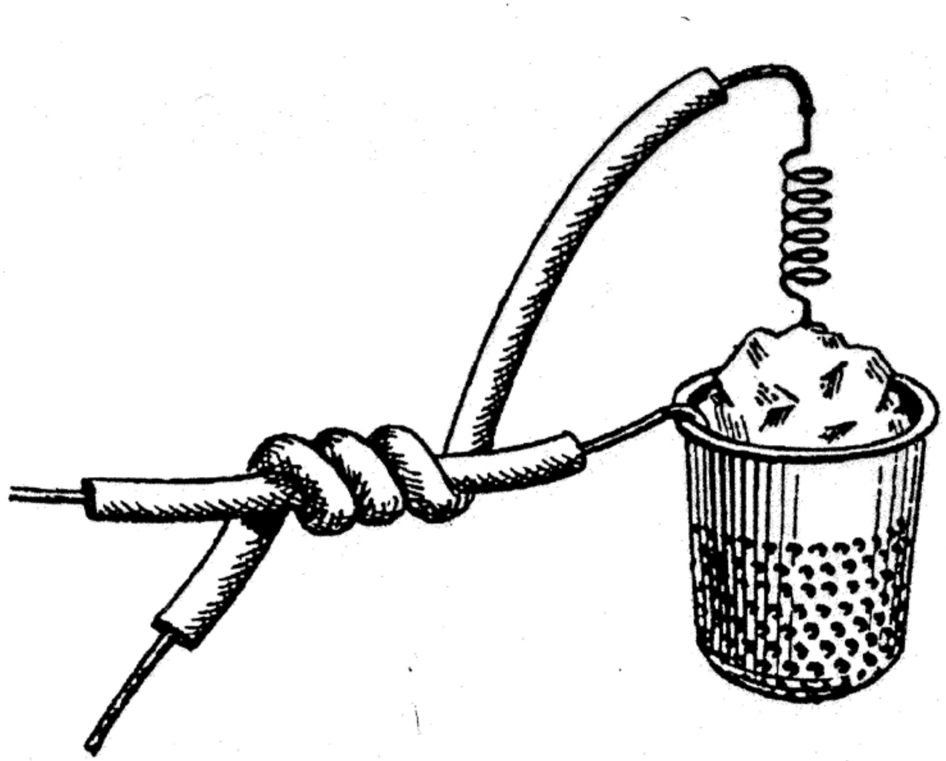
# Introduction to Semiconductor

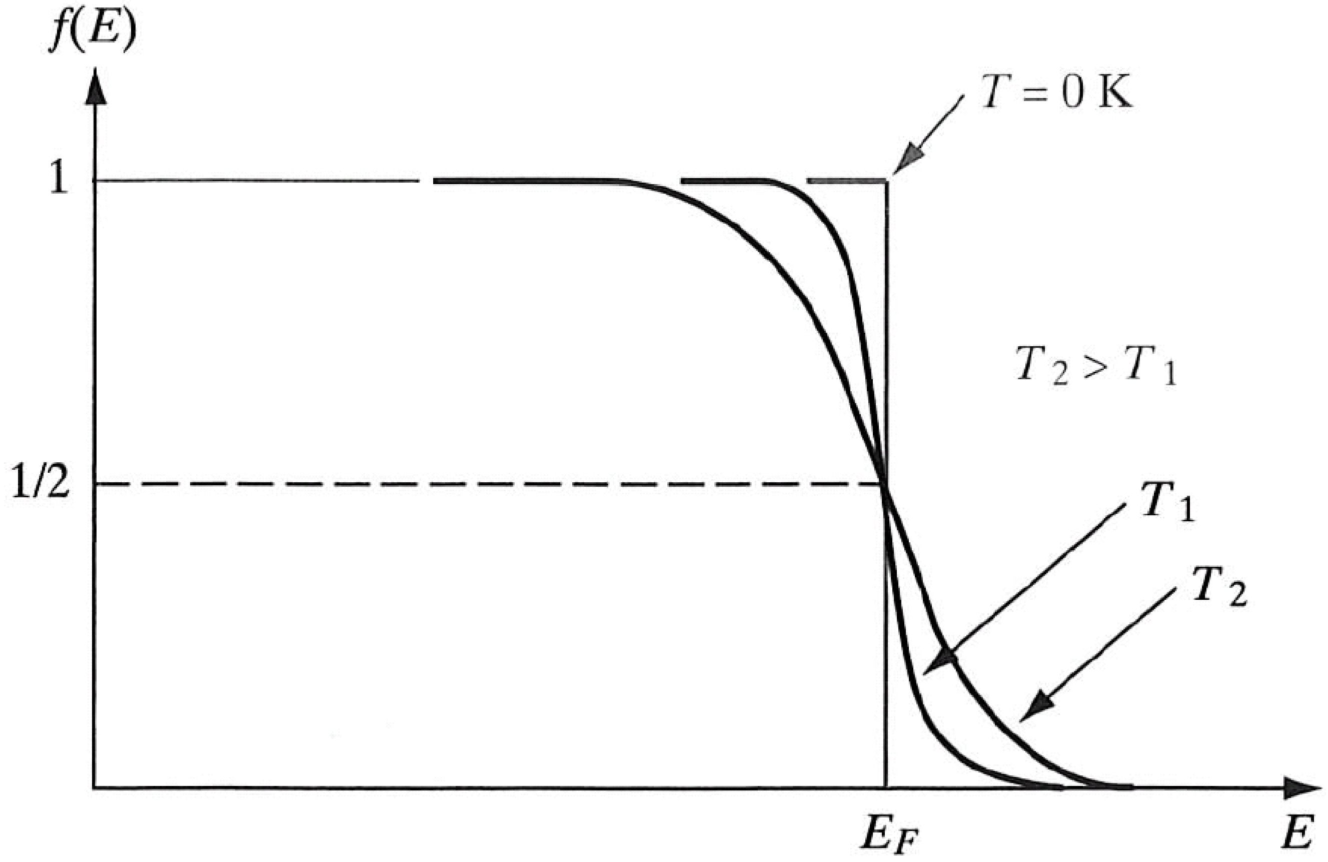


# Outline

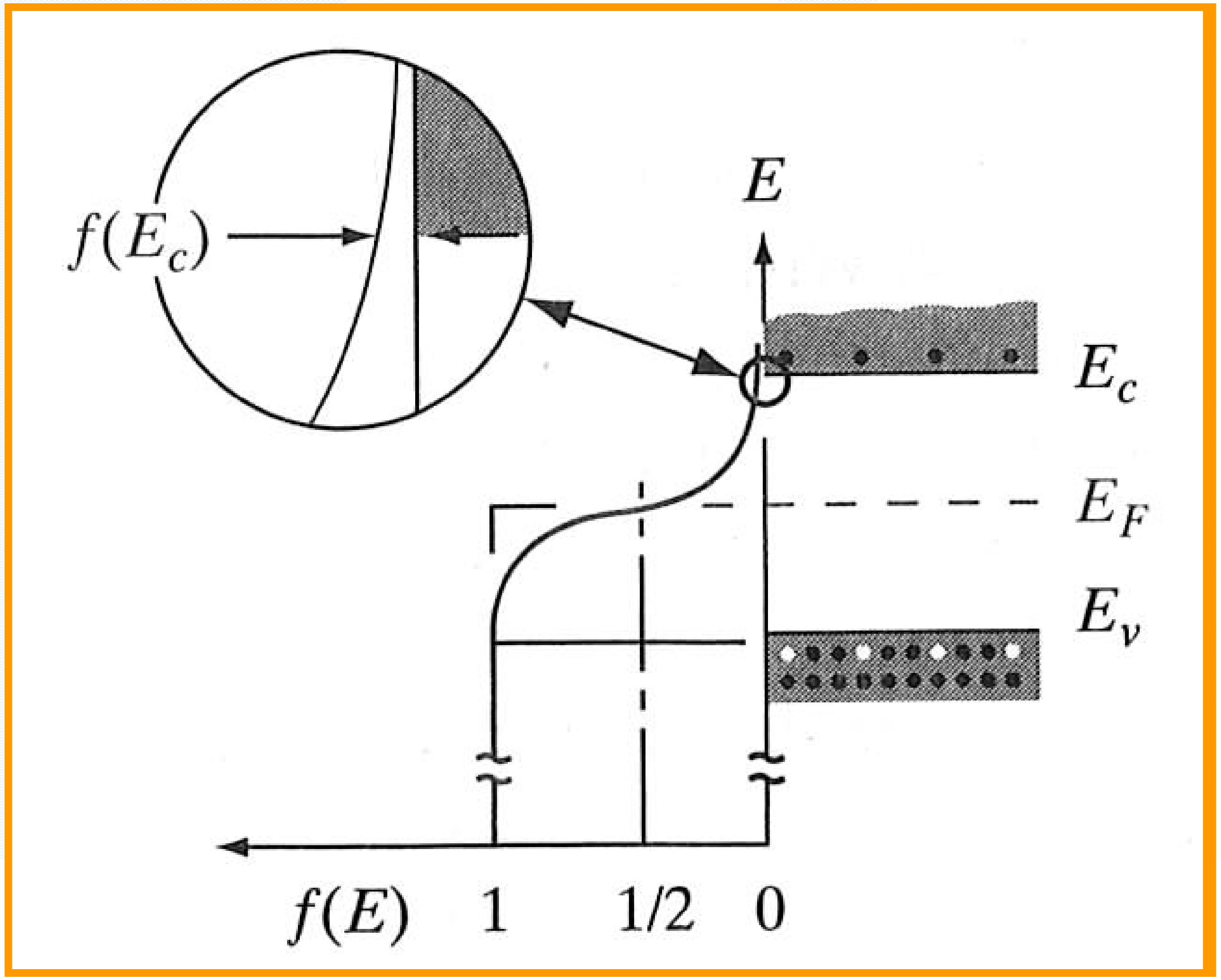
**3 Energy Bands and Charge Carriers in Semiconductors**

