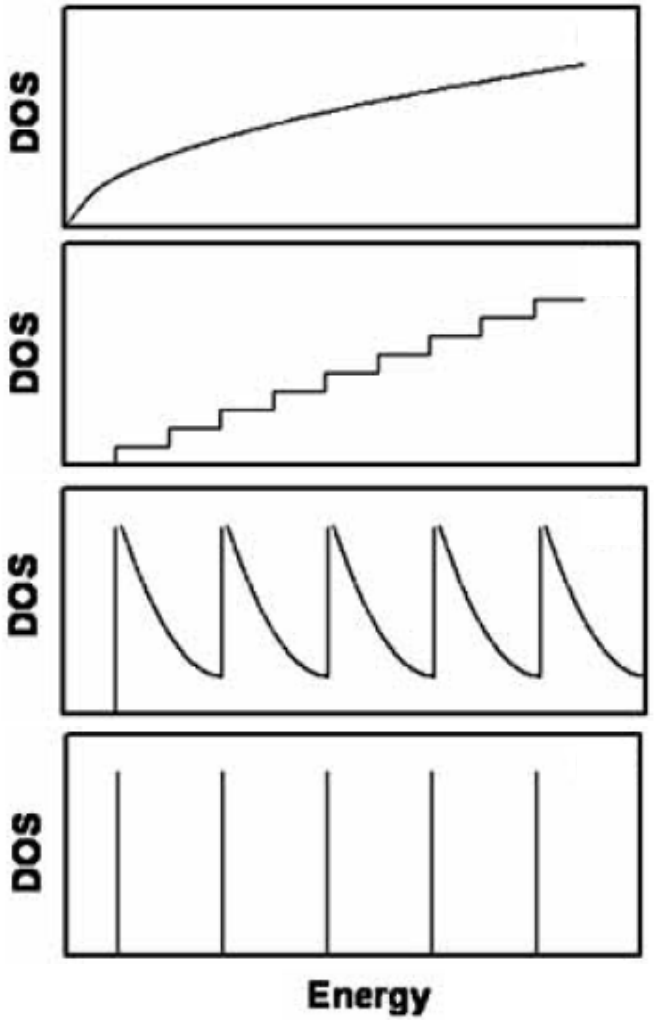
$$g(E) = 2\delta(E - E_{min})$$

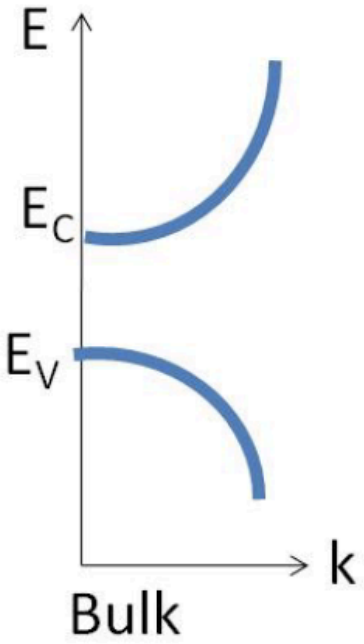


$\hbar = \frac{h}{2\pi}$, reduced planck constant

Density of States

Dimensionality of a material specifies how many dimensions do the carriers of the material act as free carriers.

- **In bulk semiconductor, continuous density of states results in both conduction and valence bands**



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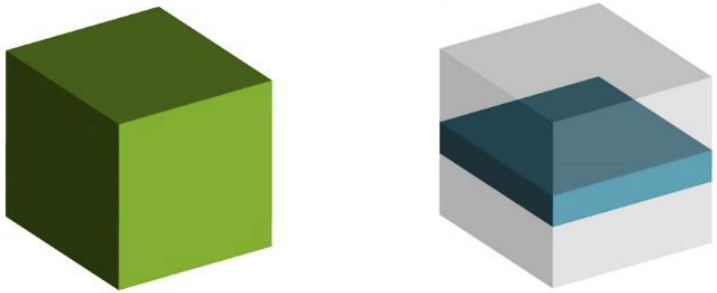

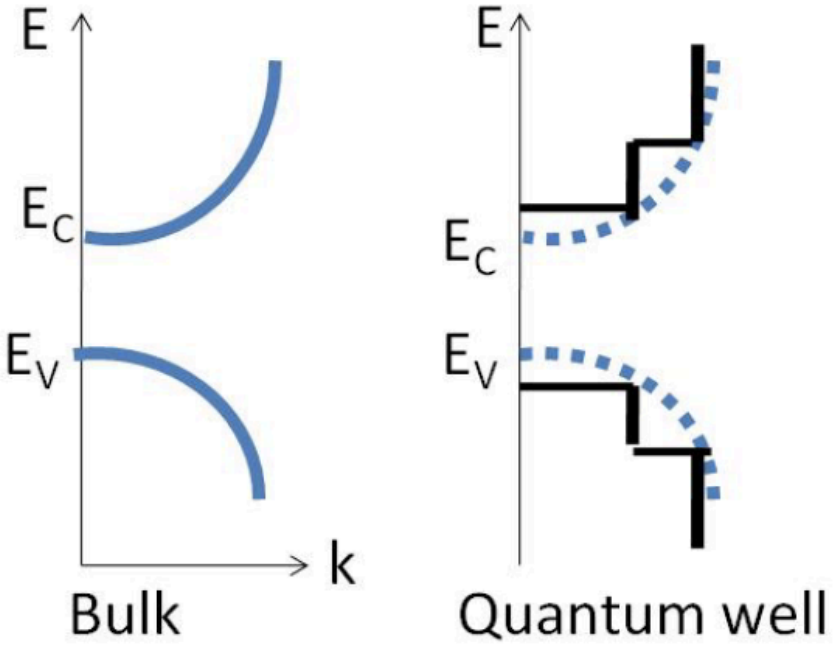

- In bulk semiconductor, continuous density of states results in both conduction and valence bands.
- **A two dimensional system where electrons are confined in one dimension and therefore possess stepwise density of states.**

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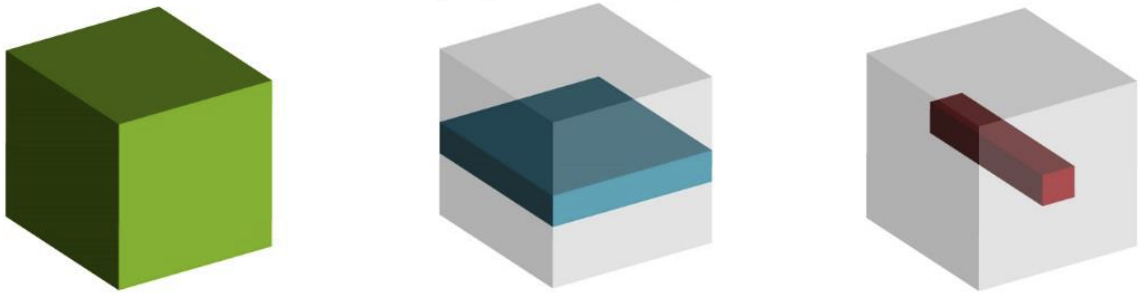

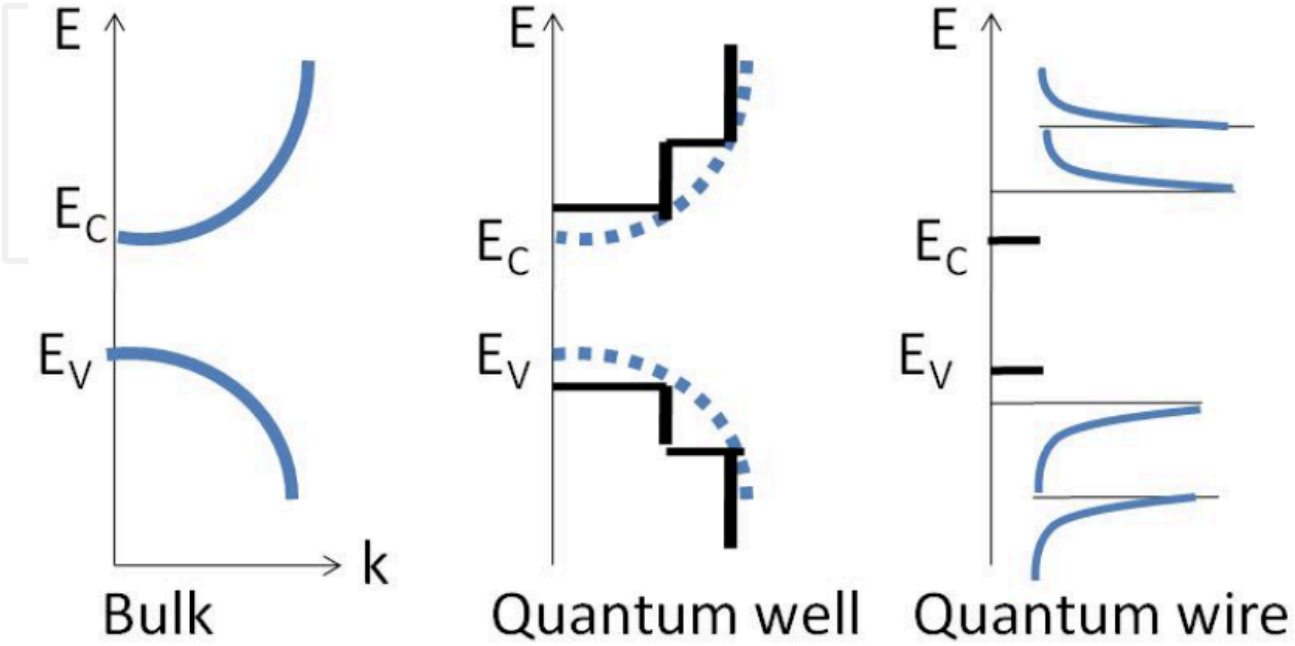

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Density of States

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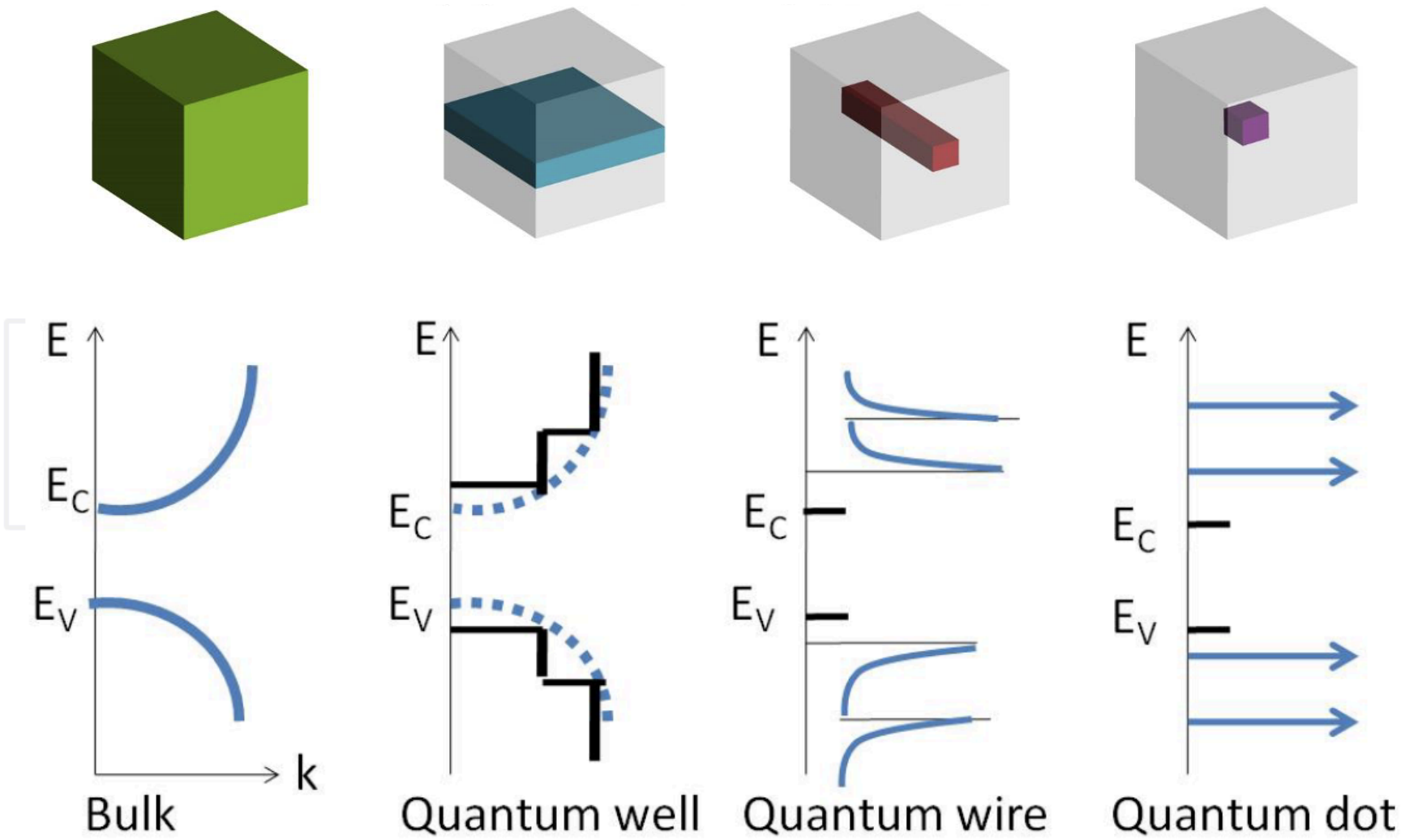

