ECE-305: Spring 2018

Carrier Properties

Pierret, *Semiconductor Device Fundamentals* (SDF)
Chapter 2 (pp. 22-49)

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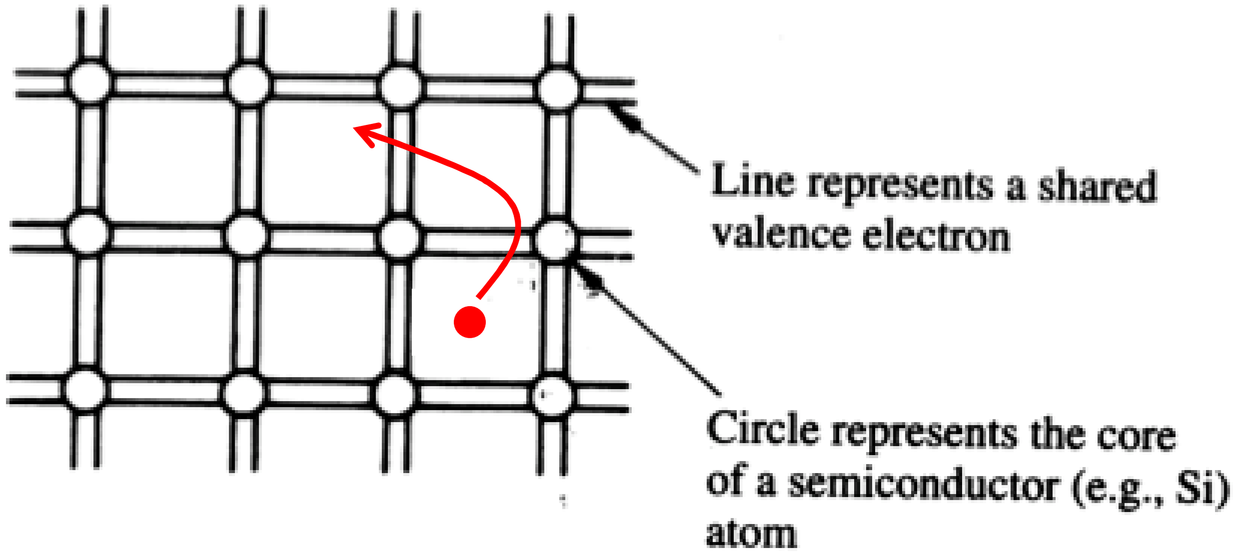
PURDUE UNIVERSITY

outline

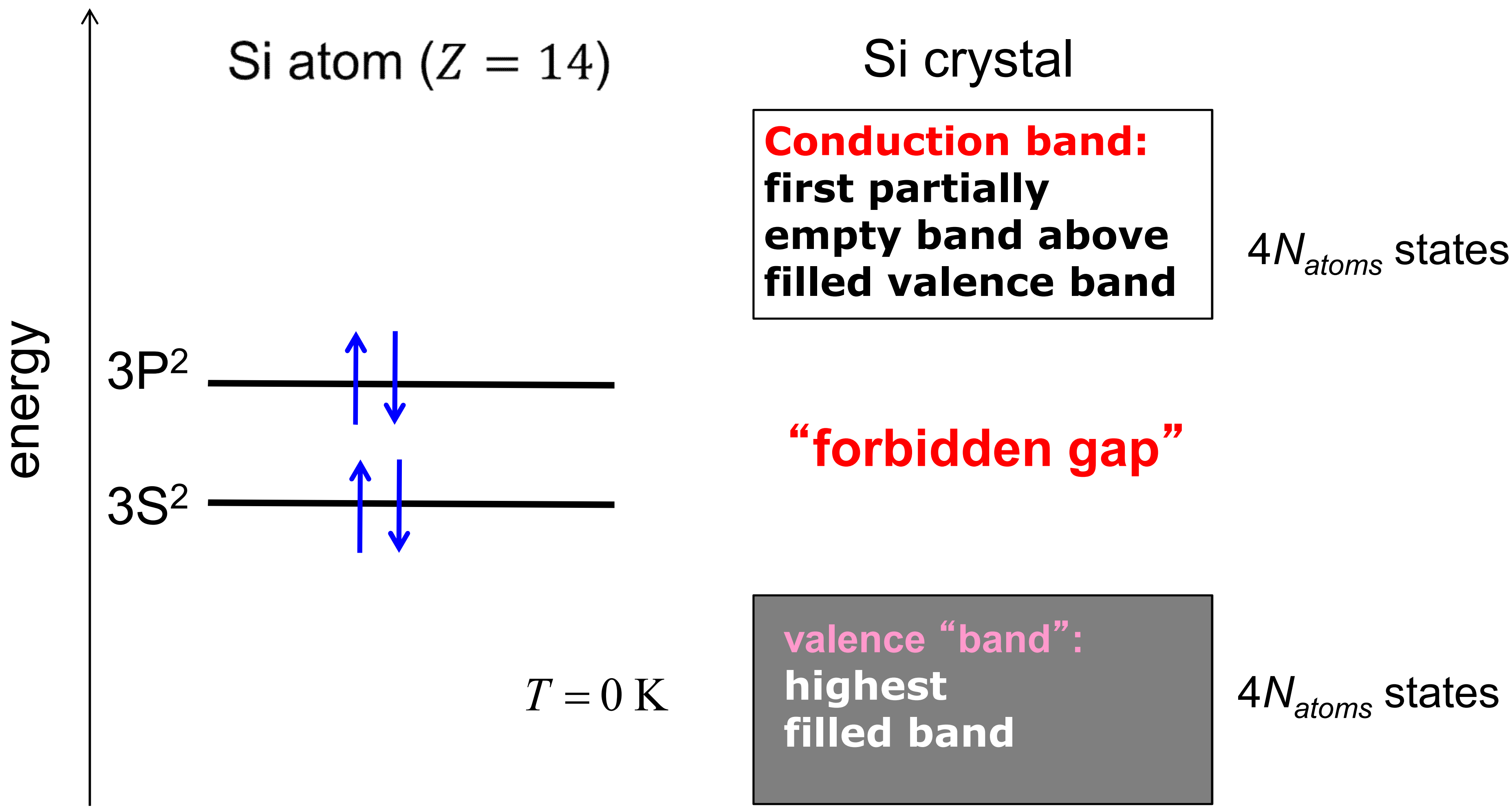
1. Electrons and Holes
2. Intrinsic carriers
3. Doping
4. Density of States
5. Carrier Distributions