# Charge Carriers concentration

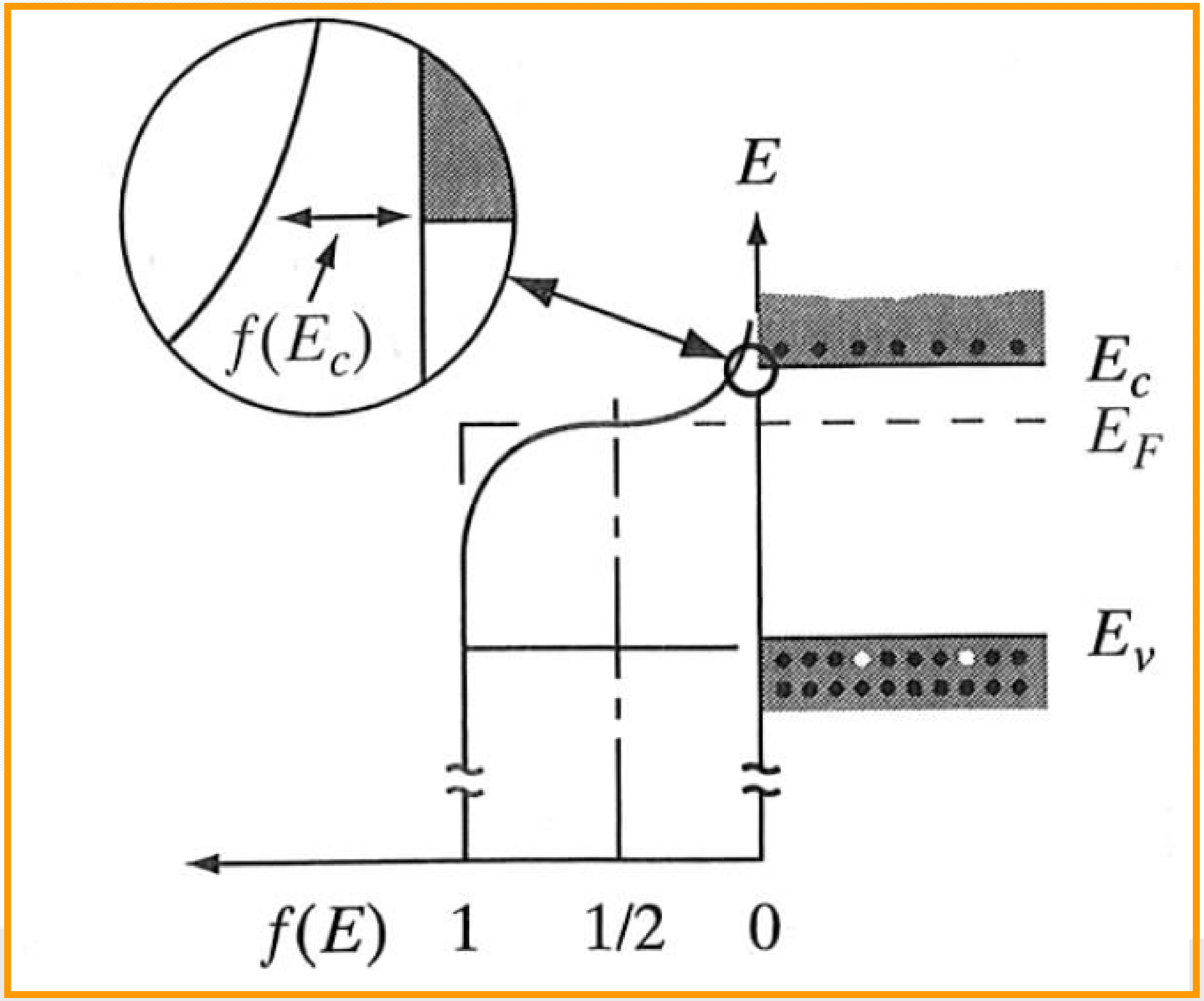
Temperature dependence



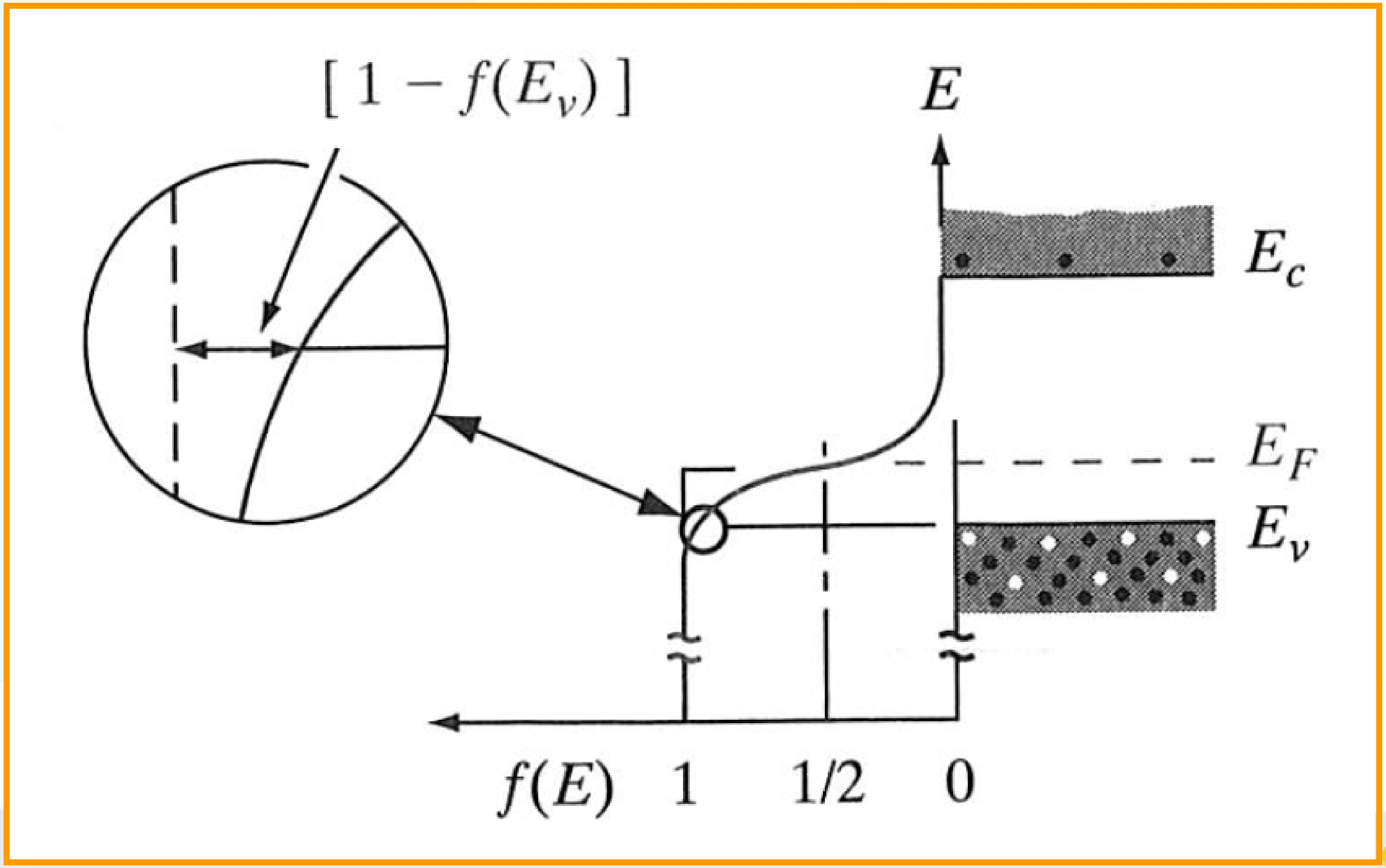
# The Fermi distribution for intrinsic (undoped) semiconductor