- In bulk semiconductor, continuous density of states results in both conduction and valence bands.
- A two dimensional system where electrons are confined in one dimension and therefore possess step like density of states.
- Quantum wire system is a one dimensional system where electrons are confined in two dimensions.
- **Quantum dot is a zero dimensional system where electron motion is confined in three dimensions. Therefore, a quantum dot possess atomic like DOS.**

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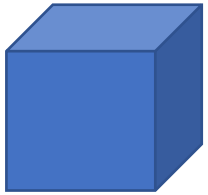

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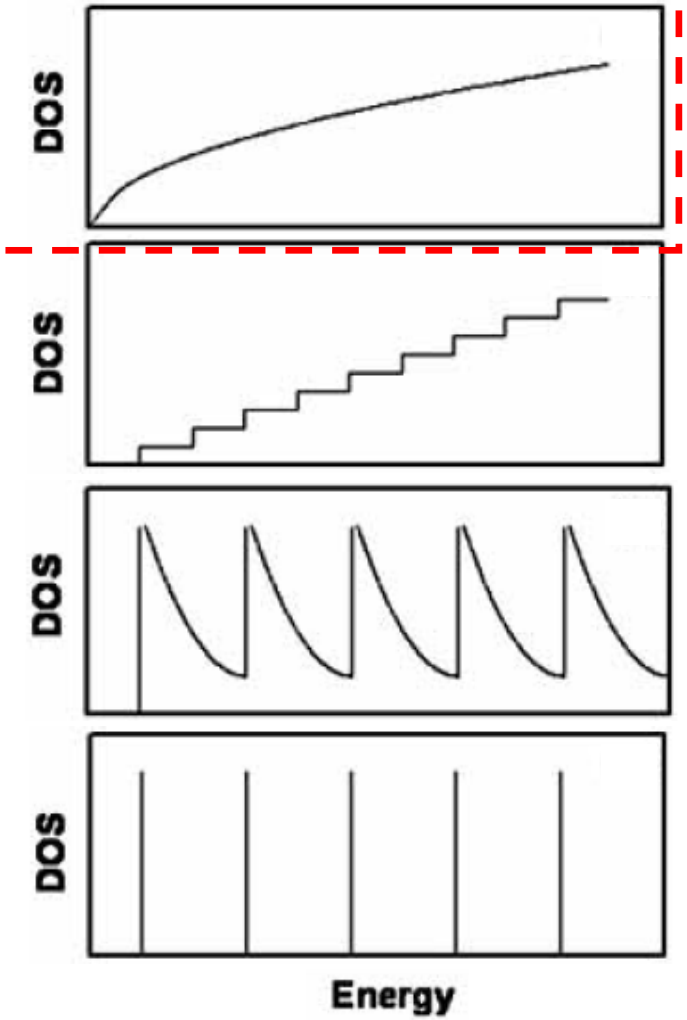

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Fermi-Dirac Distribution Function

Q. How many charge carriers?

$$\int g(E) \cdot f(E) dE$$

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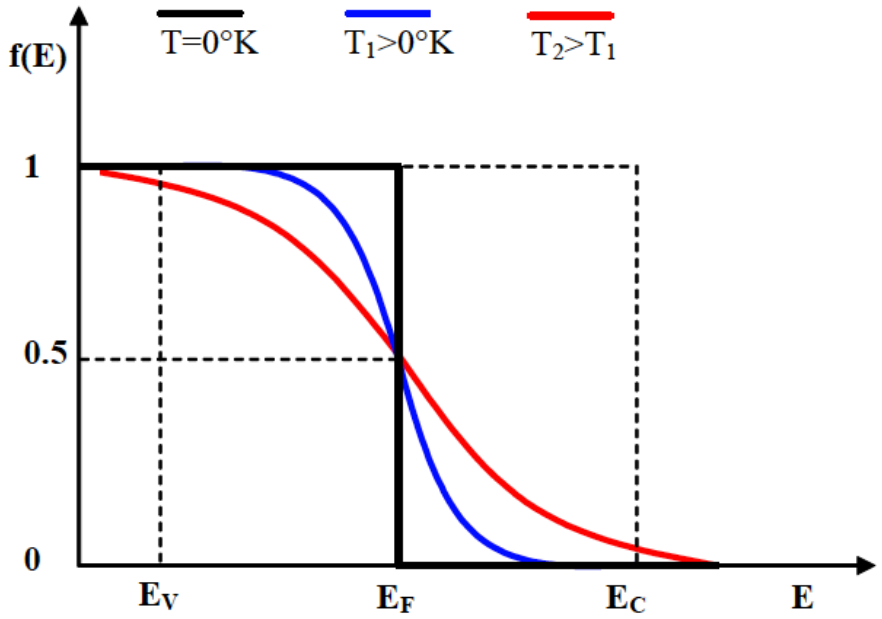
$$f(E) = \frac{1}{1 + \exp(\frac{E - E_F}{k_B T})} \qquad 0 \leq f(E) \leq 1$$



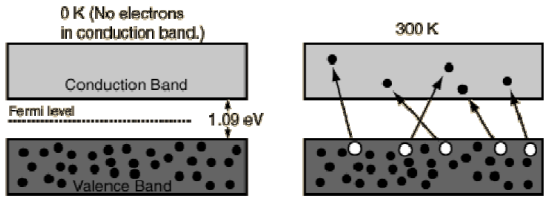
Fermi Level

At T = 0 K

E > E_F: $\frac{1}{1 + \exp(+\infty)} = 0$ E < E_F: $\frac{1}{1 + \exp(-\infty)} = 1$

Probability to find electrons above E_F increases as temperature increases.

silicon: E_g=1.09 eV



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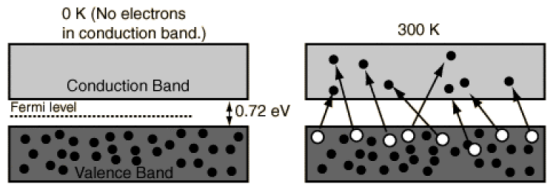

DOS and Fermi-Dirac Distribution Function

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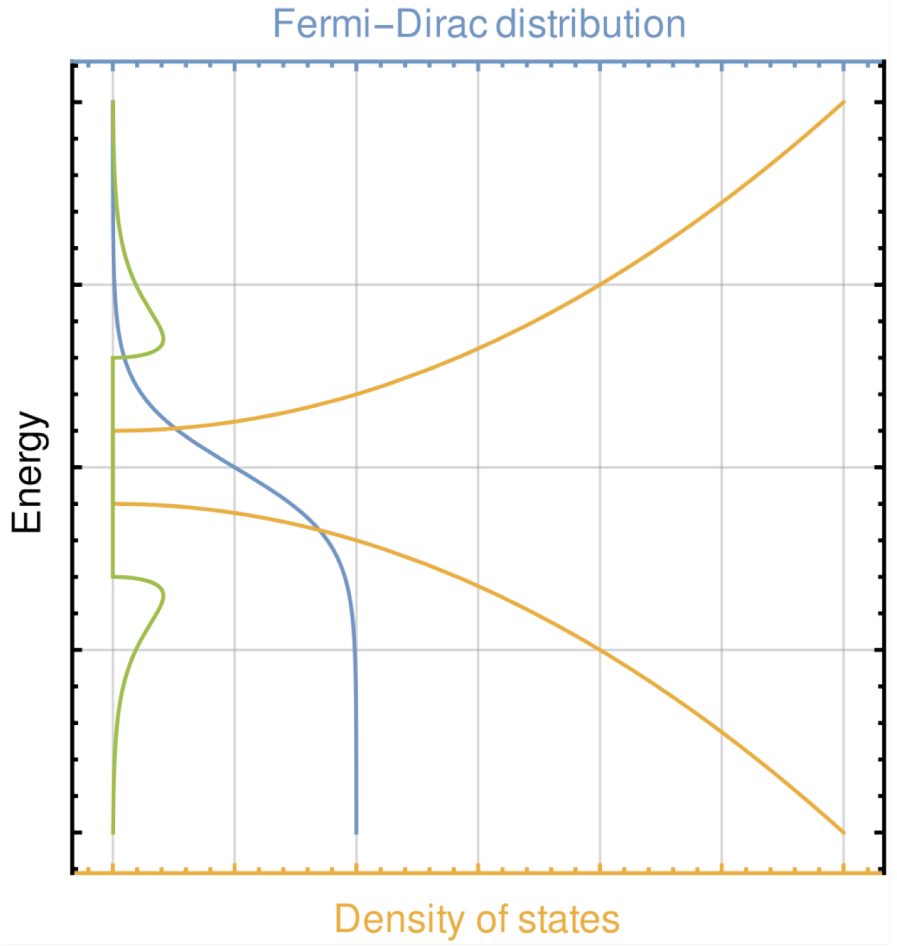
$$n = \int_{E_C}^{E_{top}} g_C(E) \cdot f(E) dE$$

$$p = \int_{E_{bottom}}^{E_V} g_{V(E)} \cdot [1 - f(E)] dE$$



This image is taken from https://en.wikipedia.org/wiki/Density_of_states

Yellow lines: DOS

Blue lines: F-D distribution

Green lines: The product

Solar Energy to The Earth

AM	Comments	Solar constant (W/cm^2)	$h\nu_{av}$	N_{ph} ($cm^{-2}sec^{-1}$)
0	Outside atmosphere	1367	1.48 eV (838 nm)	5.8×10^{17}
1	Sea level, sun at zenith	1040	1.32 eV (939 nm) **Red shift**	5.0×10^{17}
2	Sea level, sun at 60 degree from zenith	840	1.28 eV (969 nm) **Red shift**	4.3×10^{17}
3	Sea level, sun at 70.5 degree from zenith	750	1.21 eV (1025 nm) **Red shift**	3.9×10^{17}
1	Cloudy weather	120	1.44 eV (861 nm) **Blue shift**	5.2×10^{16}

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Air Mass

$$AM \approx 1/\cos(z)$$

This is reasonably accurate for value of z up to around 75 degree.

$$AM = \sqrt{(r\cos(z))^2 + 2r + 1} - r\cos(z)$$

Modelling the atmosphere as a simple spherical shell provides a reasonable approximation(1)