Two Types of Carriers: Electrons and Holes

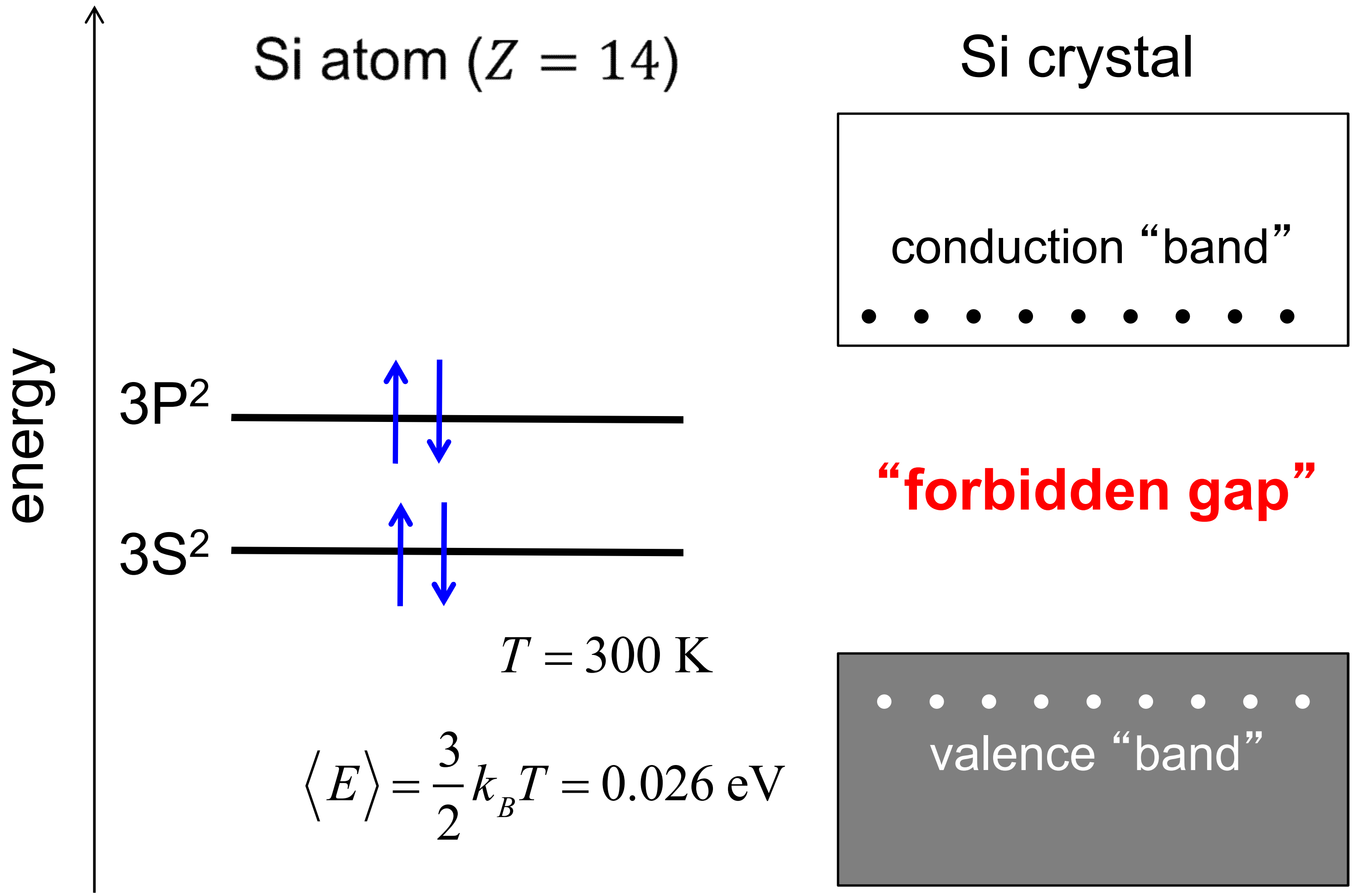


1) Electrons in conduction band can move
2) Holes (absence of electrons) in valence band can move
3) Electrons and holes can recombine