# The Fermi distribution for n-doped semiconductor



# The Fermi distribution for p-doped semiconductor



# Electron and hole concentration in equilibrium

For electrons applies

$$n_0 = \int_{E_c}^{\infty} f(E)N(E)dE$$

Where $N(E)dE$ is the density of states in cm$^{-3}$ within dE

Integrations gives (appendix IV) $\boxed{n_0 = N_c f(E_c)}$

Subscript denotes Equilibrium

# Electron concentration in equilibrium

$$N_c = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}$$

Effective density of states

$$f(E_c) = \frac{1}{1 + e^{(E_c - E_F)/kT}} \simeq e^{-(E_c - E_F)/kT}$$

$E_c$-$E_f$>$kT$

$kT$=0.0259 eV RT

$$n_0 = N_c e^{-(E_c - E_F)/kT}$$

# Hole concentration in equilibrium

$$N_v = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2}$$

Effective density of states

$$1 - f(E_v) = 1 - \frac{1}{1 + e^{(E_v - E_F)/kT}} \simeq e^{-(E_F - E_v)/kT}$$

$E_f - E_v > kT$

$$p_0 = N_v e^{-(E_F - E_v)/kT}$$

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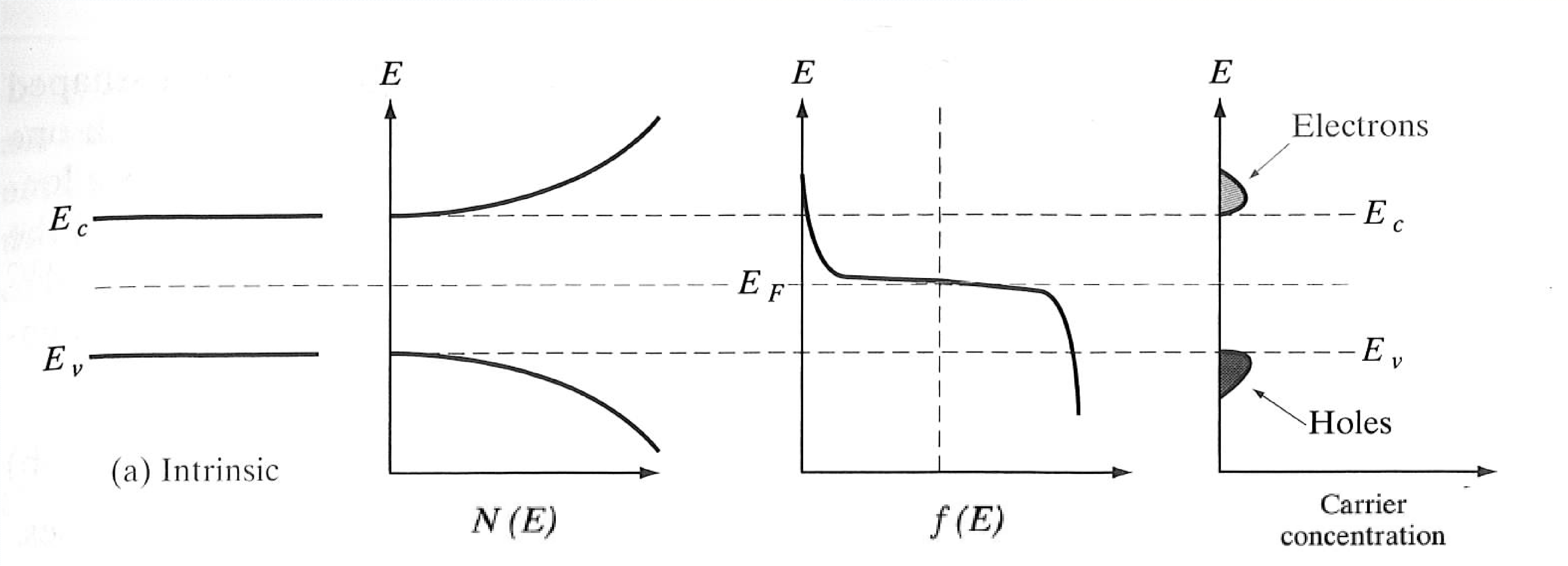
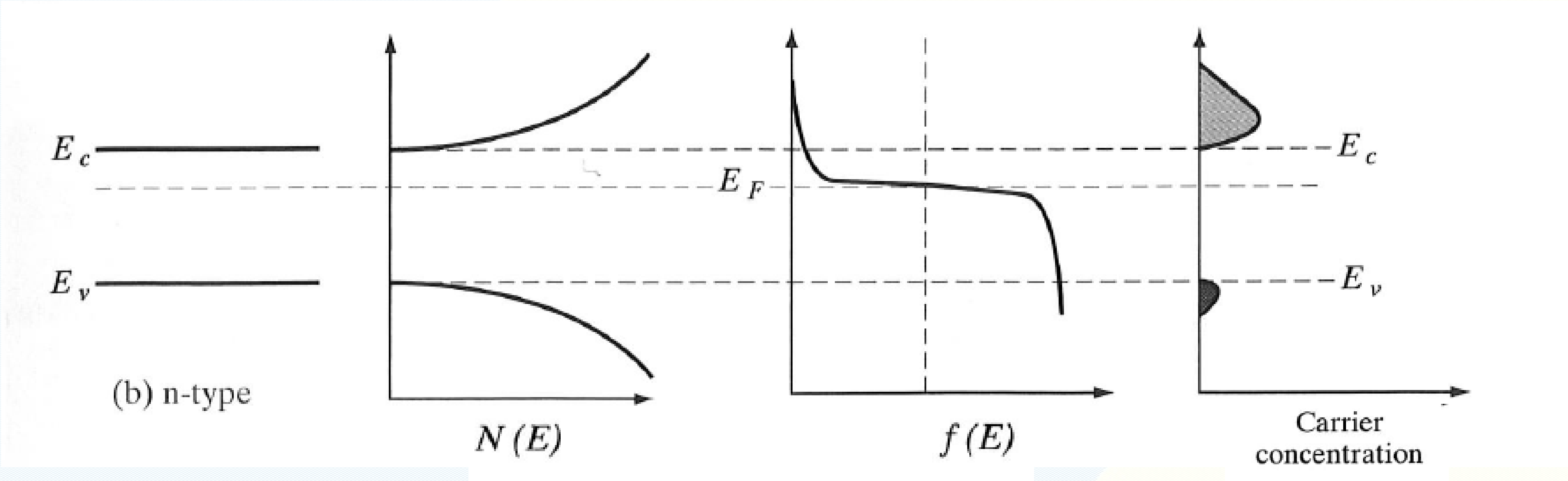
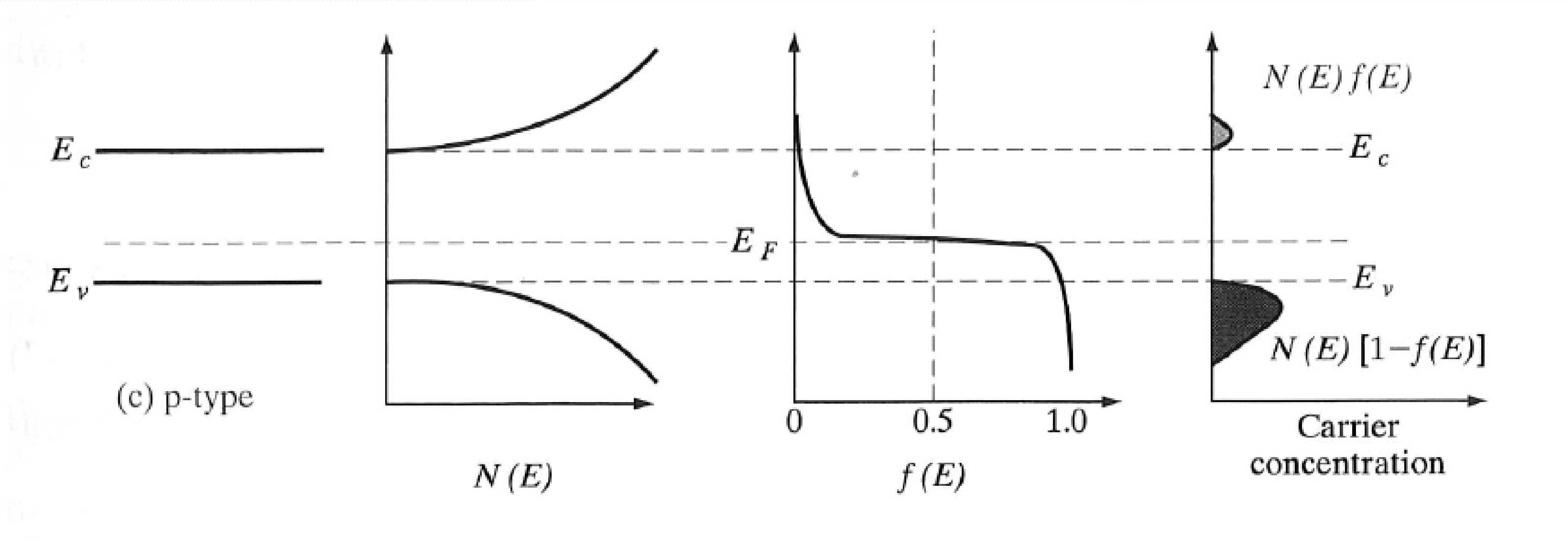
# Band-diagram (undoped)