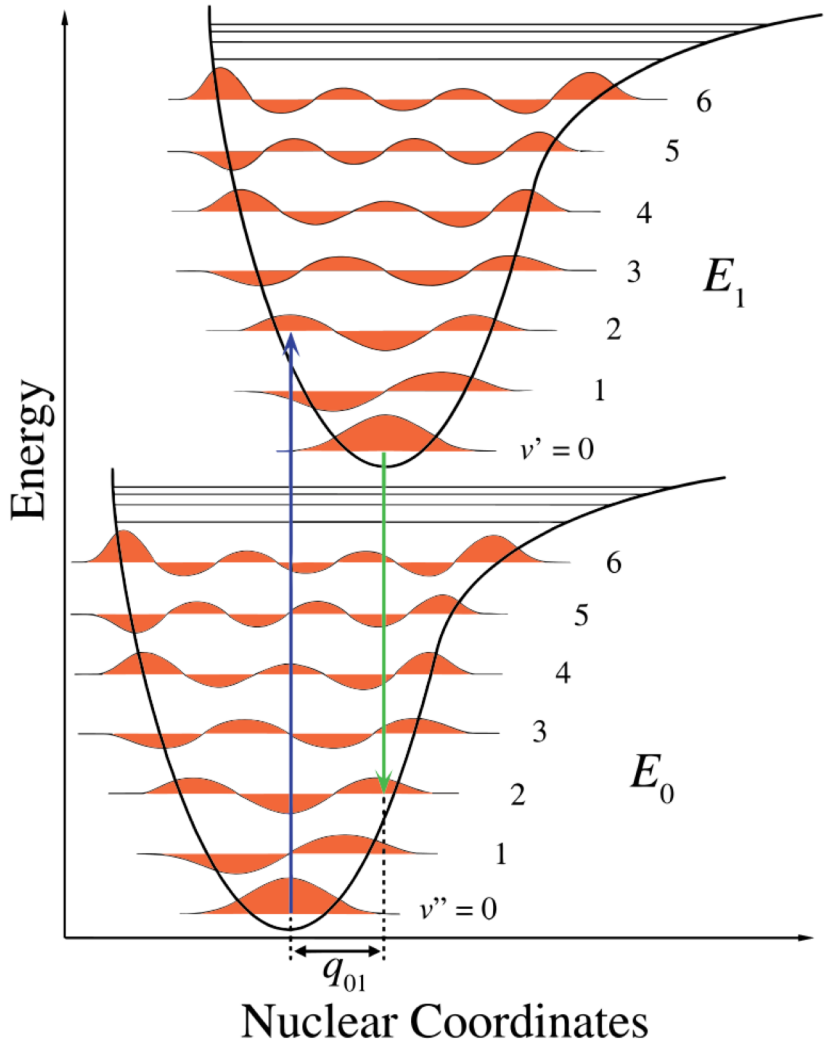
(1) Schoenberg, E. Theoretische Photometrie, g) Über die Extinktion des Lichtes in der Erdatmosphäre. In *Handbuch der Astrophysik*. Band II, erste Hälfte. Berlin: Springer (1929).

r = the radius of the Earth/the effective height of the atmosphere = 6371/9

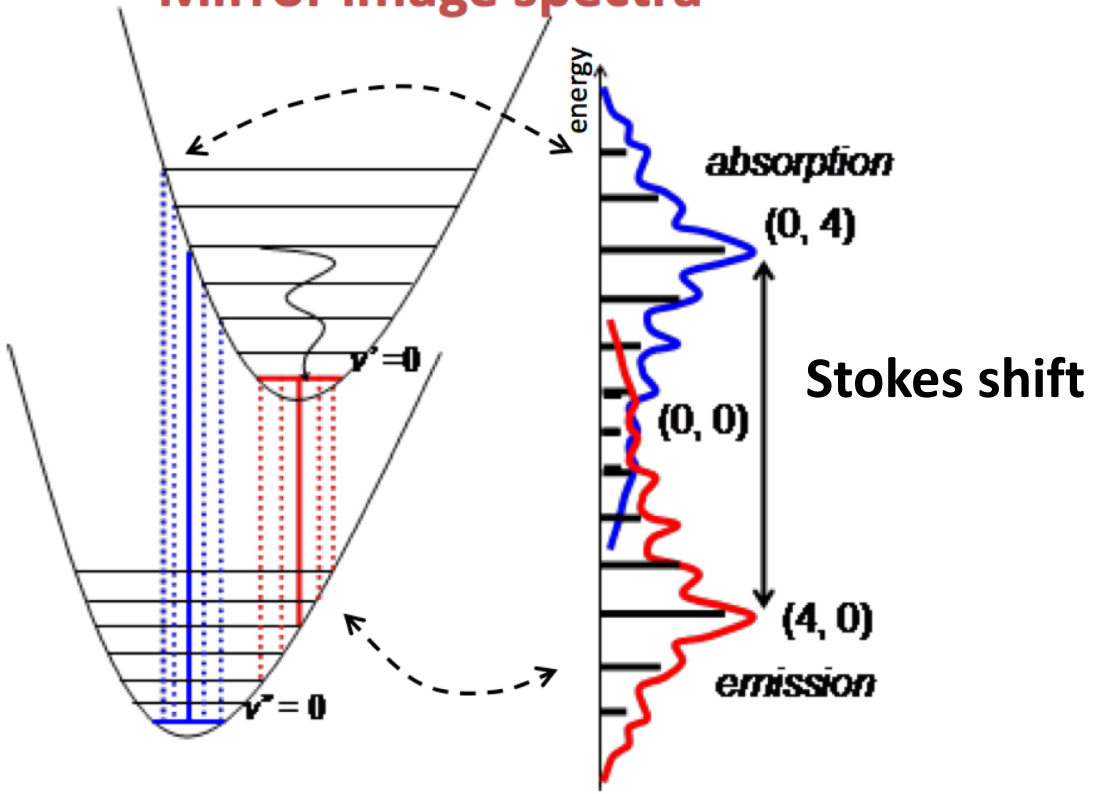
z (degree)	Flat Earth	Spherical shell	Global irradiance (W/m^2)
0	1.0	1.0	1367
48.2	1.5	2.0	840
60	2.0	2.9	710
70	2.9	3.9	620
75	3.9	5.8	470
80	5.8	11.5	254
85	11.5	28.7	96
88	28.7	∞	20
90	∞	37.6	

Recap

Franck-Condon Principle

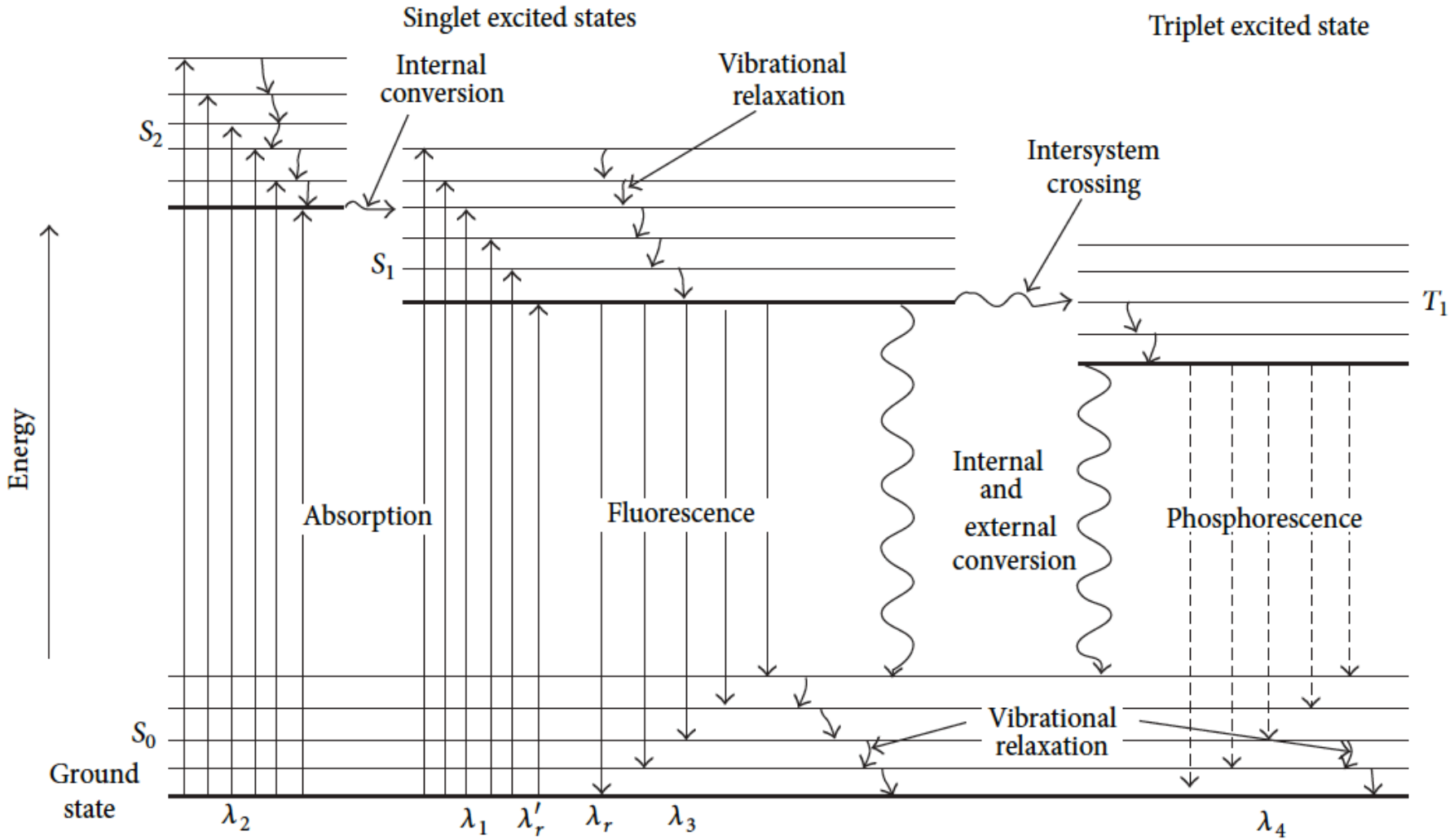


Mirror image spectra



Stokes shift

Recap



Jablonski diagram

T. H. Fereja et al., *ISRN Spectroscopy*, 2013, 12 (2013).

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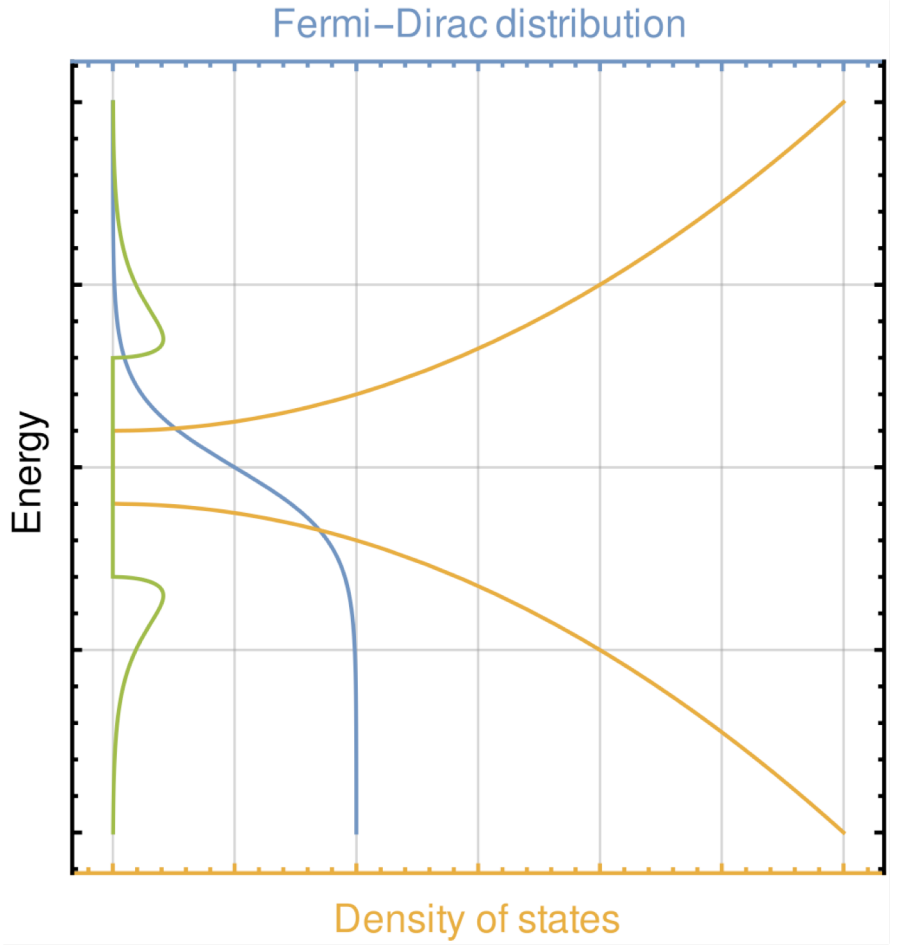

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Yellow lines: DOS

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Number of Carriers

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$f(E) = Probability\ of\ occupied\ states$

$$n = \int_{E_C}^{\infty} g_C(E) \cdot f(E) dE \qquad g_C(E) = \frac{8\pi\sqrt{2} m^{3/2} \sqrt{E - E_c} dE}{h^3} \qquad f(E) = \frac{1}{1 + \exp(\frac{E - E_F}{k_B T})}$$

Boltzmann approximation $\quad f(E) = \exp\left[\frac{-(E - E_F)}{k_B T}\right] \quad if\ E - E_F > 3k_B T$

m^* is the effective mass

$$\boldsymbol{n = 2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{\frac{3}{2}} \cdot exp\left[\frac{(E_F - E_C)}{k_B T}\right] = N_C\, exp\left[\frac{(E_F - E_C)}{k_B T}\right]}$$

N_C is the effective density of states in CB.

$$\boldsymbol{p \cong \int_{-\infty}^{E_V} \frac{8\pi\sqrt{2} m^{\frac{3}{2}} \sqrt{E_V - E}}{h^3} \cdot exp\left[\frac{(E - E_F)}{k_B T}\right] dE = 2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{\frac{3}{2}} \cdot exp\left[\frac{(E_V - E_F)}{k_B T}\right] = N_V\, exp\left[\frac{(E_V - E_F)}{k_B T}\right]}$$

N_V is the effective density of states in VB.