silicon energy levels → energy bands



silicon energy levels → energy bands



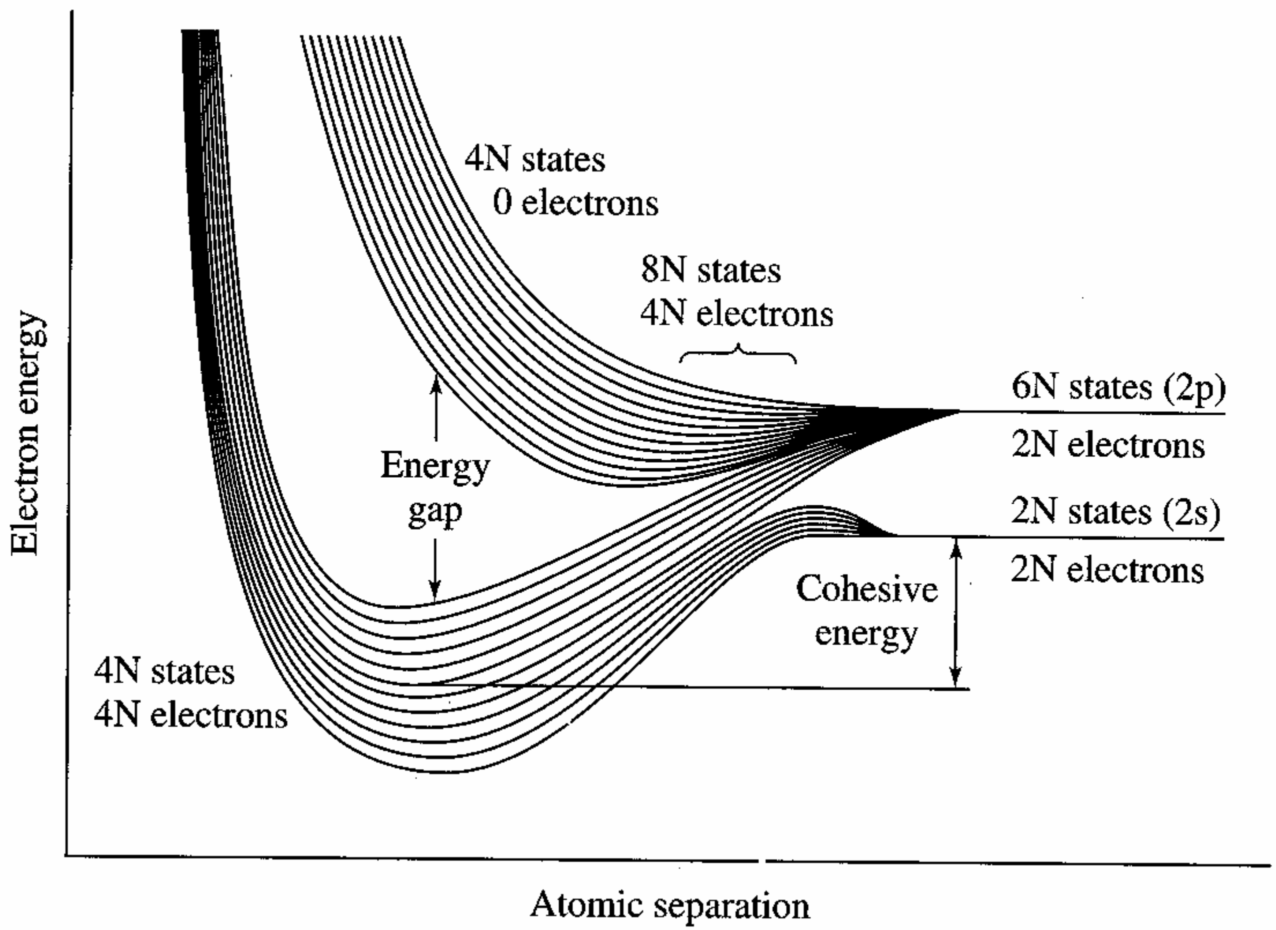
$n = p = n_i \text{ cm}^{-3}$

$p = n_i \text{ cm}^{-3}$

$T = 300 \text{ K}$