# Band-diagram n-type



# Band-diagram p-type

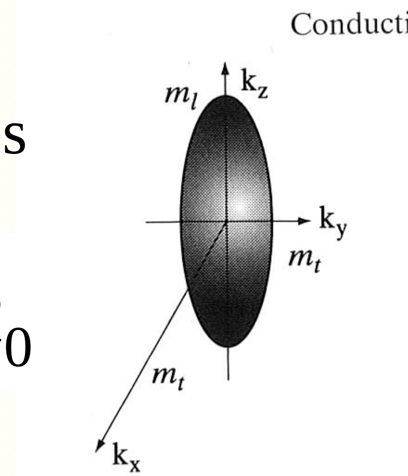


# Effective mass

•Effective mass when calculating the density of states, silicon

$$(m_n^*)^{3/2} = 6(m_l m_t^2)^{1/2}$$

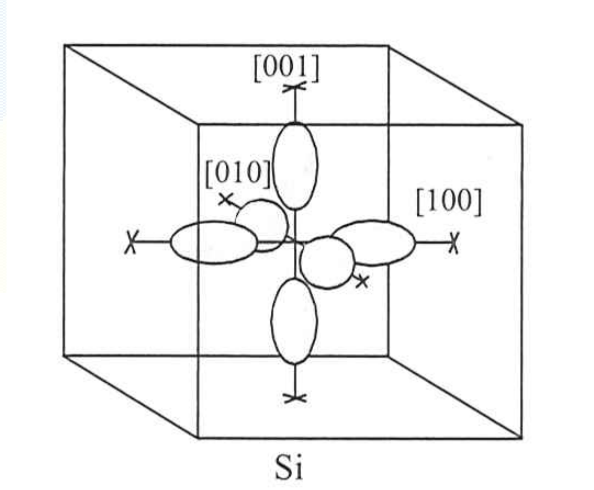
6 Energy surfaces in silicon




$$m_n^* = 1.1 m_0 \qquad m_l = 0.98 m_0 \qquad m_t = 0.19 m_0$$

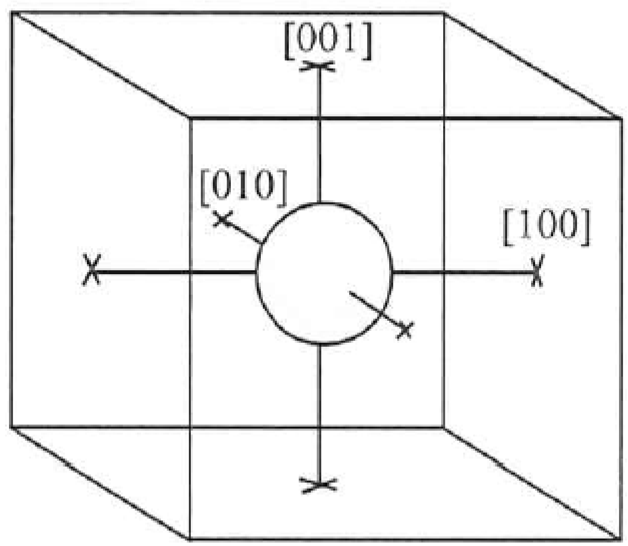
•Effective mass when calculating the conductivity (movement of charge), silicon

$$\frac{1}{m_n^*} = \frac{1}{3}\left(\frac{1}{m_l} + \frac{2}{m_t}\right) \qquad m_n^* = 0.26 m_0$$



# Effective mass

For GaAs, where the conduction band is spherically is the effective mass of the electrons in the calculation of the density of states and conductivity as ($0.067m_o$)




GaAs

# Effective mass table

| | | $E_g$ (eV) | $\mu_n$ ($cm^2$/V-s) | $\mu_p$ ($cm^2$/V-s) | $m^*_n/m_o$ ($m_l, m_t$) | $m^*_p/m_o$ ($m_{lh}, m_{hh}$) | $a$ (Å) | $\epsilon_r$ | Density ($g/cm^3$) | Melting point (°C) |
|---|---|---|---|---|---|---|---|---|---|---|
| Si | (i/D) | 1.11 | 1350 | 480 | 0.98, 0.19 | 0.16, 0.49 | 5.43 | 11.8 | 2.33 | 1415 |
| Ge | (i/D) | 0.67 | 3900 | 1900 | 1.64, 0.082 | 0.04, 0.28 | 5.65 | 16 | 5.32 | 936 |
| SiC (α) | (i/W) | 2.86 | 500 | — | 0.6 | 1.0 | 3.08 | 10.2 | 3.21 | 2830 |
| AlP | (i/Z) | 2.45 | 80 | — | — | 0.2, 0.63 | 5.46 | 9.8 | 2.40 | 2000 |
| AlAs | (i/Z) | 2.16 | 1200 | 420 | 2.0 | 0.15, 0.76 | 5.66 | 10.9 | 3.60 | 1740 |
| AlSb | (i/Z) | 1.6 | 200 | 300 | 0.12 | 0.98 | 6.14 | 11 | 4.26 | 1080 |
| GaP | (i/Z) | 2.26 | 300 | 150 | 1.12, 0.22 | 0.14, 0.79 | 5.45 | 11.1 | 4.13 | 1467 |
| GaAs | (d/Z) | 1.43 | 8500 | 400 | 0.067 | 0.074, 0.50 | 5.65 | 13.2 | 5.31 | 1238 |
| GaN | (d/Z, W) | 3.4 | 380 | — | 0.19 | 0.60 | 4.5 | 12.2 | 6.1 | 2530 |
| GaSb | (d/Z) | 0.7 | 5000 | 1000 | 0.042 | 0.06, 0.23 | 6.09 | 15.7 | 5.61 | 712 |
| InP | (d/Z) | 1.35 | 4000 | 100 | 0.077 | 0.089, 0.85 | 5.87 | 12.4 | 4.79 | 1070 |
| InAs | (d/Z) | 0.36 | 22600 | 200 | 0.023 | 0.025, 0.41 | 6.06 | 14.6 | 5.67 | 943 |
| InSb | (d/Z) | 0.18 | $10^5$ | 1700 | 0.014 | 0.015, 0.40 | 6.48 | 17.7 | 5.78 | 525 |
| ZnS | (d/Z, W) | 3.6 | 180 | 10 | 0.28 | — | 5.409 | 8.9 | 4.09 | 1650* |
| ZnSe | (d/Z) | 2.7 | 600 | 28 | 0.14 | 0.60 | 5.671 | 9.2 | 5.65 | 1100* |
| ZnTe | (d/Z) | 2.25 | 530 | 100 | 0.18 | 0.65 | 6.101 | 10.4 | 5.51 | 1238* |
| CdS | (d/W, Z) | 2.42 | 250 | 15 | 0.21 | 0.80 | 4.137 | 8.9 | 4.82 | 1475 |
| CdSe | (d/W) | 1.73 | 800 | — | 0.13 | 0.45 | 4.30 | 10.2 | 5.81 | 1258 |
| CdTe | (d/Z) | 1.58 | 1050 | 100 | 0.10 | 0.37 | 6.482 | 10.2 | 6.20 | 1098 |
| PbS | (i/H) | 0.37 | 575 | 200 | 0.22 | 0.29 | 5.936 | 17.0 | 7.6 | 1119 |
| PbSe | (i/H) | 0.27 | 1500 | 1500 | — | — | 6.147 | 23.6 | 8.73 | 1081 |
| PbTe | (i/H) | 0.29 | 6000 | 4000 | 0.17 | 0.20 | 6.452 | 30 | 8.16 | 925 |

All values at 300 K.