Number of Carriers in Si

$$N_C = 2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{\frac{3}{2}} = 2\left(\frac{2\pi \times 1.08 \times 9.11 \times 10^{-31} kg \times 1.38 \times 10^{-23} m^2 kg s^{-2} K^{-1} \times 300K}{(6.626 \times 10^{-34} m^2 kg s^{-1})^2}\right)^{\frac{3}{2}} = 2.81 \times 10^{25}\ m^{-3}$$

$$= 2.81 \times 10^{19}\ cm^{-3}$$

$$N_V = 2\left(\frac{2\pi m_h^* k_B T}{h^2}\right)^{\frac{3}{2}} = 1.83 \times 10^{19}\ cm^{-3} \qquad with\ m_h^* = 0.81 \times 9.11 \times 10^{-31} kg$$

In an intrinsic semiconductor in the equilibrium *n = p = n_i* (Mass action law)

$$np = n_i^2 = N_C \exp\left[\frac{(E_F - E_C)}{k_B T}\right] \times N_V \exp\left[\frac{(E_V - E_F)}{k_B T}\right] = N_C N_V \exp\left[\frac{(E_V - E_C)}{k_B T}\right] = N_C N_V \exp\left(\frac{-E_g}{k_B T}\right)$$

which is independent of the position of the Fermi level.

$$\boldsymbol{n_i = 8.87 \times 10^9\ cm^{-3}}$$

With $E_g = 1.12\ eV$

$k_B T = 0.0259\ eV$

Calculation results

Name	Symbol	Germanium	Silicon	Gallium Arsenide
Energy bandgap at 300 K	E_g (eV)	0.66	1.12	1.424
Effective mass for density of states calculations				
Electrons	$m_e^*{}_{,dos}/m_0$	0.56	1.08	0.067
Holes	$m_h^*{}_{,dos}/m_0$	0.29	0.81	0.47
Effective density of states in the conduction band at 300 K	N_C (cm^{-3})	1.05×10^{19}	2.82×10^{19}	4.35×10^{17}
Effective density of states in the valence band at 300 K	N_V (cm^{-3})	3.91×10^{18}	1.83×10^{19}	8.07×10^{18}
Intrinsic carrier density at 300 K	**n_i (cm^{-3})**	**1.83×10^{13}**	**8.87×10^{9}**	**2.05×10^{6}**
Effective density of states in the conduction band at 100 ° C (373.15 K)	N_C (cm^{-3})	1.46×10^{19}	3.90×10^{19}	6.03×10^{17}
Effective density of states in the valence band at 100 ° C	N_V (cm^{-3})	5.43×10^{18}	2.53×10^{19}	1.12×10^{19}
Intrinsic carrier density at 100 ° C	**n_i (cm^{-3})**	**3.11×10^{14}**	**8.59×10^{11}**	**6.29×10^{8}**

The Intrinsic Fermi Level

In an intrinsic semiconductor, *n* = *p*. Therefore $E_C - E_F \approx E_F - E_V$ and the Fermi level is nearly at the middle of the band gap, i.e., $E_F \approx E_C - E_g/2$.

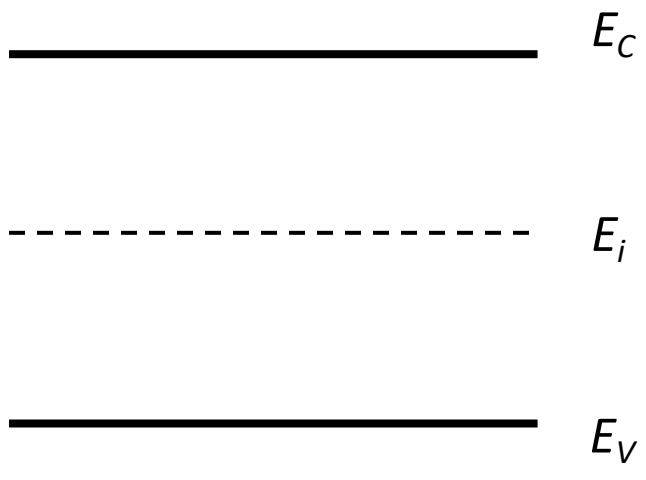
We use these the equation previously mentioned:

$$np = n_i^2 = N_C \exp\left[\frac{(E_F - E_C)}{k_B T}\right] \times N_V \exp\left[\frac{(E_V - E_F)}{k_B T}\right]$$

We denote the position of the Fermi level in the intrinsic material E_i.

$$n_i = N_C \exp\left[\frac{(E_i - E_C)}{k_B T}\right] = N_V \exp\left[\frac{(E_V - E_i)}{k_B T}\right]$$

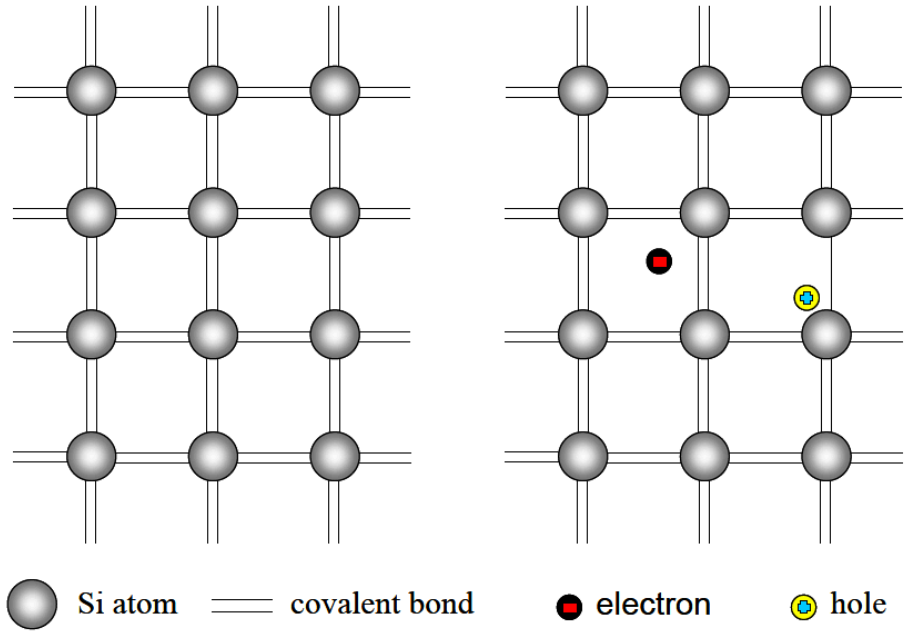
$$\boldsymbol{E_i = \frac{E_C + E_V}{2} + \frac{k_B T}{2} ln\left(\frac{N_V}{N_C}\right) = E_C - \frac{E_g}{2} + \frac{k_B T}{2} ln\left(\frac{N_V}{N_C}\right)}$$



A slight shift is caused by the difference in N_C and N_V,
ex) 0.01 eV for Si

Doped Semiconductors

Intrinsic SC



At 0 K **> 0 K**

Electrical conductivity of intrinsic Si!

$$\sigma = e(n\mu_e + p\mu_h)$$

Intrinsic carrier concentration: 8.87 x 10^9 cm^{-3}
Electron mobility = 1000 $cm^2V^{-1}s^{-1}$
Hole mobility = 500 $cm^2V^{-1}s^{-1}$

$$\sigma = 2.13 \times 10^{-6}\ \Omega^{-1}cm^{-1}$$

Doped Semiconductors

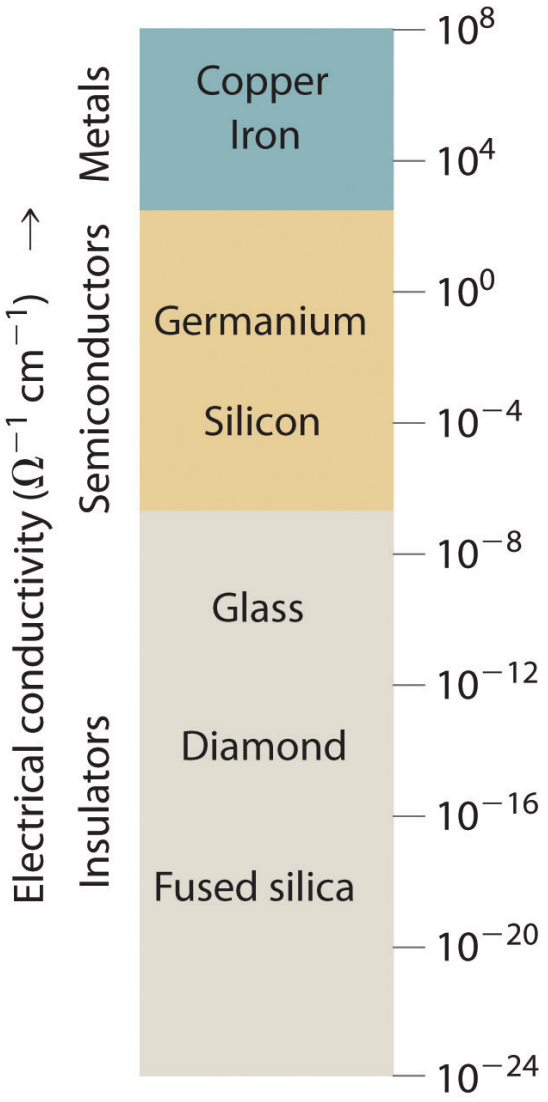


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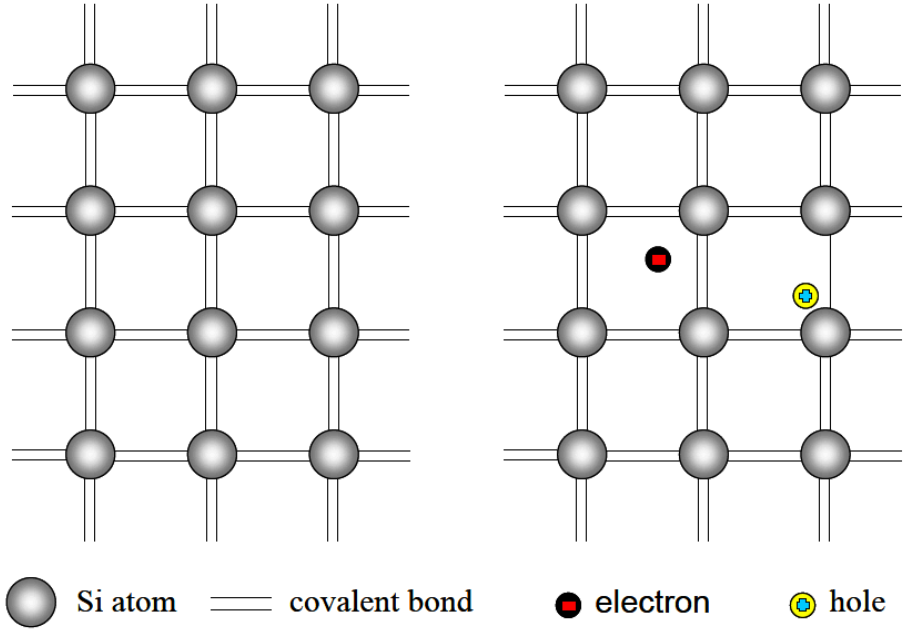
Image taken from
https://chem.libretexts.org/Courses/Northern_Michigan_University/CH_215%3A_Chemistry_of_the_Elements_Fall_2023/05%3A_Solids_and_Solid-State_Chemistry/5.14%3A_Bonding_in_Metals