$$\langle E \rangle = \frac{3}{2} k_B T = 0.026 \text{ eV}$$

energy bands versus atomic separation



Si atoms
$1s^2 2s^2 2p^6 3s^2 2p^2$
C atoms
$1s^2 2s^2 2p^2$

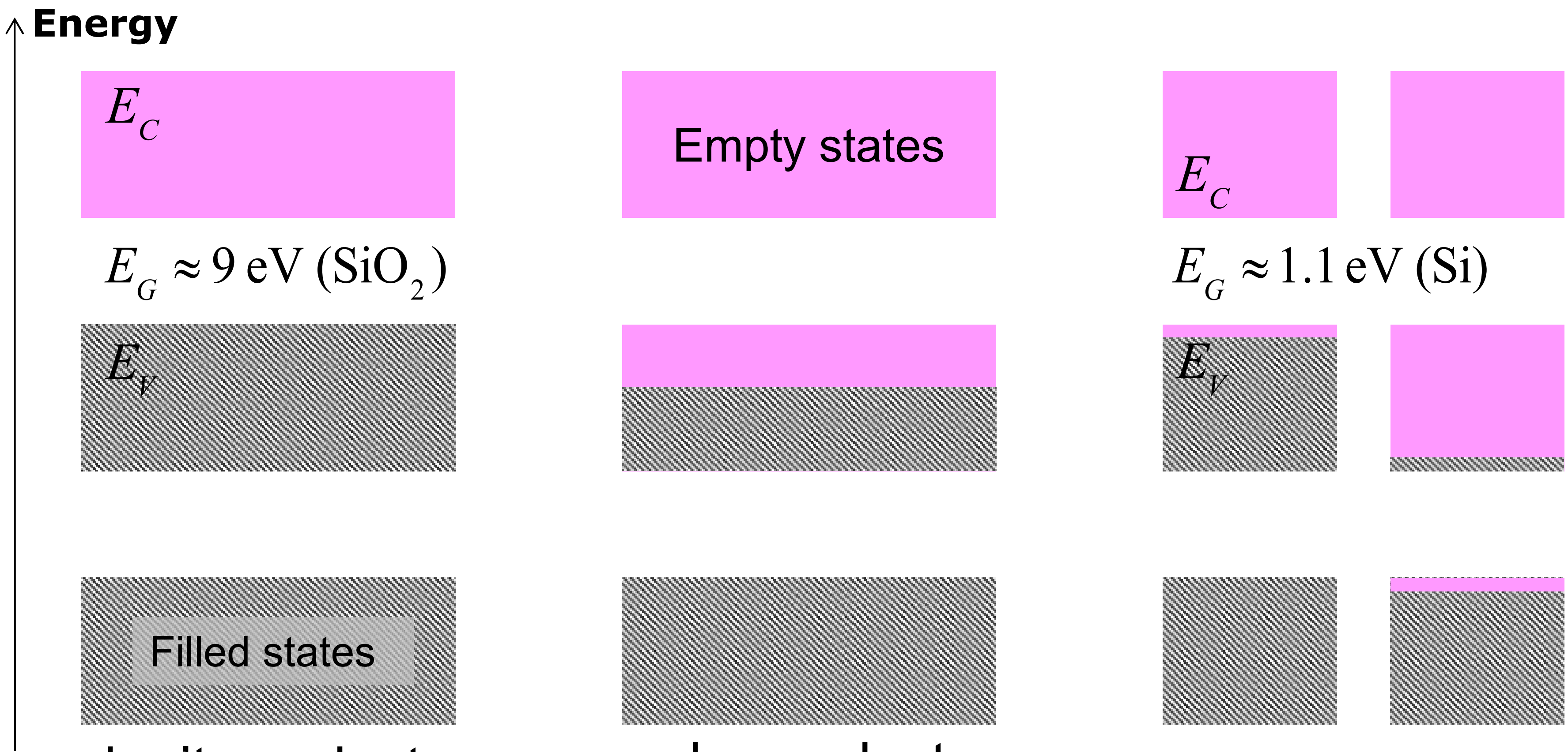
2s – 2 states
2p – 6 states

For N atoms:

2s line –
2N-fold degenerate

2p line –
6N-fold degenerate

insulators | metals | semiconductors



don't conduct electricity well

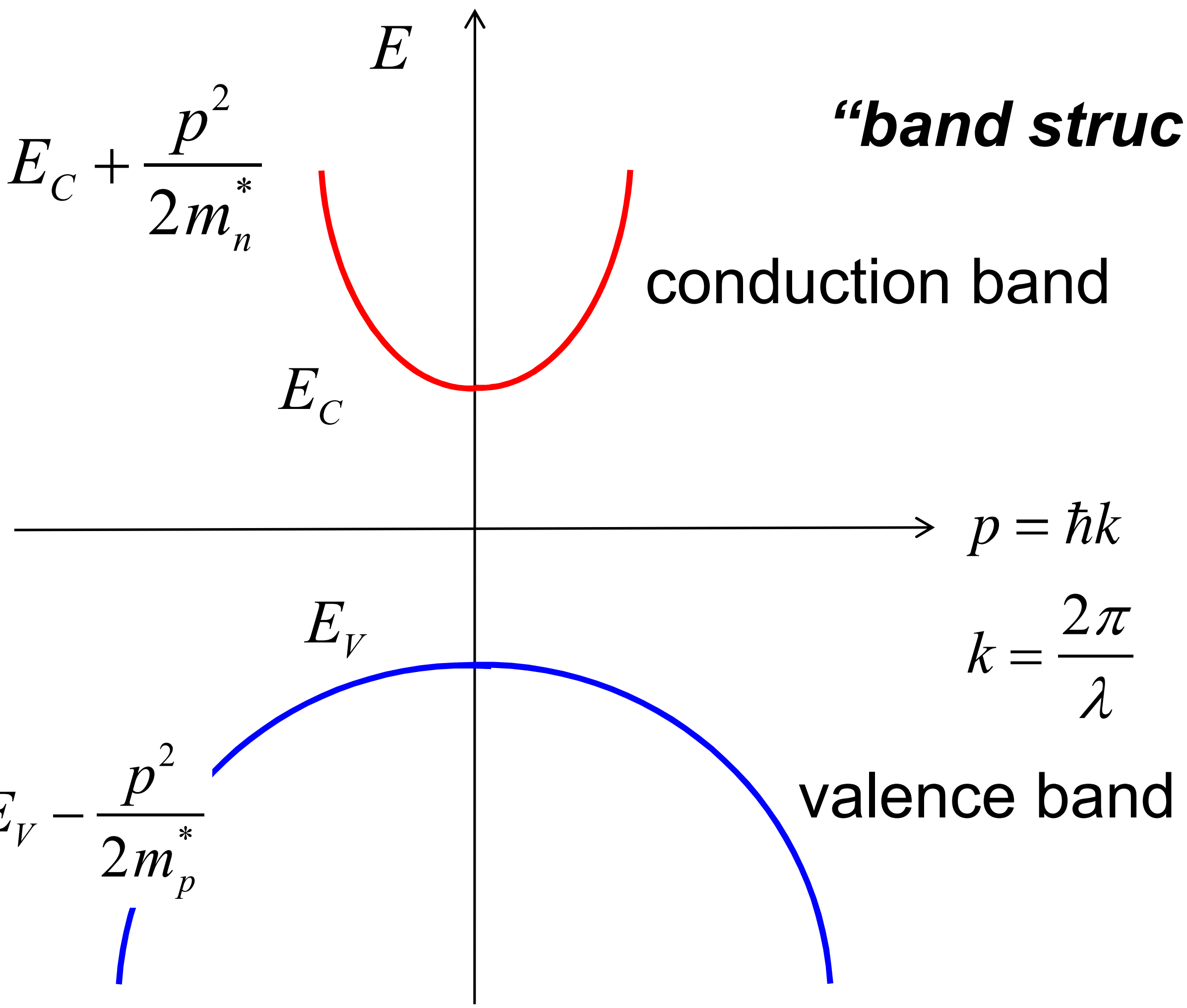
do conduct electricity well

in-between, **but** can be controlled

Conduction and valence bands

"band structure"

$$E = \frac{p^2}{2m_0} \rightarrow E = E_C + \frac{p^2}{2m_n^*}$$



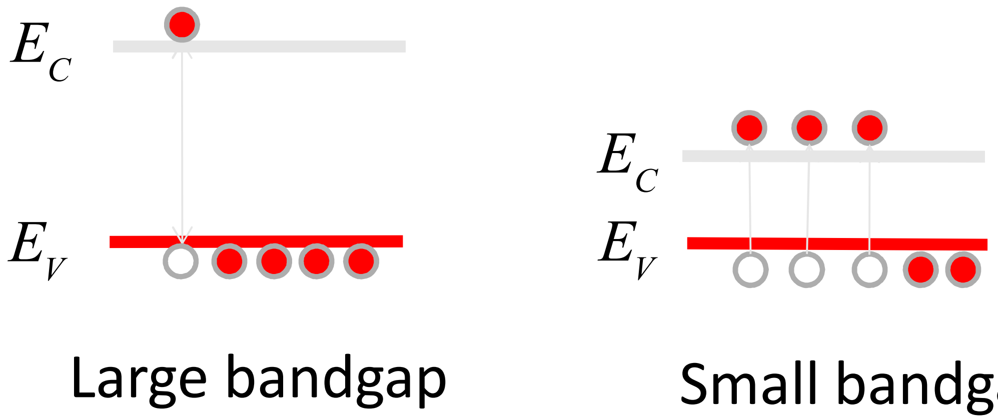
$$k = \frac{2\pi}{\lambda}$$

$$E = \frac{p^2}{2m_0} \rightarrow E = E_V - \frac{p^2}{2m_p^*}$$

outline

1. Electrons and Holes
2. Intrinsic carriers
3. Doping
4. Density of States
5. Carrier Distributions

In pure semiconductors, only free carriers matter



$$n_i = Ae^{-E_G/2k_BT} \qquad A \equiv \sqrt{N_C N_V}$$

$$n_i(\mathrm{Si}) = 1\times10^{10}\ \mathrm{cm}^{-3} .....E_G = 1.1\ \mathrm{eV}$$

$$n_i(\mathrm{Ge}) = 1\times10^{13}\ \mathrm{cm}^{-3} ....E_G = 0.66\ \mathrm{eV}$$

$$n_i(\mathrm{GaAs}) = 1\times10^{6}\ \mathrm{cm}^{-3} ..E_G = 1.42\ \mathrm{eV}$$

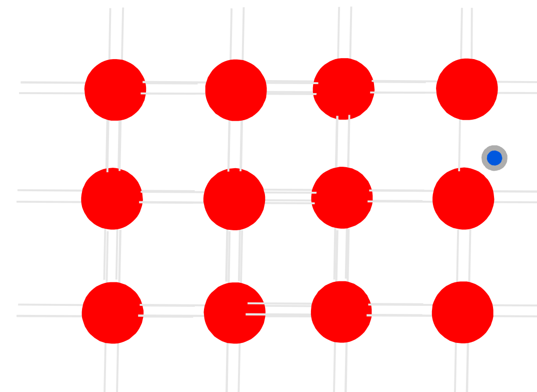
@Room Temp.

Why is the current so low …

$$n_i(\mathrm{Si}) = 1\times10^{10}\ \mathrm{cm}^{-3} \ldots\ldots E_G = 1.1\,eV$$

$$n_i(\mathrm{Ge}) = 1\times10^{13}\ \mathrm{cm}^{-3} \ldots\ldots E_G = 0.66\,eV$$

$$n_i(\mathrm{GaAs}) = 1\times10^{6}\ \mathrm{cm}^{-3} \ldots E_G = 1.42\,eV$$



$$N_{atoms} = N_{atoms} = 5\times10^{22}\ \mathrm{cm}^{-3}$$

$$\text{bonds/atom} = 4$$

$$N_{total} = 2\times10^{23}\ \mathrm{cm}^{-3}$$

Only 1 out of 20 trillion electrons in Silicon are free to move!