*Vaporizes

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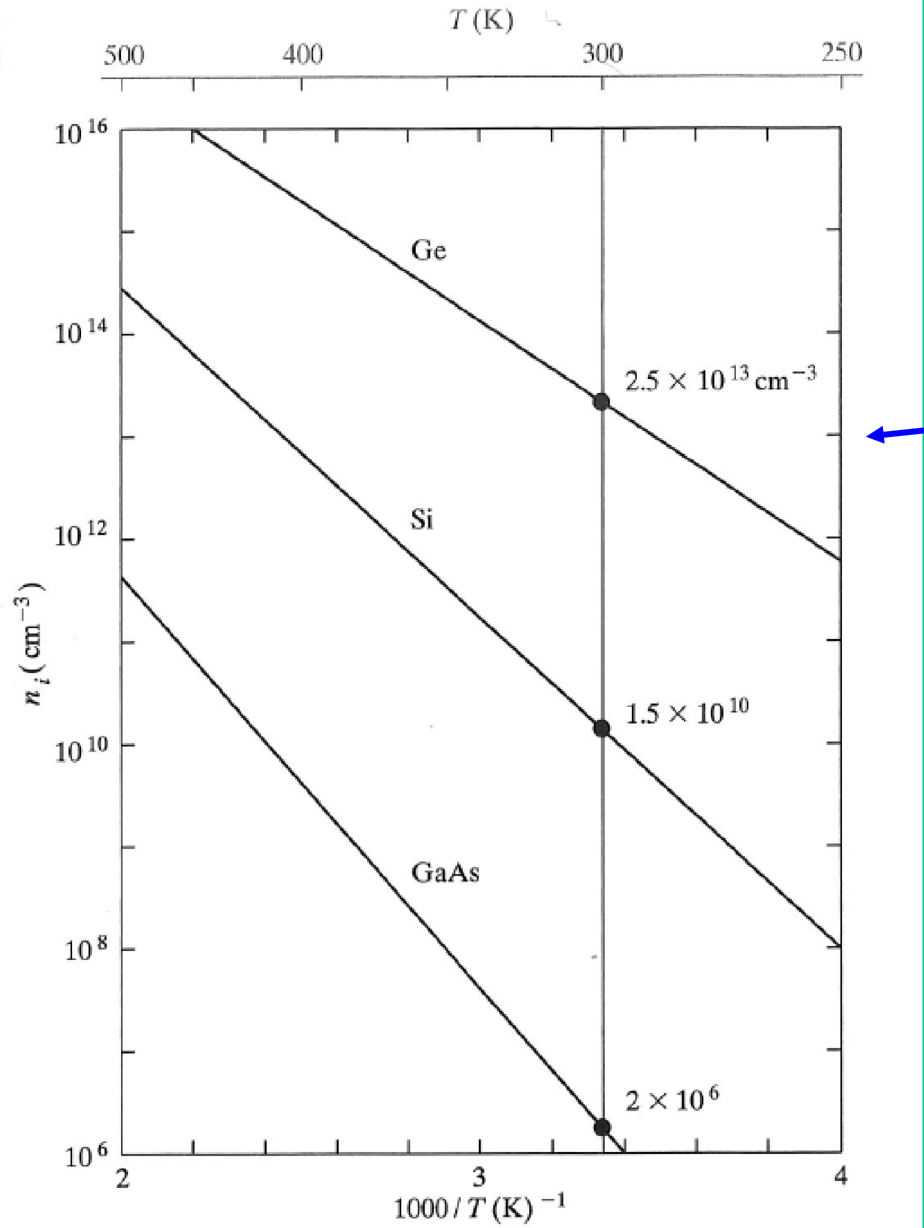
# The temperature dependence of the carrier concentration



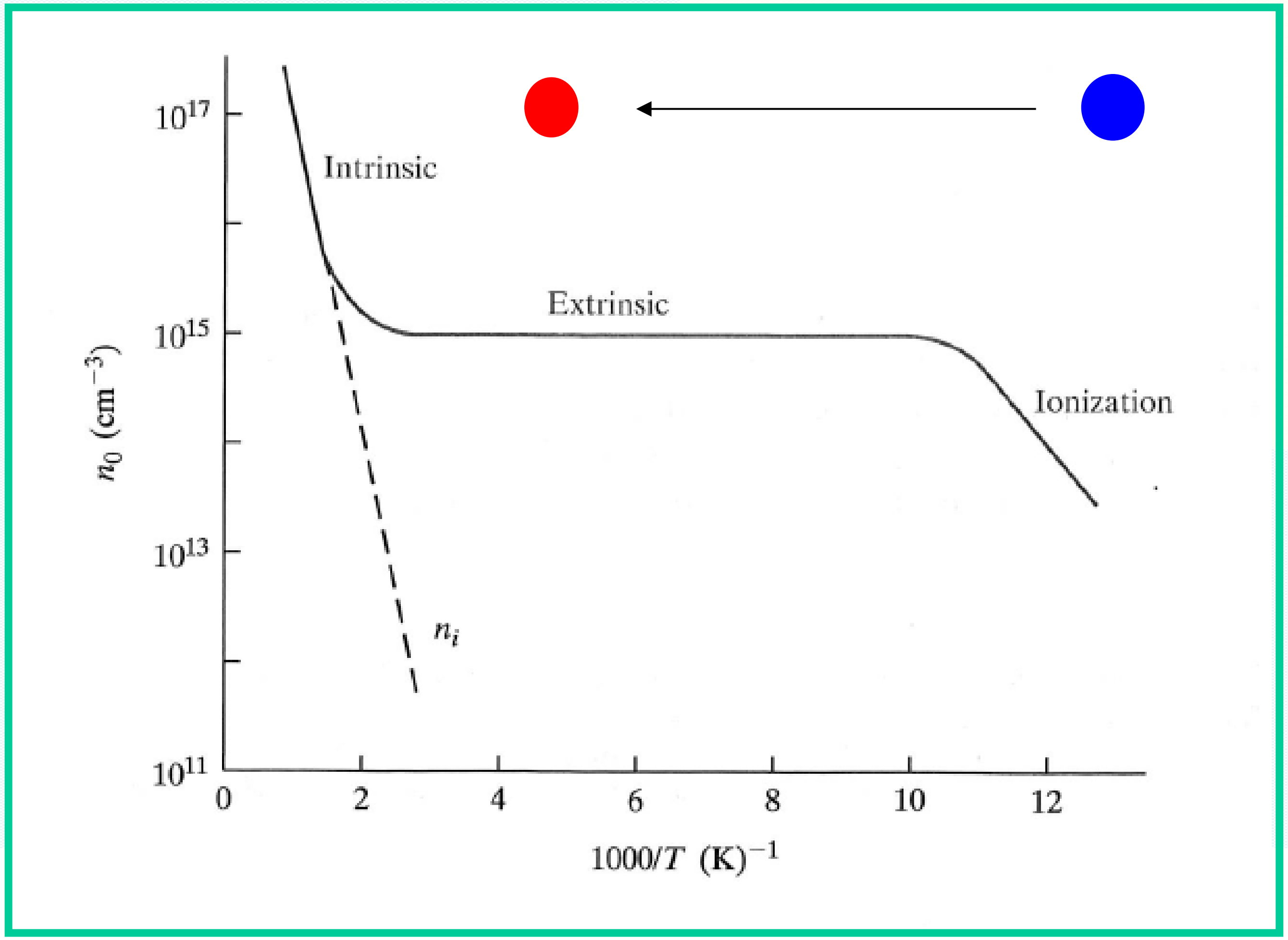

$$n_i(T) = 2\left(\frac{2\pi kT}{h^2}\right)^{3/2}(m_n^* m_p^*)^{3/4} e^{-E_g/2kT}$$

Arrenius-plot!

The law of mass action at equilibrium

$$n_0 p_0 = n_i^2$$

# Compensating and charge neutrality

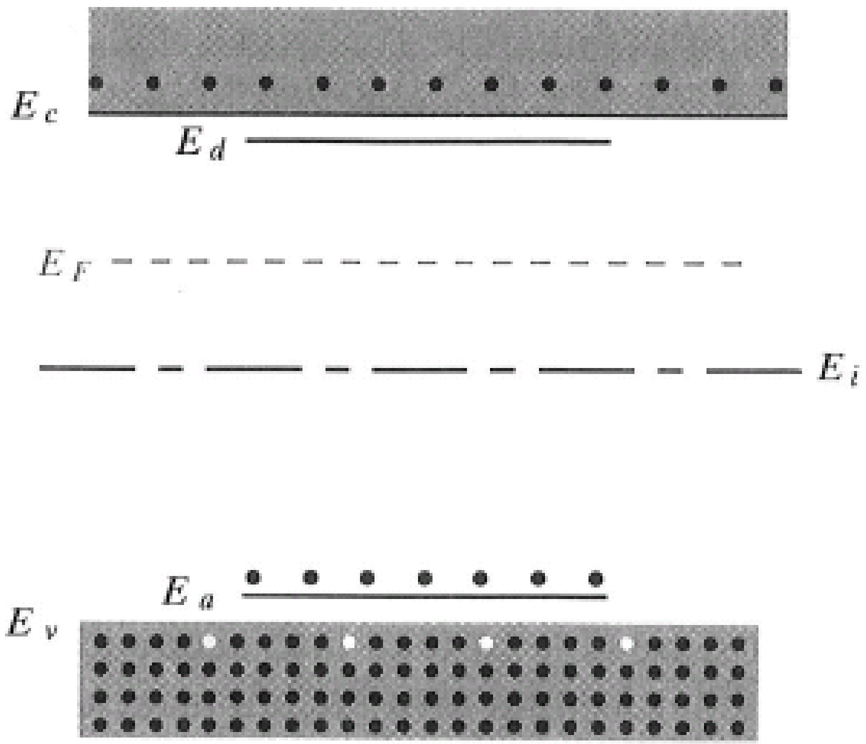



Doped with $10^{15}$ cm$^{-3}$

Donators (n-type)