Doped Semiconductors

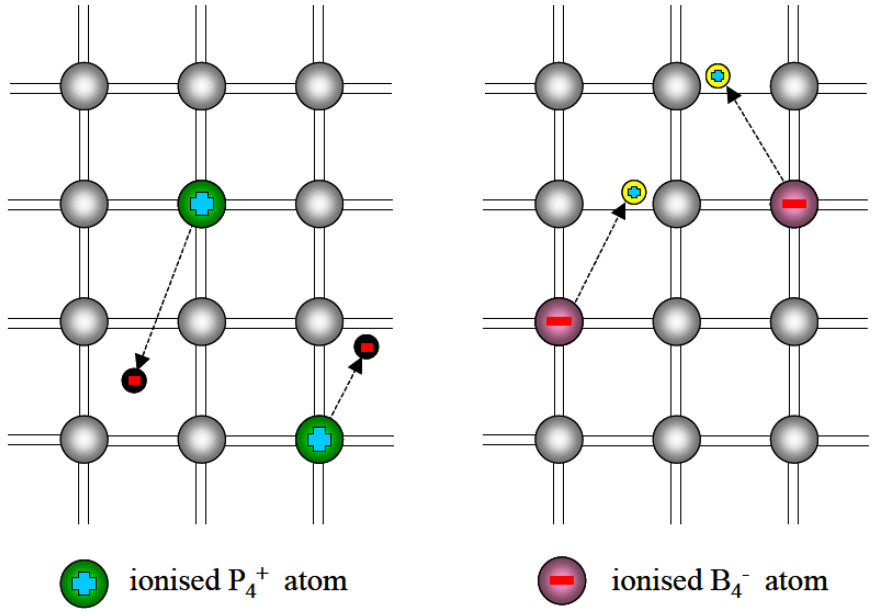
The doping process can greatly alter the electrical characteristics of the semiconductor.
This doped semiconductor is called an extrinsic material.

Intrinsic SC

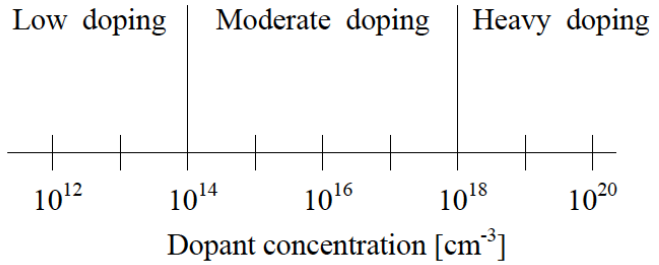


At 0 K **> 0 K**

Extrinsic SC



Donor (D, N_D) **Acceptor (A, N_A)**



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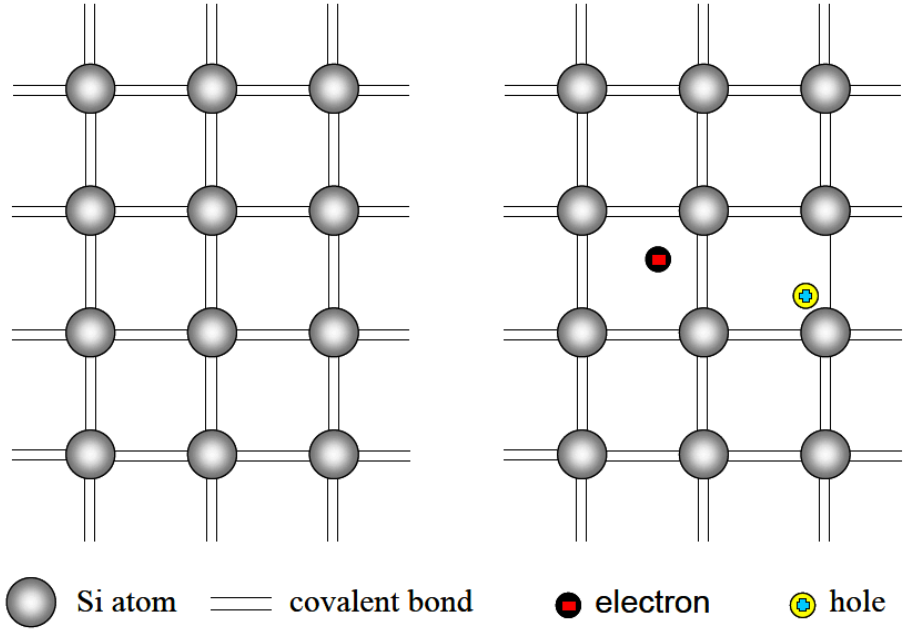
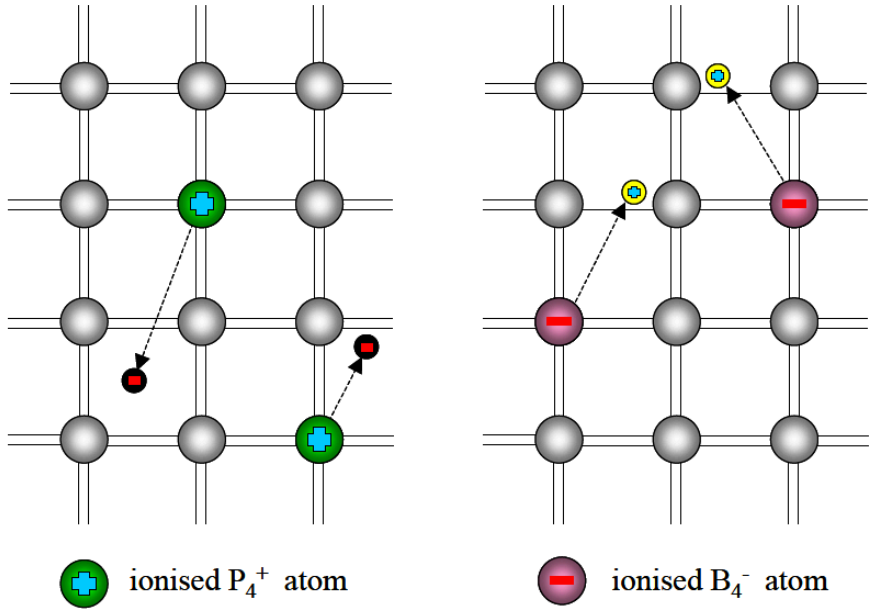


At 0 K **> 0 K**

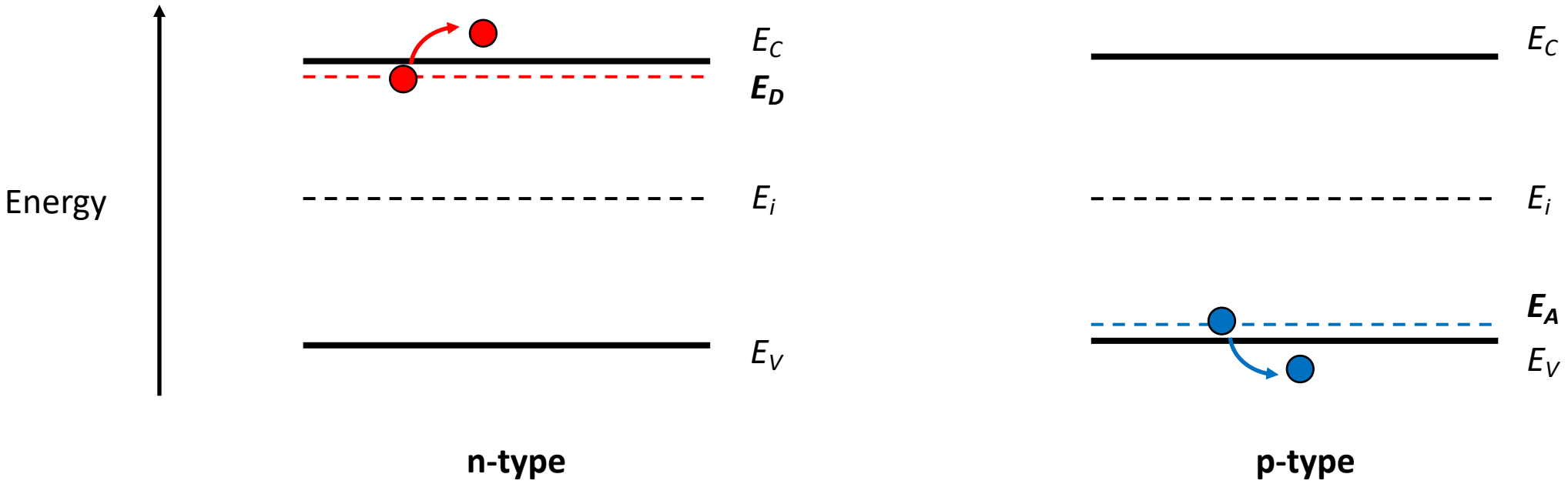
Extrinsic SC



	n-type	p-type
Majority carriers	**e^-**	**h^+**
Minority carriers	**h^+**	**e^-**

Ionization

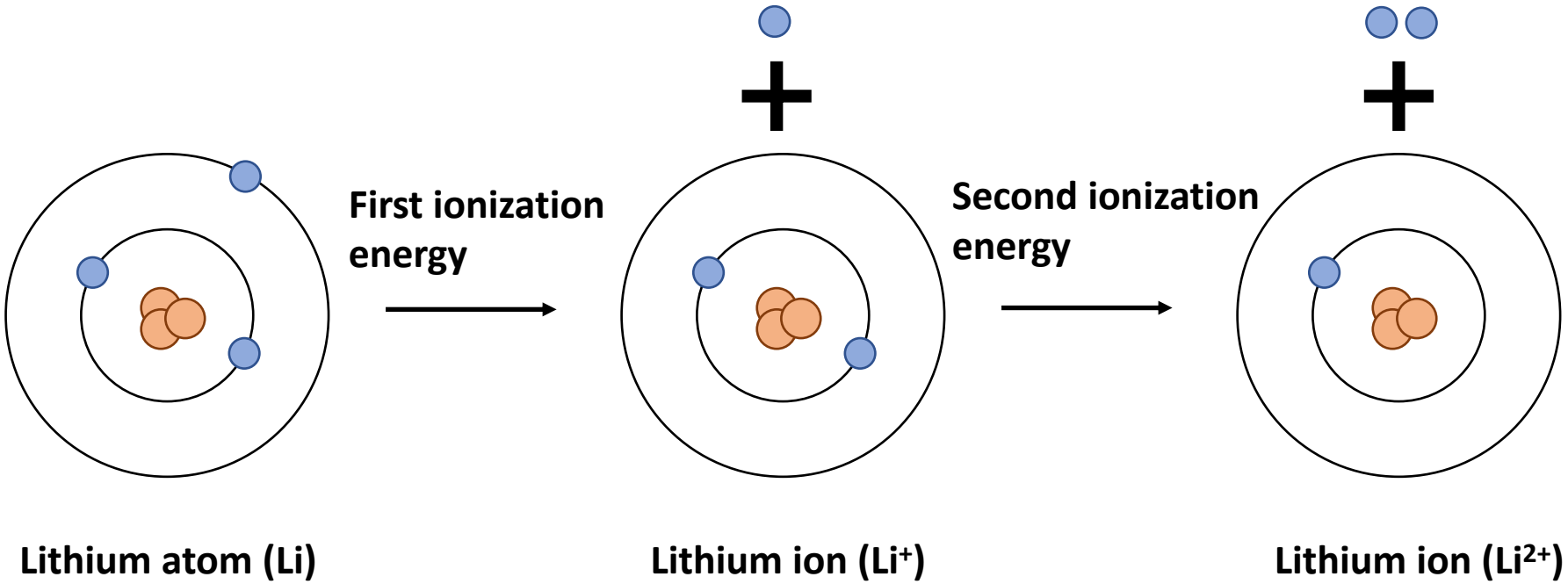
The concentration of electrons and holes is influenced by the amount of the impurity atoms that substitute semiconductor atoms in the lattice.
Donor (Acceptor) atoms introduce donor energy levels, E_D (Acceptor Energy levels, E_A) near the C.B (V.B.) so that the electrons (the holes) exited to C.B. (V.B.) at R.T: **Ionization**.