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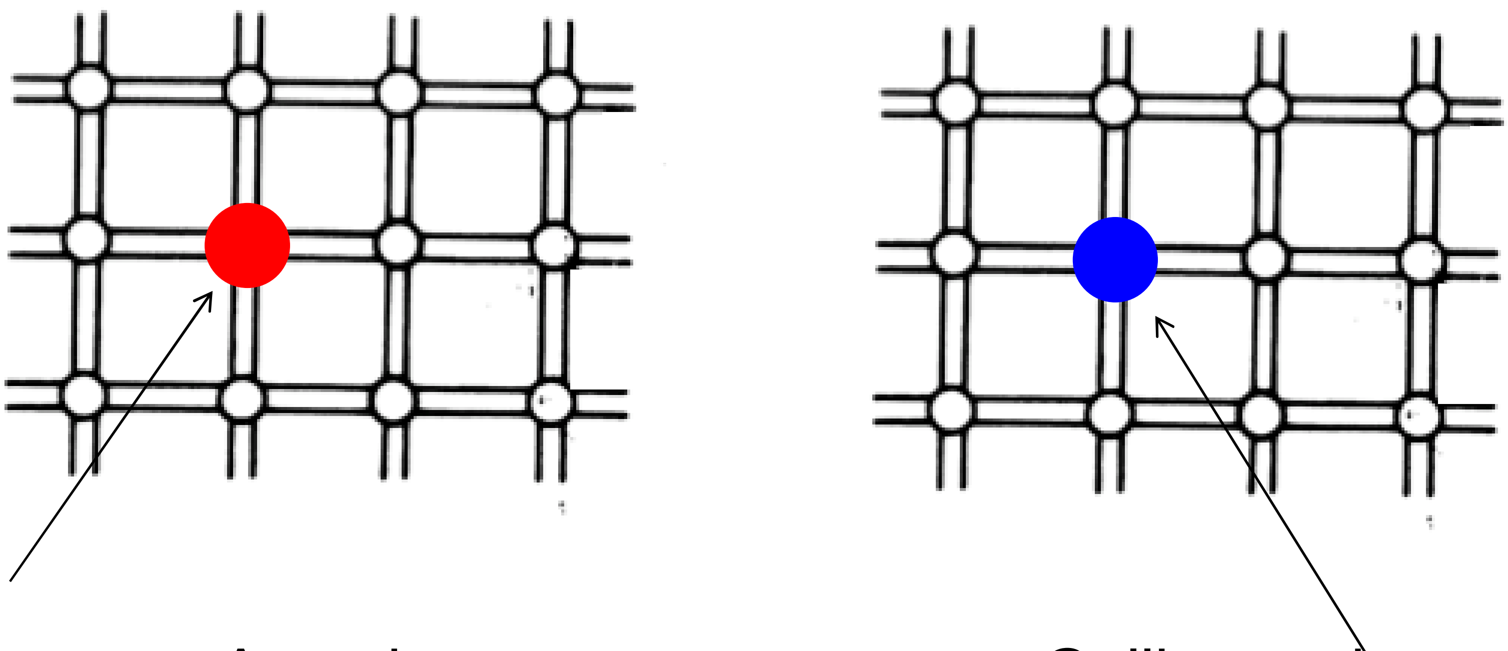
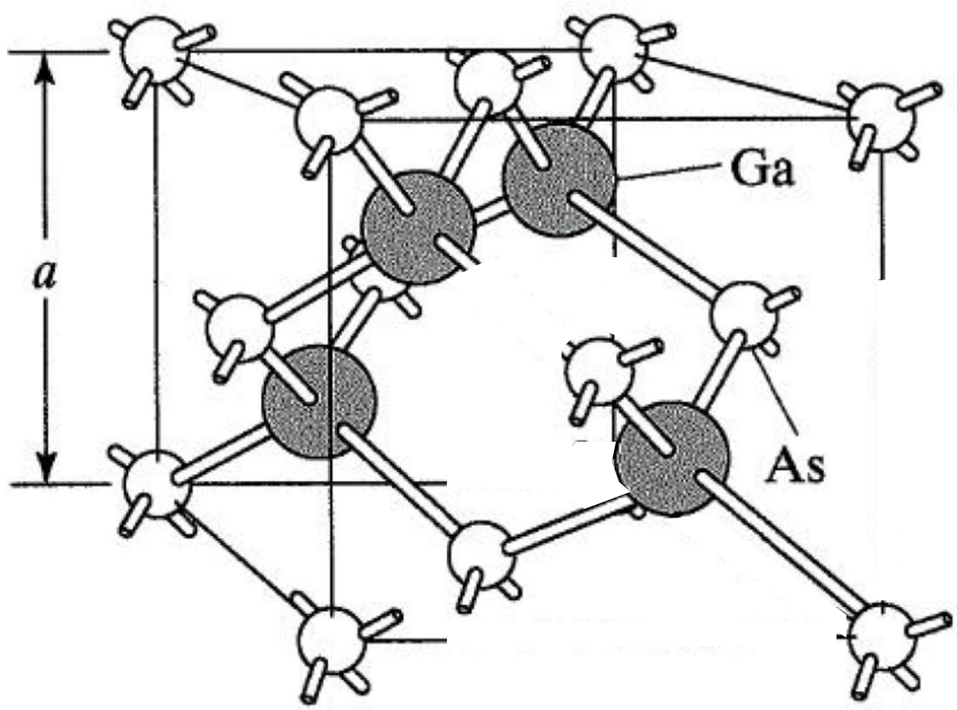
doping