# Compensating and charge neutrality

$N_d > N_a$



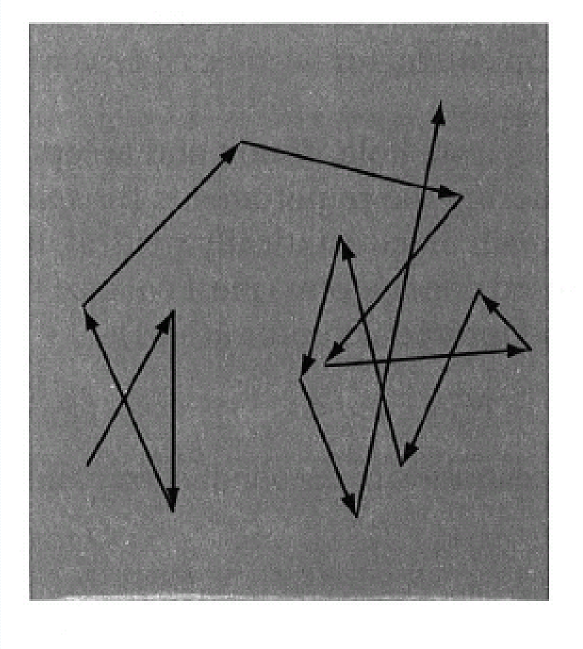

$$p_0 + N_d^+ = n_0 + N_a^-$$

$$n_0 = p_0 + (N_d^+ - N_a^-)$$

$N_d = N_a$ $\longrightarrow$ $n_0 = p_0 = n_i$

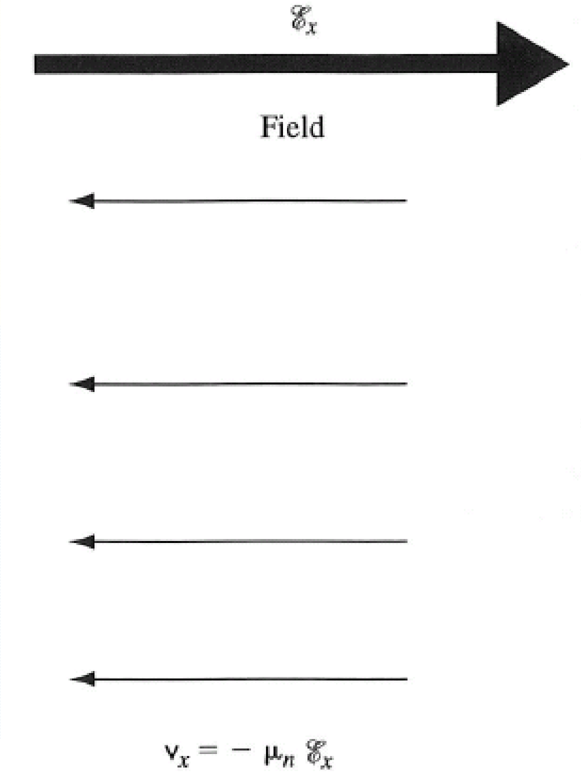
# Conductivity and mobility

Thermal motion of the electron in the material.



On average, for a greater number of electrons, no net movement can be seen

Drift velocity in electric field




With an electric field, we get a net movement of electrons

# Conductivity and mobility

$$\langle v_x \rangle = \frac{\langle p_x \rangle}{m_n^*} = -\frac{q\bar{t}}{m_n^*}\mathscr{E}_x$$

$p_x$ and t depends on the electrons scattering in the crystal lattice

$\bar{t}$ is the average time between two scatterings

$$J_x = -qn\langle v_x \rangle$$

$$\frac{\text{ampere}}{\text{cm}^2} = \frac{\text{coulomb}}{\text{electron}} \cdot \frac{\text{electrons}}{\text{cm}^3} \cdot \frac{\text{cm}}{\text{s}}$$

$$J_x = \sigma \mathscr{E}_x, \quad \text{where } \sigma \equiv \frac{nq^2\bar{t}}{m_n^*}$$

$$\sigma = qn\mu_n, \quad \text{where } \mu_n \equiv \frac{q\bar{t}}{m_n^*}$$

mobility

Can also be written as

$$\mu_n = -\frac{\langle v_x \rangle}{\mathscr{E}_x}$$

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# Conductivity and mobility

Effective mass for conductivity is calculated for electrons in Silicon with;
Or can be downloaded from the table!

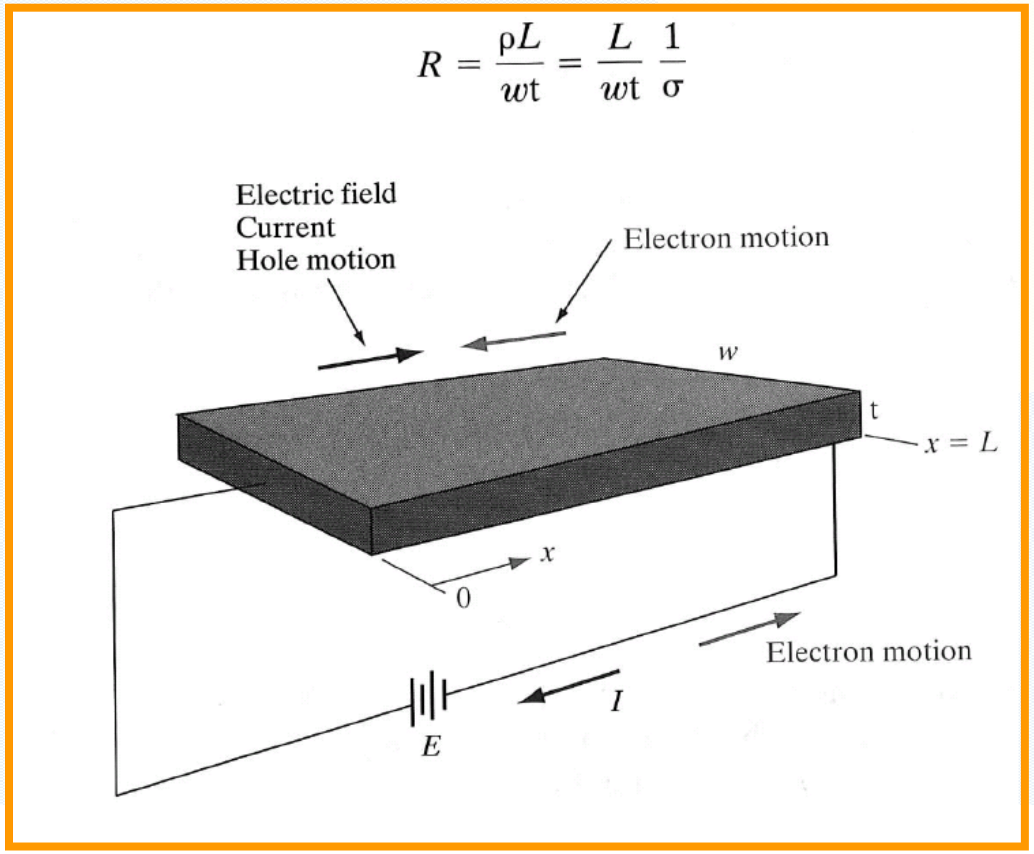
$$\frac{1}{m_n^*} = \frac{1}{3}\left(\frac{1}{m_l} + \frac{2}{m_t}\right)$$

Both holes and electrons!