Ionization Energy

Ionization energy (I.E.) (Ionization potential) is **the amount of energy** required to remove the most loosely attached **1 mole electron** from **an isolated gaseous 1 mole neutral atom**, which forms an ion (eV or kJ/mol).

$$X + \text{I.E.}\ (1^{st}) \rightarrow X^{+} + e^{-}$$
$$X^{+} + \text{I.E.}\ (2^{nd}) \rightarrow X^{2+} + e^{-}$$



Ionization Energy of Donors and Acceptors

The energy required to ionize a donor atom (i.e., to free the extra electron and leave a positive ion behind) can be estimated by modifying the theory of the ionization energy of a hydrogen atom,

$$E_H = \frac{m_0 q^4}{8\varepsilon_0^2 h^2} = 13.6 \text{ eV}$$

Small modification includes:

$$E_{ion} = \frac{m^* q^4}{8(\varepsilon_0 \varepsilon_r)^2 h^2}$$

The result is about 24.6 meV and 37.1 meV for donor energy and acceptor energy. Because of such small ionization energies, they are usually fully ionized at room temperature.

	Donors			Acceptors		
Dopant	Sb	P	As	B	Al	In
Ionization Energy (meV)	39	44	54	45	57	160
	$E_C - E_D$			$E_A - E_V$		

Carrier Concentration in Doped Semiconductors

Under equilibrium conditions, the local charge is zero in the uniformly doped semiconductor
= the charge neutrality condition

$$p + N_D^+ - n - N_A^- = 0$$

By definition

$$N_D^+ = N_D - n_D$$

$$N_A^- = N_A - p_A$$

$$p + (N_D - n_D) = n + (N_A - p_A)$$

n : thermal-equilibrium concentration of electrons
p : thermal-equilibrium concentration of holes
n_D : concentration of electrons in the donor energy state
p_A : concentration of holes in the acceptor energy state
N_D : concentration of donor atoms
N_A : concentration of acceptor atoms
N_D^+ : concentration of positively charged donors (ionized donors)
N_A^- : concentration of negatively charged acceptors (ionized acceptors)

At room temperature we assume complete ionization. $n_D = p_A = 0$

$$p + N_D = n + N_A$$

Mass action law: $np = n_i^2$

$$\boldsymbol{n = 1/2\left[(N_D - N_A) + ((N_D - N_A)^2 + 4n_i^2)^{1/2}\right]} \qquad \boldsymbol{N_D > N_A} \qquad \text{For n-type}$$

$$\boldsymbol{p = 1/2\left[(N_A - N_D) + ((N_A - N_D)^2 + 4n_i^2)^{1/2}\right]} \qquad \boldsymbol{N_A > N_D} \qquad \text{For p-type}$$

Determine the thermal equilibrium e^- and h^+ concentrations

Example 1) Consider a silicon semiconductor at T = 300 °K in which N_D = 10^{16} cm^{-3} and N_A = 3 x 10^{15} cm^{-3}. Assume that n_i =1 x 10^{10} cm^{-3}. Calculate the carrier concentrations (electrons and holes)!

Solution 1)
The majority carrier electron concentration is
$n = 1/2\left[(N_D - N_A) + ((N_D - N_A)^2 + 4n_i^2)^{1/2}\right]$ = 7 x 10^{15} cm^{-3}

The minority carrier hole concentration is
$p = n_i^2/n$ = (1 x 10^{10})^2/(7 x 10^{16}) = 1.43 x 10^4 cm^{-3}

if $N_D - N_A \gg n_i$ $\quad n = N_D - N_A$ $\quad p = n_i^2/(N_D - N_A)$

if $N_A - N_D \gg n_i$ $\quad p = N_A - N_D$ $\quad n = n_i^2/(N_A - N_D)$

Determine the thermal equilibrium e^- and h^+ concentrations

Example 2) Consider an n-type silicon semiconductor at T = 300 °K in which $N_D = 10^{16}$ cm^{-3} and $N_A = 0$. The intrinsic carrier concentration is assumed to be $n_i = 1 \times 10^{10}$ cm^{-3}. Calculate the carrier concentrations!

Solution 2)
The majority carrier electron concentration is
$n = 1/2\left[(N_D - N_A) + ((N_D - N_A)^2 + 4n_i^2)^{1/2}\right] = 10^{16}$ cm^{-3}

The minority carrier hole concentration is
$p = n_i^2/n = (1 \times 10^{10})^2/10^{16} = 1 \times 10^4$ cm^{-3}

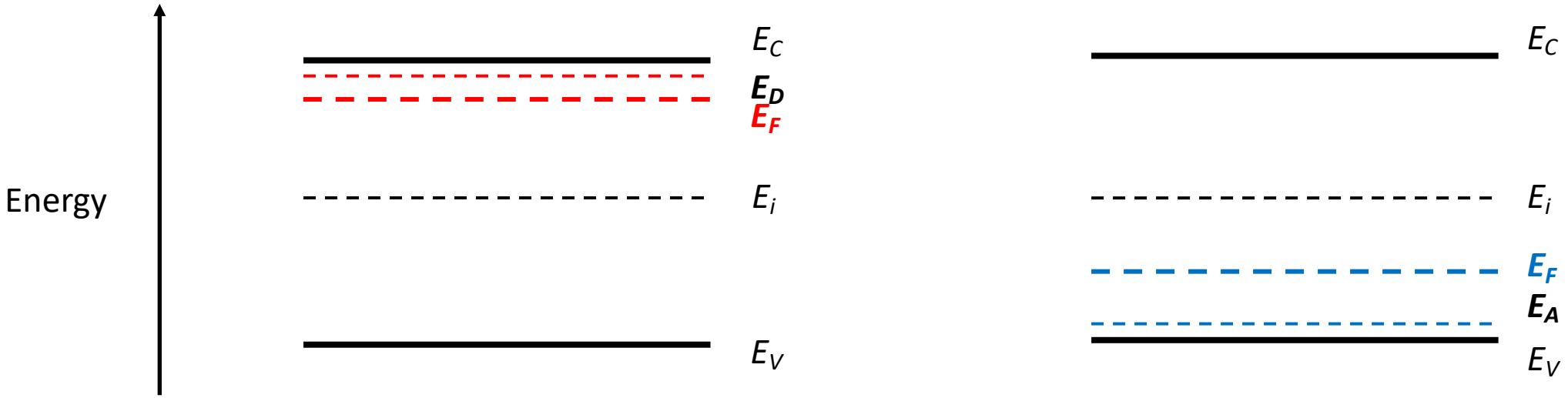
if $\boldsymbol{N_D \gg N_A}$	$\boldsymbol{n = N_D}$	$\boldsymbol{p = n_i^2/N_D}$
if $\boldsymbol{N_A \gg N_D}$	$\boldsymbol{p = N_A}$	$\boldsymbol{n = n_i^2/N_A}$

The Fermi Level in Doped Semiconductors

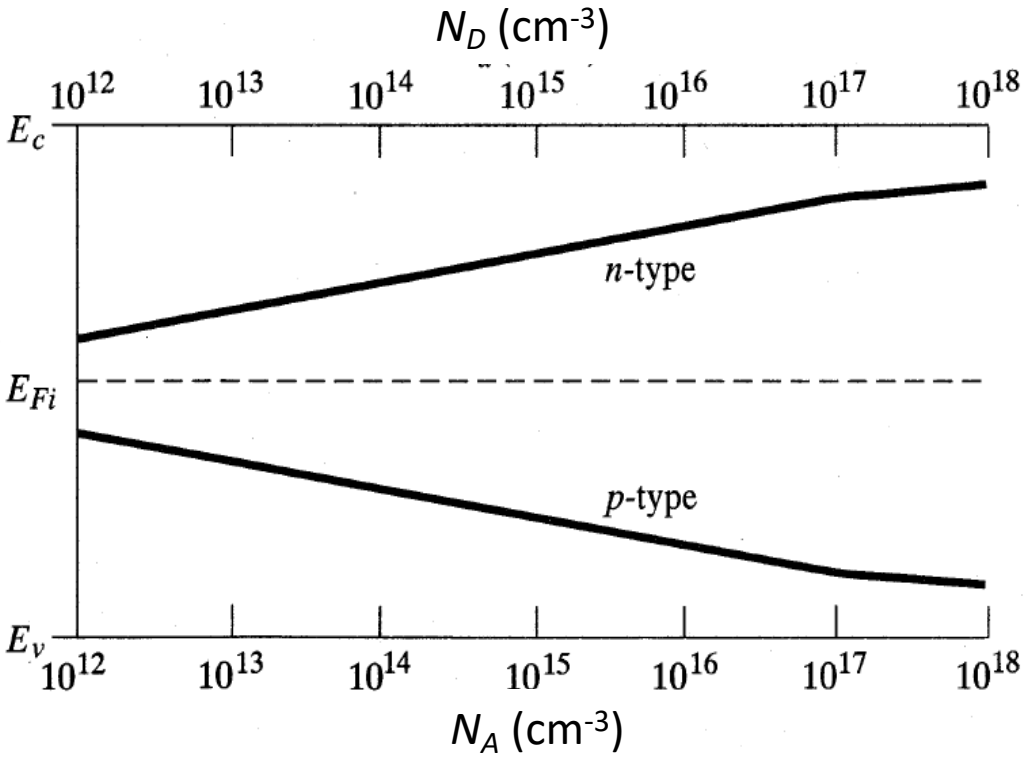
Example) Where is E_F located in the energy band of silicon, at 300 °K with n = 10^{17} cm^{-3}? And for p = 10^{14} cm^{-3}?

Solution) $n = N_C \exp\left[\frac{(E_F - E_C)}{k_B T}\right] \longrightarrow E_C - E_F = k_B T ln\left(\frac{N_C}{n}\right) = 0.146\ eV$ $\quad with\ N_C = 2.81 \times 10^{19}\ cm^{-3}$

Solution) $p = N_V \exp\left[\frac{(E_V - E_F)}{k_B T}\right] \longrightarrow E_F - E_V = k_B T ln\left(\frac{N_V}{p}\right) = 0.314\ eV$ $\quad with\ N_V = 1.83 \times 10^{19}\ cm^{-3}$



The Fermi Level in Doped Semiconductors



Position of Fermi level as a function of donor and acceptor concentration.

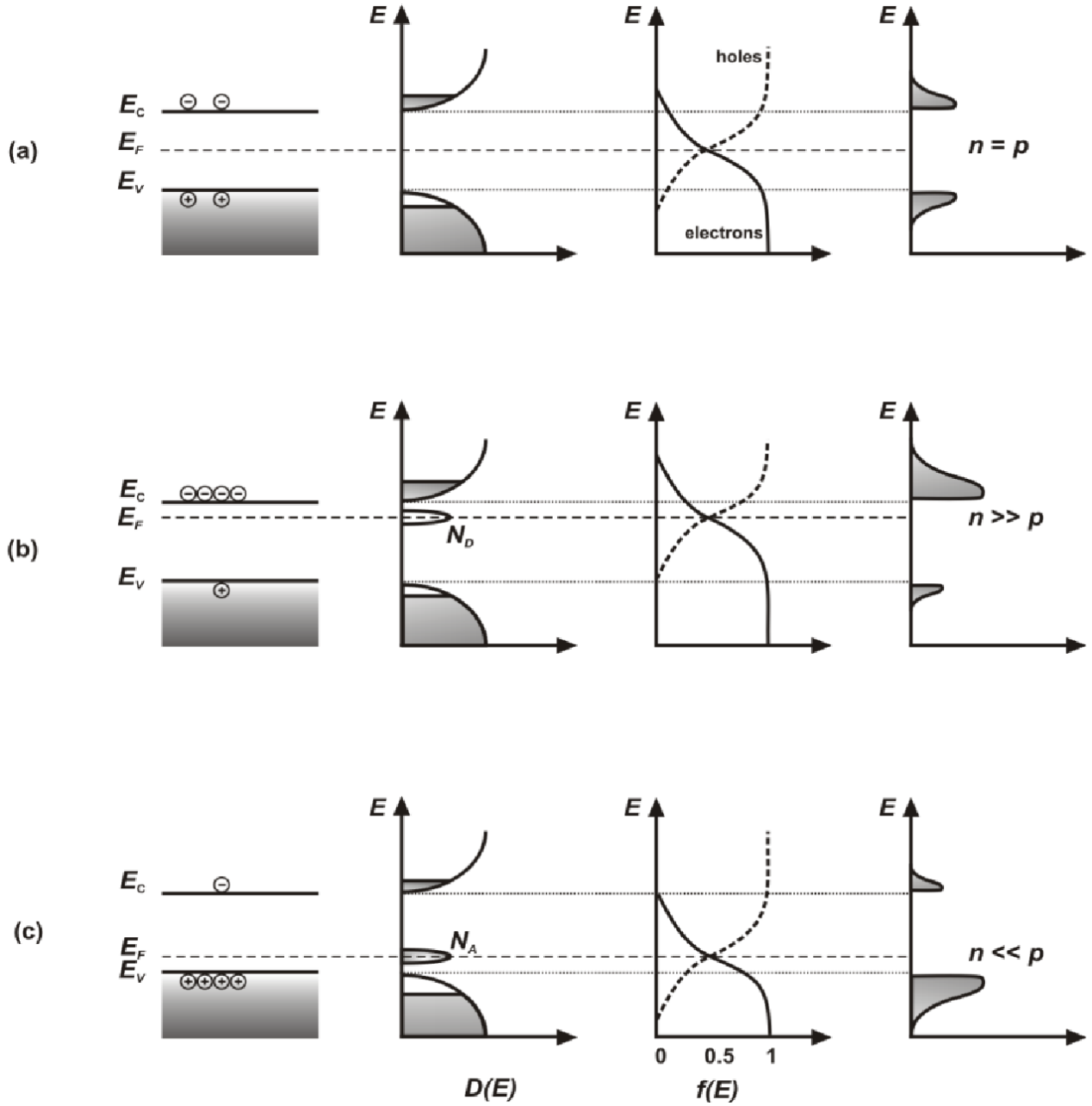
$$\boldsymbol{E_F\ for\ n-type} \qquad E_C - E_F = k_B T ln\left(\frac{N_C}{n}\right) = k_B T ln\left(\frac{N_C}{N_D}\right)$$