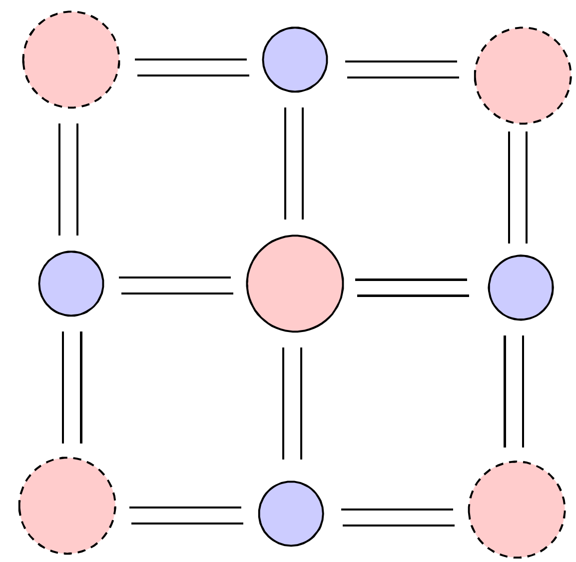


Phosphorus or Arsenic

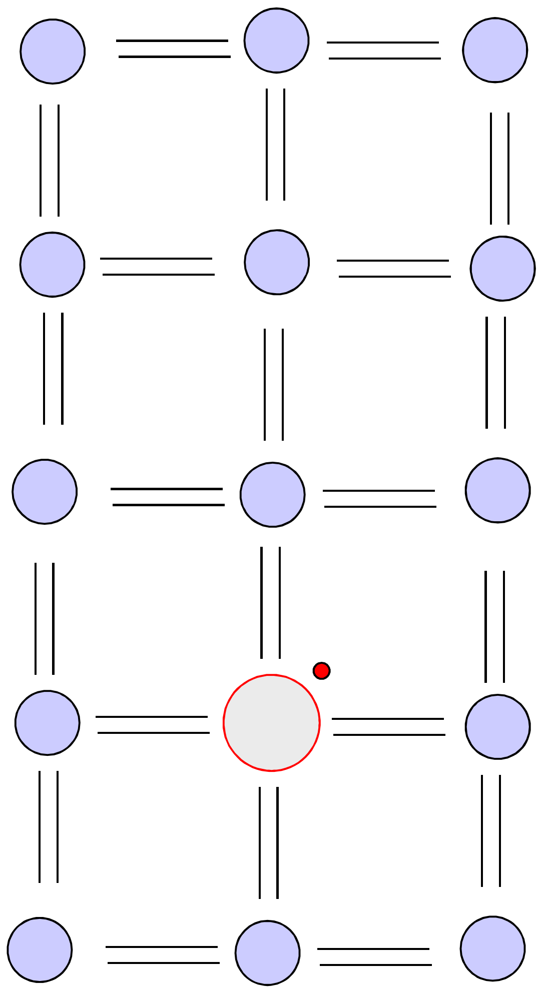
Gallium or boron

Simplified Planar View of Atoms





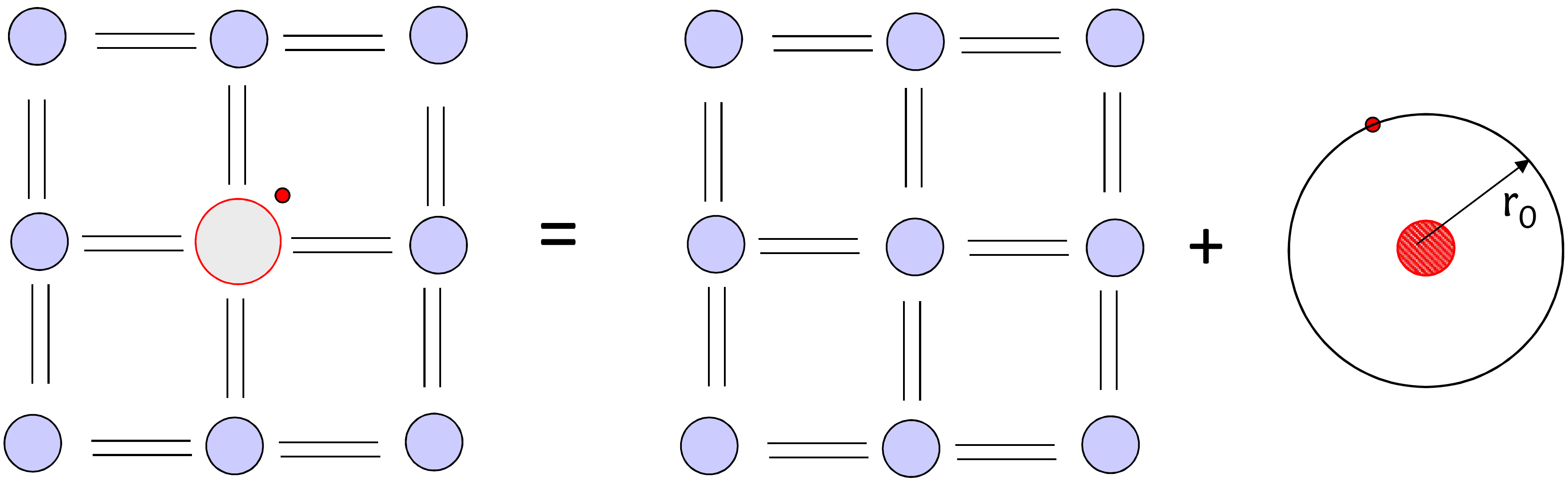
Donor Atoms



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

Even with donors, material is charge neutral

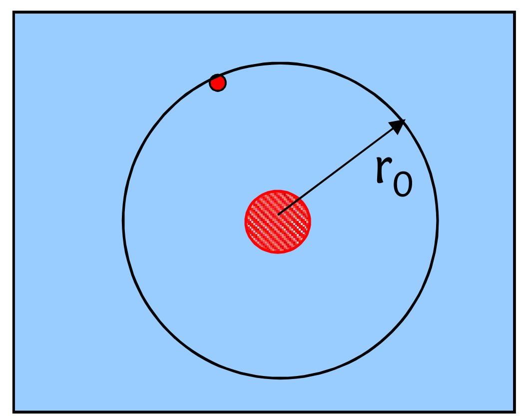
Donor Atoms in H_2-analogy