$$J_x = q(n\mu_n + p\mu_p)\mathscr{E}_x = \sigma\mathscr{E}_x$$

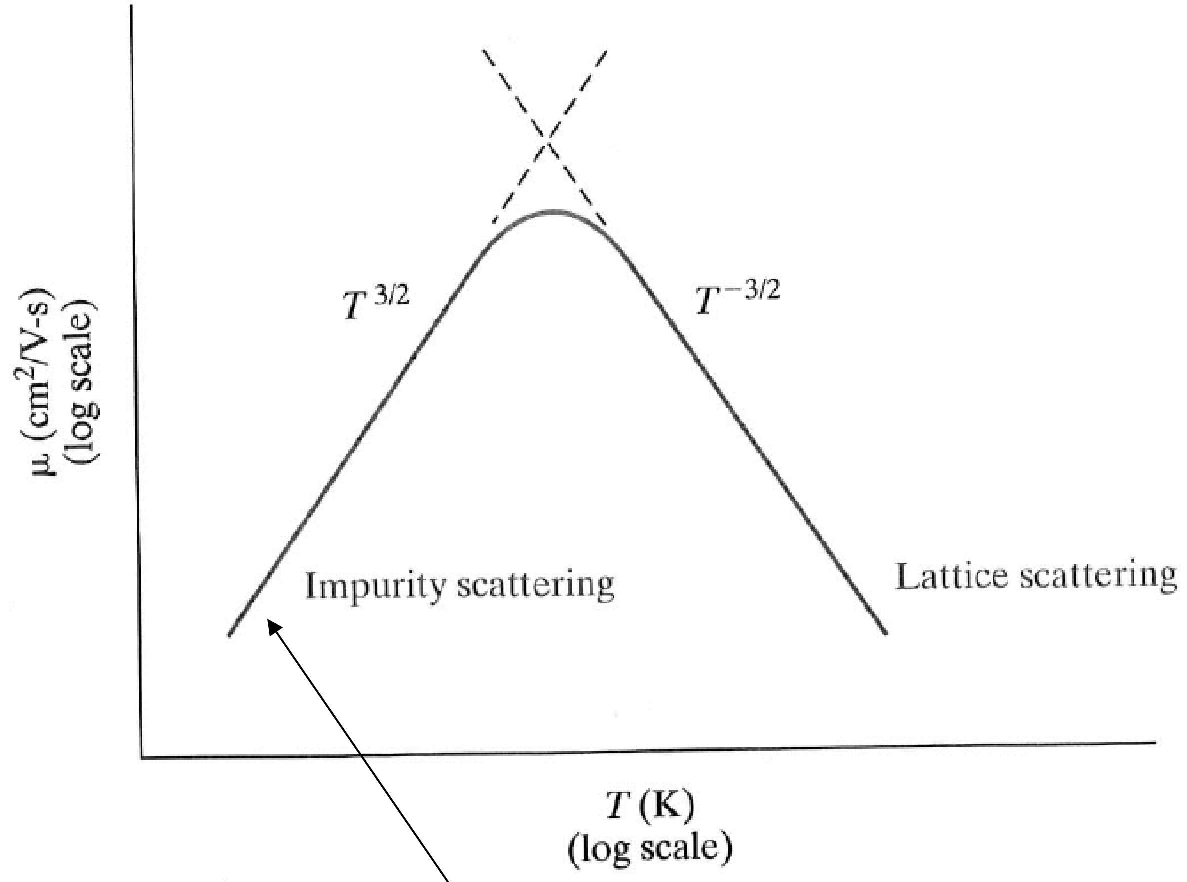
$$\mu_p = +\langle v_x \rangle / \mathscr{E}_x$$

# Drift and Resistance




Both hole and electron movement in the material.

# Temperature and doping effects on mobility



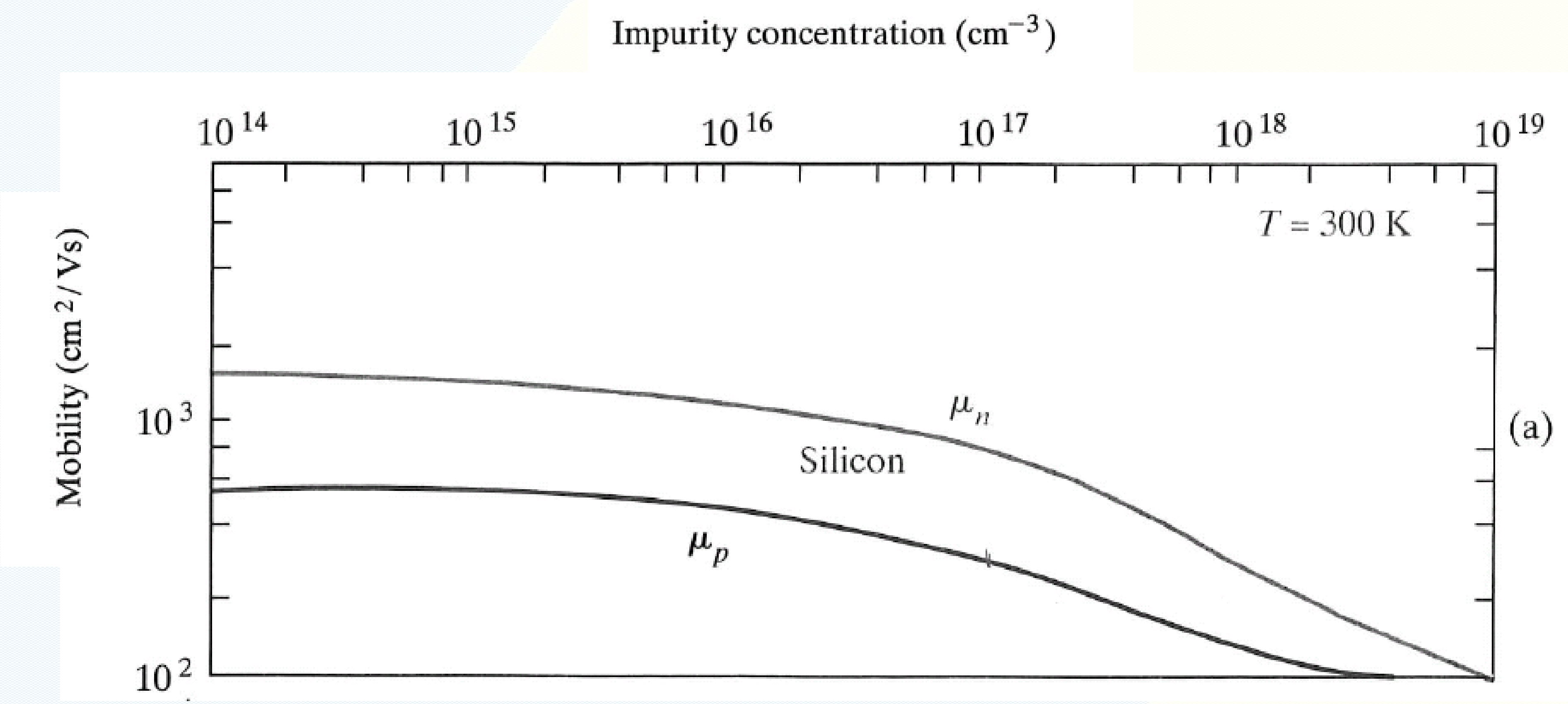

Calculation of mobility

$$\frac{1}{\mu} = \frac{1}{\mu_1} + \frac{1}{\mu_2} + \dots$$

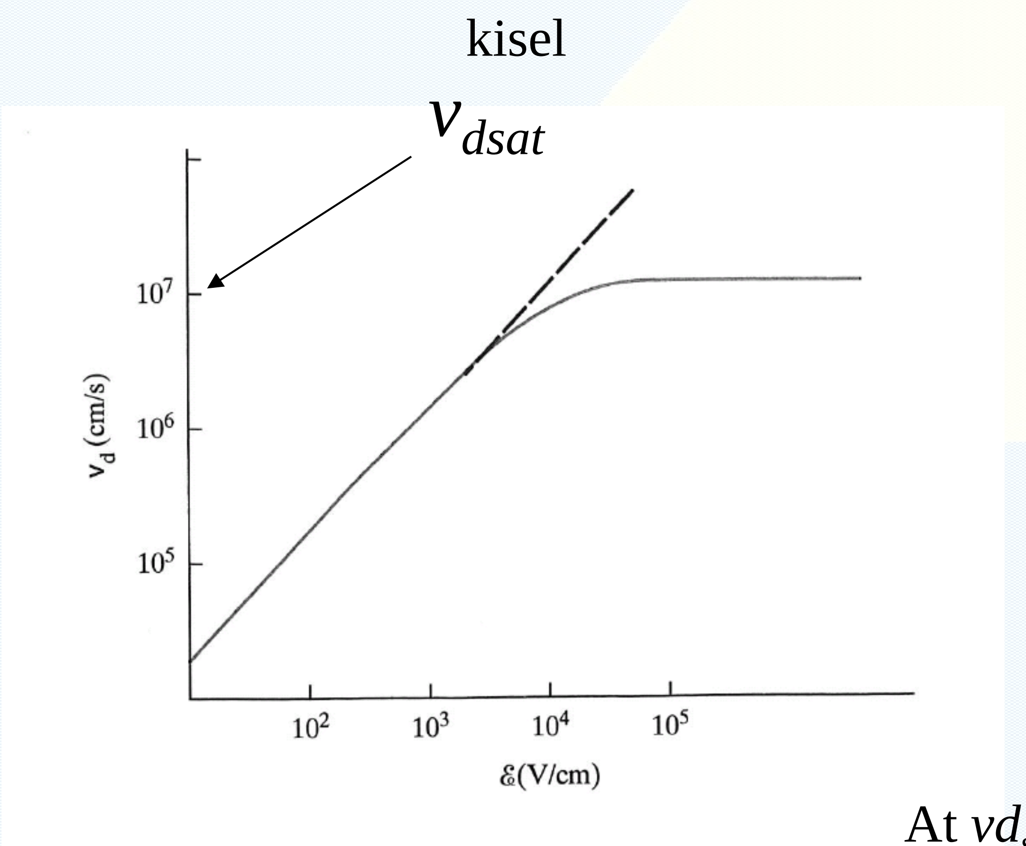
The mechanism that causes the lowest mobility dominates!