$$E_F - E_{Fi} = k_B T ln\left(\frac{n}{n_i}\right)$$

$$\boldsymbol{E_F\ for\ p-type} \qquad E_F - E_V = k_B T ln\left(\frac{N_V}{p}\right) = k_B T ln\left(\frac{N_V}{N_A}\right)$$

$$E_{Fi} - E_F = k_B T ln\left(\frac{p}{n_i}\right)$$

Carrier Concentration in Intrinsic and Extrinsic SCs



Doped Semiconductors

At room temperature we assumed complete ionization. $n_D = p_A = 0$

If this is not true???

The derivation of the Fermi-Dirac probability function was derived considering the Pauli exclusion principle. This principle also applies to the donor and acceptor states.

$$f(E) = \frac{1}{1 + \exp(\frac{E - E_F}{k_B T})} \quad \rightarrow \quad \frac{n_D}{N_D} = \frac{1}{1 + \frac{1}{g}\exp(\frac{E_D - E_F}{k_B T})}$$

g = 2 for electron
g = 4 for holes (Si, GaAs due to two-fold degeneracy of the V.B. e.g. heavy hole and light hole)

We assumed $E_D - E_F \gg k_B T$, $\quad n_D \approx \frac{N_D}{\frac{1}{2}\exp(\frac{E_D - E_F}{k_B T})} = 2N_D \exp(\frac{E_F - E_D}{k_B T})$

$$\frac{electrons\ in\ the\ donor\ state}{total\ electrons} = \frac{n_D}{n_D + n} = \frac{2N_D \exp(\frac{E_F - E_D}{k_B T})}{2N_D \exp(\frac{E_F - E_D}{k_B T}) + N_C \exp\left(\frac{E_F - E_C}{k_B T}\right)} = \frac{1}{1 + \frac{N_C}{2N_D}\exp\left(\frac{E_D - E_C}{k_B T}\right)}$$

Doped Semiconductors

Let's determine the fraction of electrons are still in the donor state at T = 300 ^{o}K in the case of P donor atoms in Si (N_D=10^{17} cm^{-3}).

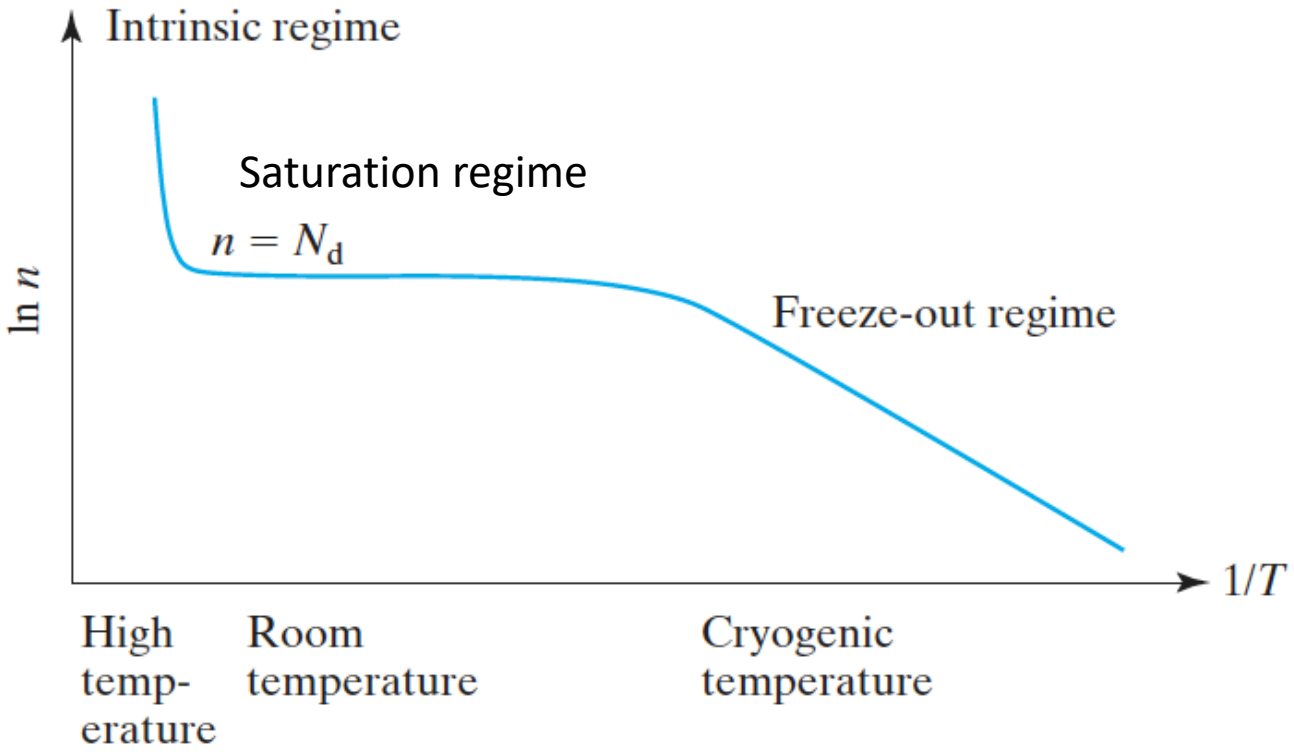
$$\frac{n_D}{n_D + n} = \frac{1}{1 + \frac{2.82 \times 10^{19}}{2(10^{17})} \exp\left(\frac{44\ meV}{25.9\ meV}\right)} = 0.0013 = 0.13\%$$

This example shows that at RT only few electrons are in the donor state compared with the C.B. Only 0.13% of the donor states contain electrons.
The same is valid for the acceptor states.

What if T = 0 ^{o}K or much higher than RT?

Temperature Dependence of the Carrier Concentration

- In Freeze-out regime, donor atoms are only partially ionized.
- In the saturation regime, donors are fully ionized and carrier concentration is a constant.
- At high T, it behaves like an intrinsic semiconductor.



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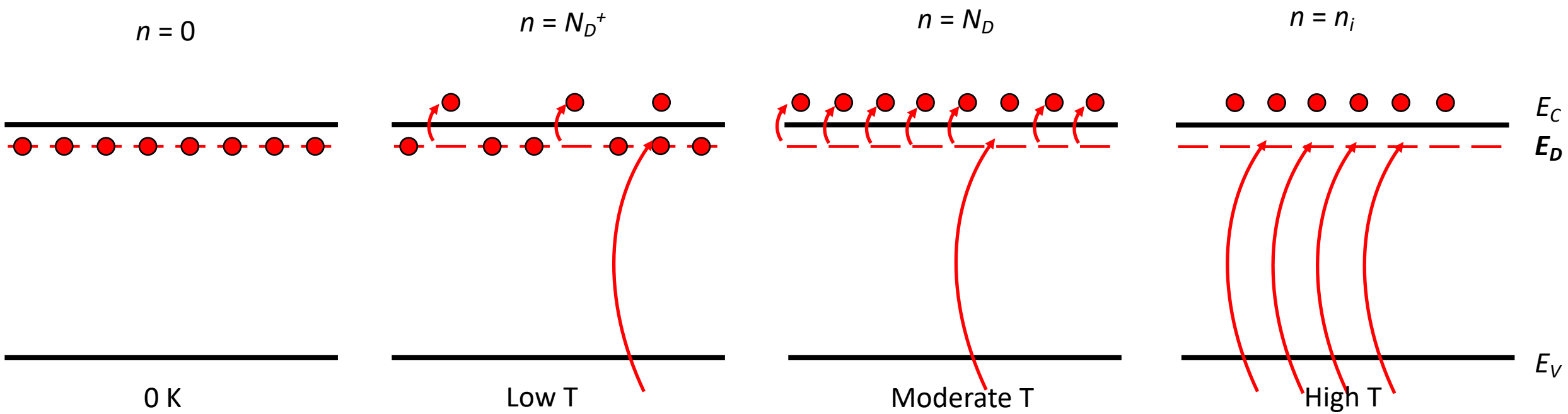
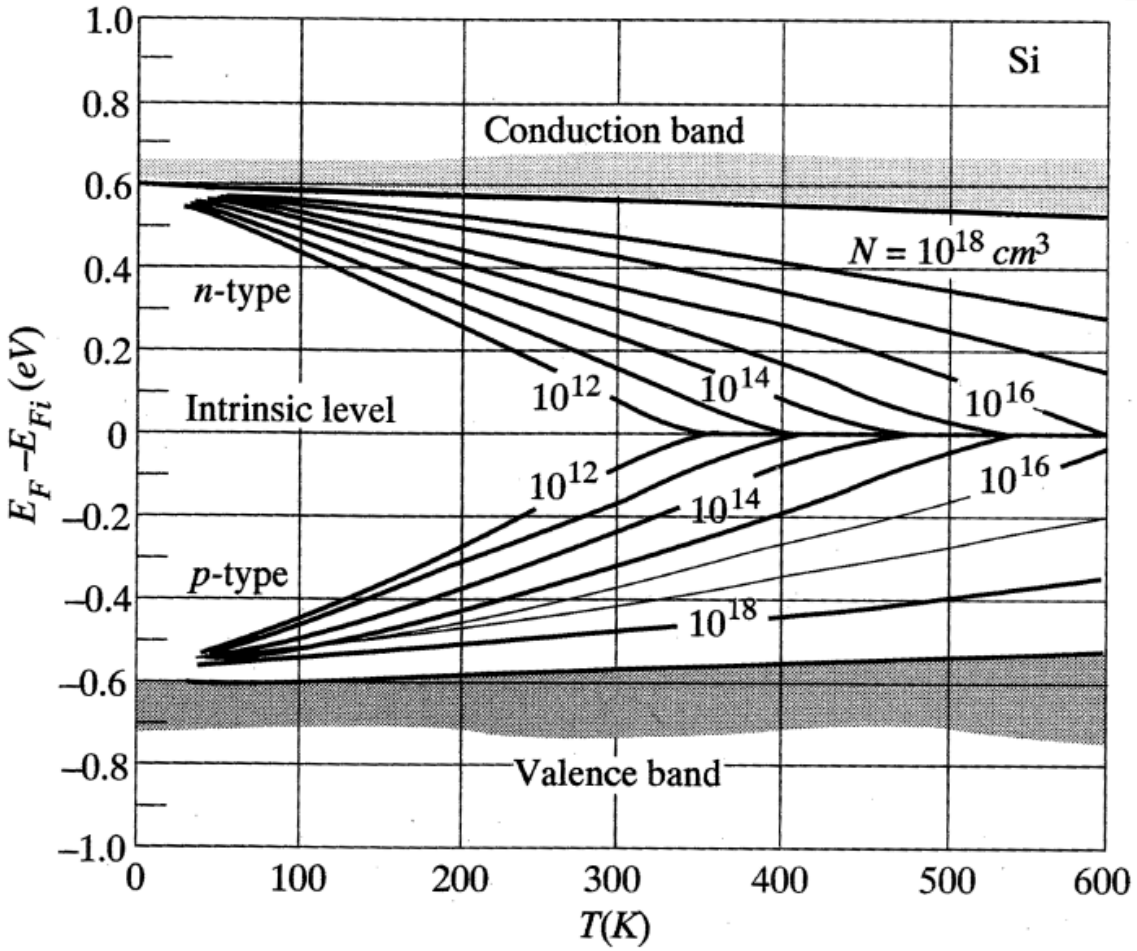


Mini calculator for intrinsic carrier concentration: https://www.pveducation.org/pvcdrom/pn-junctions/intrinsic-carrier-concentration

Temperature Dependence of the Carrier Concentration

Position of Fermi level as a function of T for various doping concentrations



- n_i strongly depends from T
- E_F is a function of T.
- As T increases, n_i increases.
- As T increases, $E_F \rightarrow E_i$
- At high T the semiconductor loses the extrinsic characteristics and behaves as intrinsic.
- At low T freeze-out occurs, Boltzmann approximation is not longer valid.

  The equations we derived the Fermi level position no longer apply.

  $E_F \rightarrow E_D$ for n-type and $E_F \rightarrow E_A$ for p-type

Ways to Change Carrier Concentrations

Current Flow: Motion of electron and hole

Generation: Local creation of electron-hole pairs

Recombination: Local annihilation of electron-hole pairs

Carrier Transport Properties

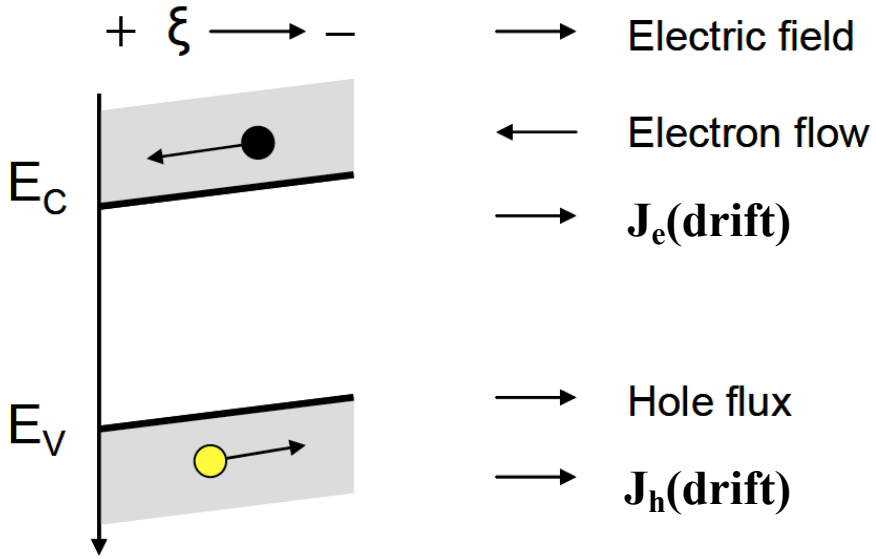
The net flow of the electrons and holes in a semiconductor will generate currents. The process by which these charged particles move is called transport.

The two basic transport mechanisms in a semiconductor:

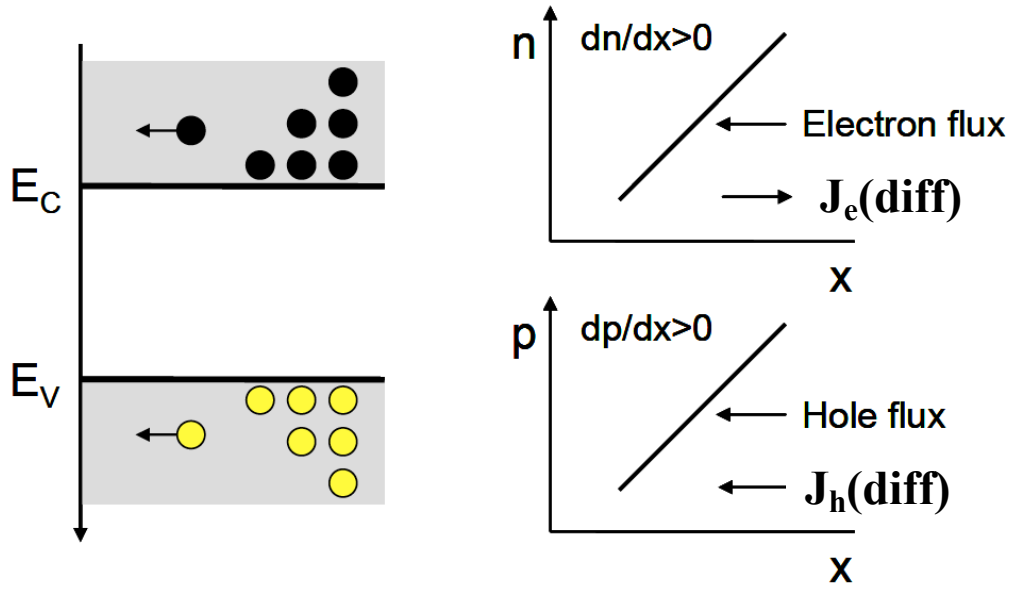
- Drift: the movement of charge due to electric fields

- Diffusion: the flow of charge to cancel any spatial inhomogeneity in carrier density

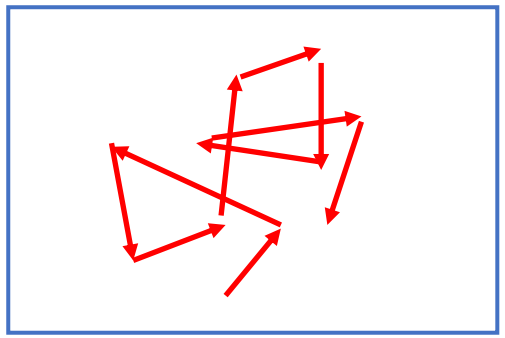
Drift



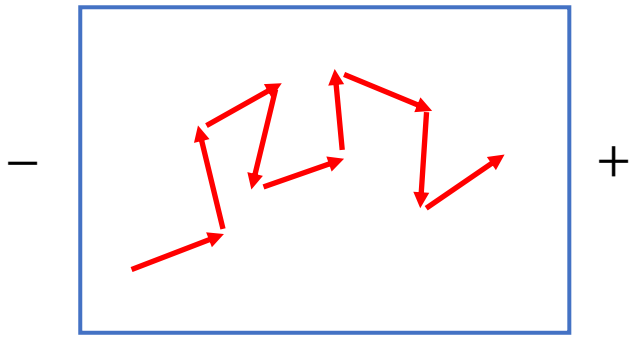
Diffusion



Drift

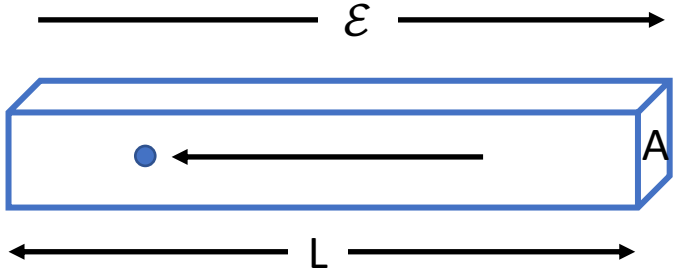


- Electrons and holes in solid at thermal equilibrium move in random directions.
- Electrons and holes scatter randomly by lattice, impurity (ionized or neutral), and defects.
- No net velocity



- In the presence of an electric field, electrons (holes) drift: Electrons in the opposite direction of the E-field and holes in the direction of the E-field.
- Motion is non-directional on a local scale but has a net direction on a macroscopic scale, which gives rise to a current.
- Average net motion is described by the average drift velocity, $\boldsymbol{v_d}$.

Drift



Assumption: All the carriers in the semiconductor move with the same average velocity.

$$I = \frac{Q}{t_r} = \frac{Q}{L/v_{drift}}$$

where t_r is the transit time of a particle, traveling with average velocity, v_d, over the distance L

$$J = \frac{Q}{AL/v_d} = \rho v_{drift}$$

J is drift current density and ρ is positive volume charge density = *p x q or n x q*.

$$\boldsymbol{J_{e(drift)} = -env_e} \quad \text{and} \quad \boldsymbol{J_{h(drift)} = epv_h}$$

$$v_e = -\mu_e \mathcal{E}$$

$$v_h = \mu_h \mathcal{E}$$

For low electric field, the average drift velocities are directly proportional to the E-field.

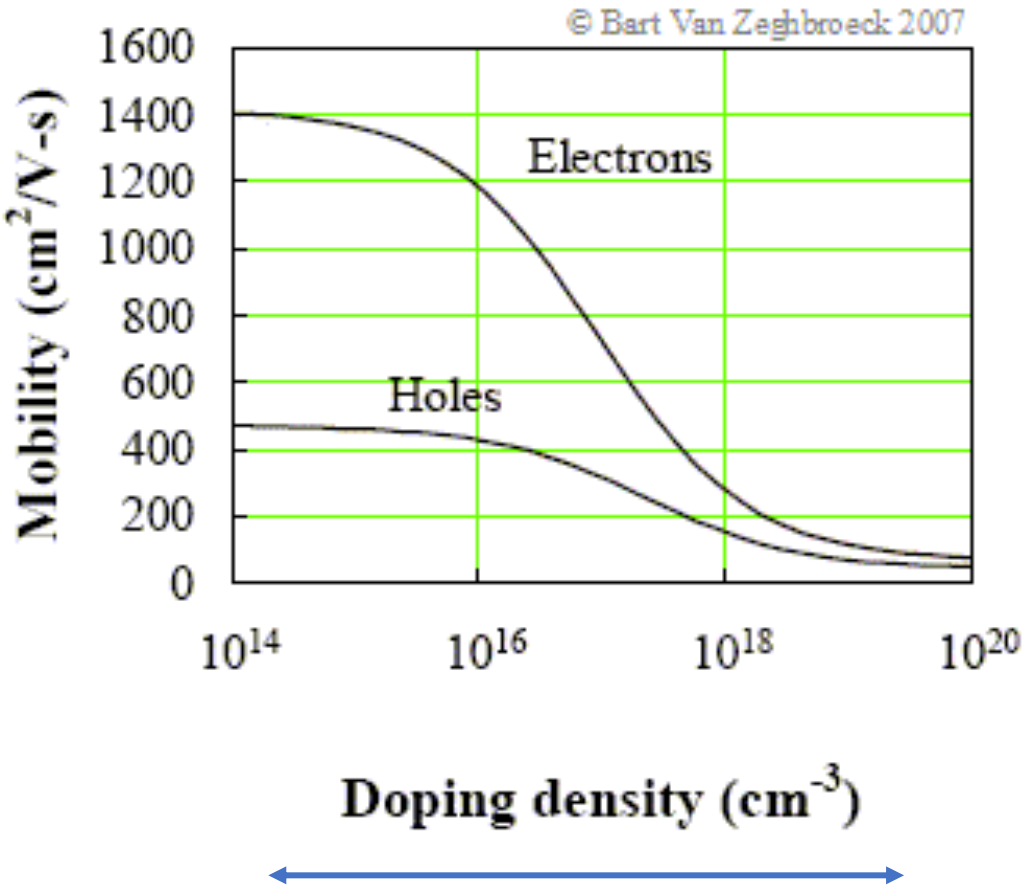
$$\boldsymbol{J_{e(drift)} = en\mu_e \mathcal{E}}$$

$$\boldsymbol{J_{h(drift)} = ep\mu_h \mathcal{E}}$$

$$J_{total(drift)} = en\mu_e \mathcal{E} + ep\mu_h \mathcal{E} = (en\mu_e + ep\mu_h)\mathcal{E} = \sigma \mathcal{E}$$

Drift

Mobility depends on doping level and whether carrier is majority or minority-type.



$$\mu = \mu_{min} + \frac{\mu_{max} - \mu_{min}}{1 + \left(\frac{N}{N_r}\right)^{\alpha}}$$

	As	P	B
μ_{min} (cm²/V·sec)	52.2	68.5	44.9
μ_{max} (cm²/V·sec)	1417	1414	470.5
N_r (cm⁻³)	9.68x10¹⁶	9.20x10¹⁶	2.23x10¹⁷
α	0.68	0.711	0.719

Phonon scattering

impurity scattering