The probability increases for scattering when the thermal speed decreases for the charge carrier and the probability of scattering against ionized impurities (doping) increases

# Temperature and doping effect on mobility



# Effects at high field

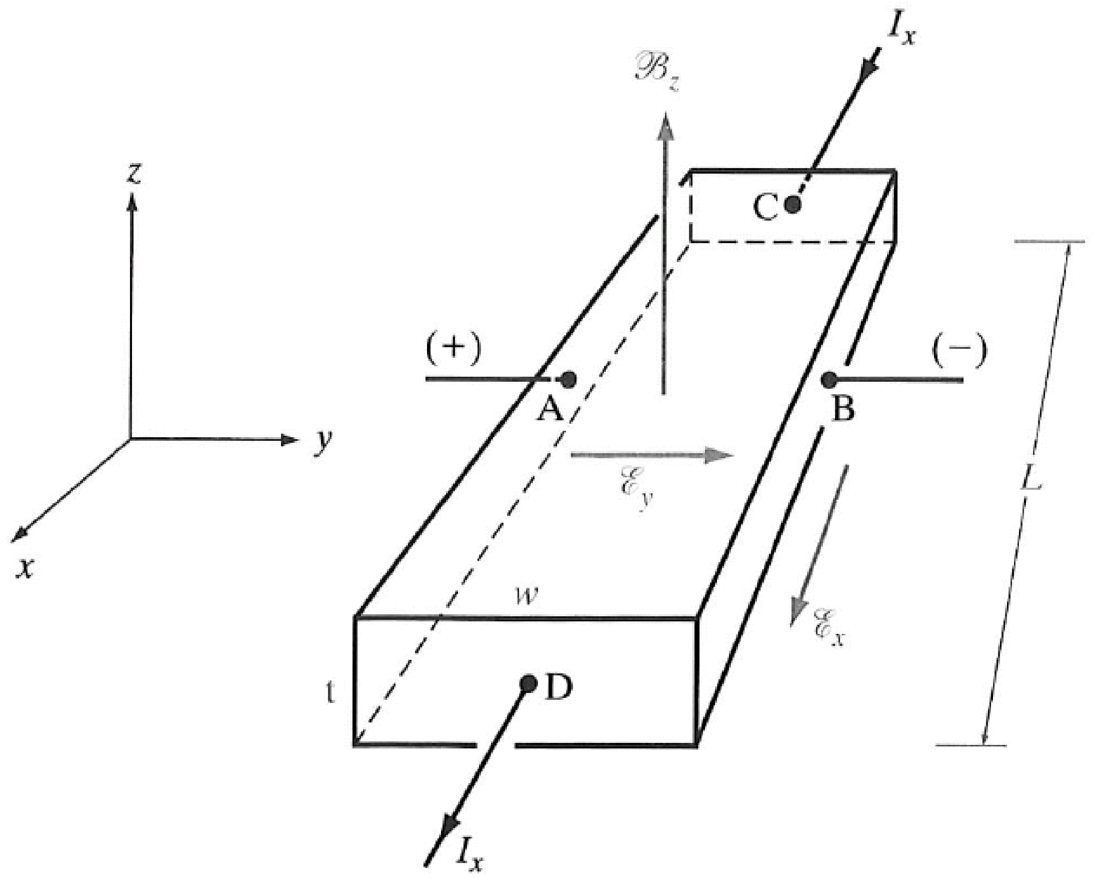



Charge carrier velocity has a maximum value!

$$\mu_n = -\frac{\langle v_x \rangle}{\mathscr{E}_x}$$

At $vd_{sat}$ reduces the mobility with increased electrical field

# Hall effect ( in a p-type semiconductor)




$$\mathbf{F} = q(\mathscr{E} + \mathrm{v} \times \mathscr{B})$$

$$F_y = q(\mathscr{E}_y - \mathrm{v}_x \mathscr{B}_z)$$

Magnetic force acting on the holes

$$\mathscr{E}_y = \mathrm{v}_x \mathscr{B}_z$$

An electric field arises that prevents further movement of holes

$$\mathscr{E}_y = \frac{J_x}{qp_0}\mathscr{B}_z = R_H J_x \mathscr{B}_z, \qquad R_H \equiv \frac{1}{qp_0}$$

Hall coefficient

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# Hall effect ( in a p-type semiconductor)

$$p_0 = \frac{1}{qR_H} = \frac{J_x \mathcal{B}_z}{q\mathcal{E}_y} = \frac{(I_x/wt)\mathcal{B}_z}{q(V_{AB}/w)} = \frac{I_x \mathcal{B}_z}{qtV_{AB}}$$

Measurement of Hall voltage gives an accurate measurement of hole concentration

$$\rho(\Omega\text{−cm}) = \frac{Rwt}{L} = \frac{V_{CD}/I_x}{L/wt}$$

$$\mu_p = \frac{\sigma}{qp_0} = \frac{1/\rho}{q(1/qR_H)} = \frac{R_H}{\rho}$$

Hall coefficient and resistivity produces a measurement of mobility

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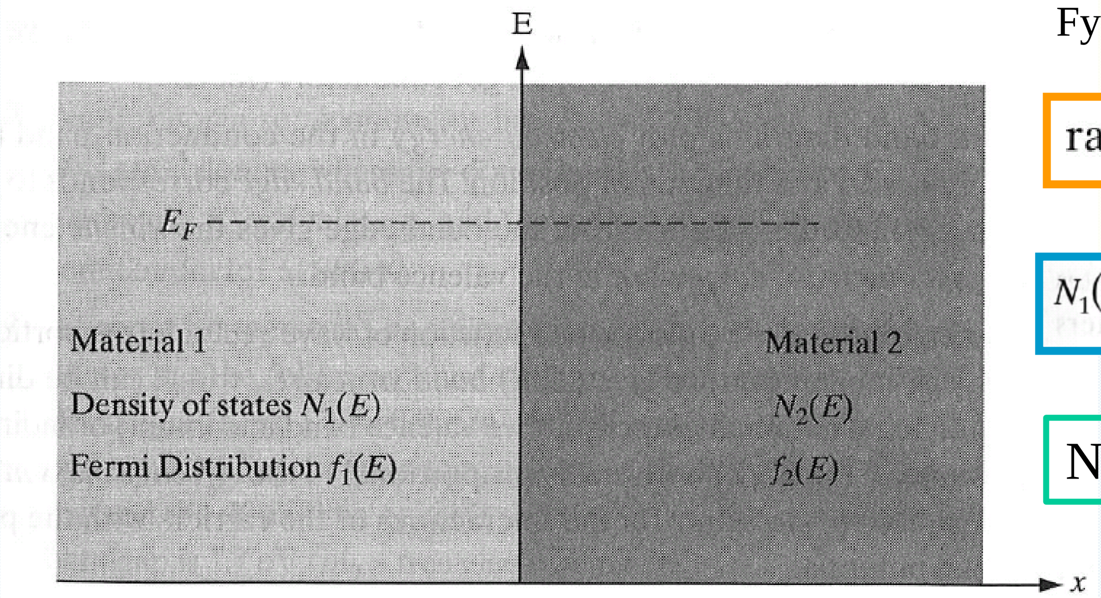
# Fermi level at equilibrium




$$\boxed{\text{rate from 1 to 2} \propto N_1(E)f_1(E) \cdot N_2(E)[1 - f_2(E)]}$$

Fyllda tillstånd i M1

Ofyllda tillstånd i M2

$$\boxed{\text{rate from 2 to 1} \propto N_2(E)f_2(E) \cdot N_1(E)[1 - f_1(E)]}$$

$$\boxed{N_1(E)f_1(E) \cdot N_2(E)[1 - f_2(E)] = N_2(E)f_2(E) \cdot N_1(E)[1 - f_1(E)]}$$

$$\boxed{N_1f_1N_2 - N_1f_1N_2f_2 = N_2f_2N_1 - N_2f_2N_1f_1}$$

$$\boxed{f_1(E) = f_2(E), \quad \text{that is,} \quad [1 + e^{(E - E_{F1})/kT}]^{-1} = [1 + e^{(E - E_{F2})/kT}]^{-1}}$$

$$\boxed{E_{F1} = E_{F2}}$$