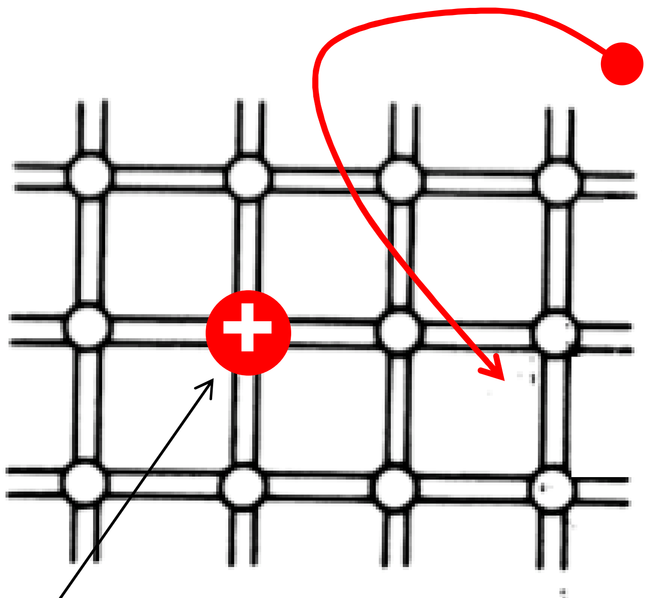
E_T ~10s meV

$$r_{1,P} = 12.9\ \text{Å}$$

=



n-type doping



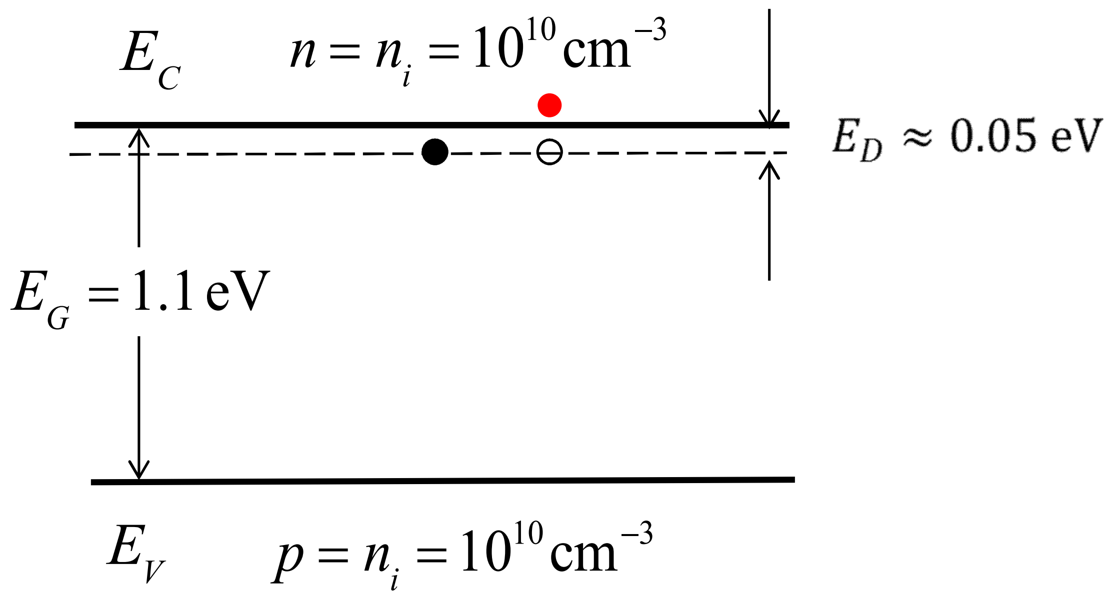
"Ionized donor"

$$N_D^+ \approx n$$

Phosphorus or Arsenic

energy band view (n-type)

n-doped Si

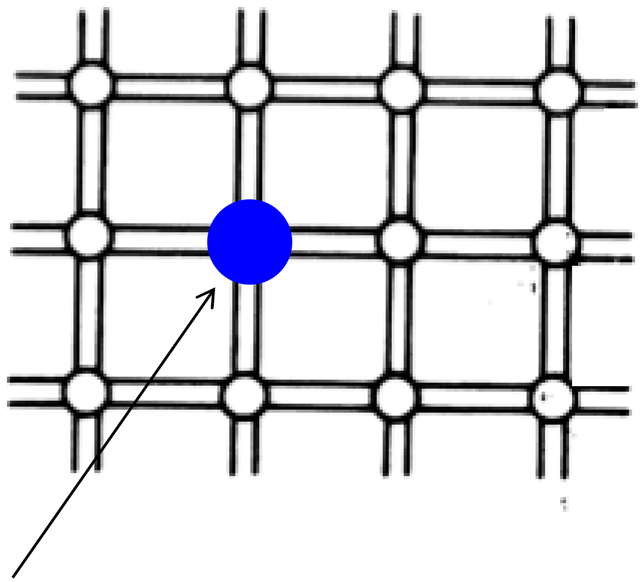


$$N_D = 10^{18}\,\text{cm}^{-3}$$

$$N_D^+ = 10^{18}\,\text{cm}^{-3}$$

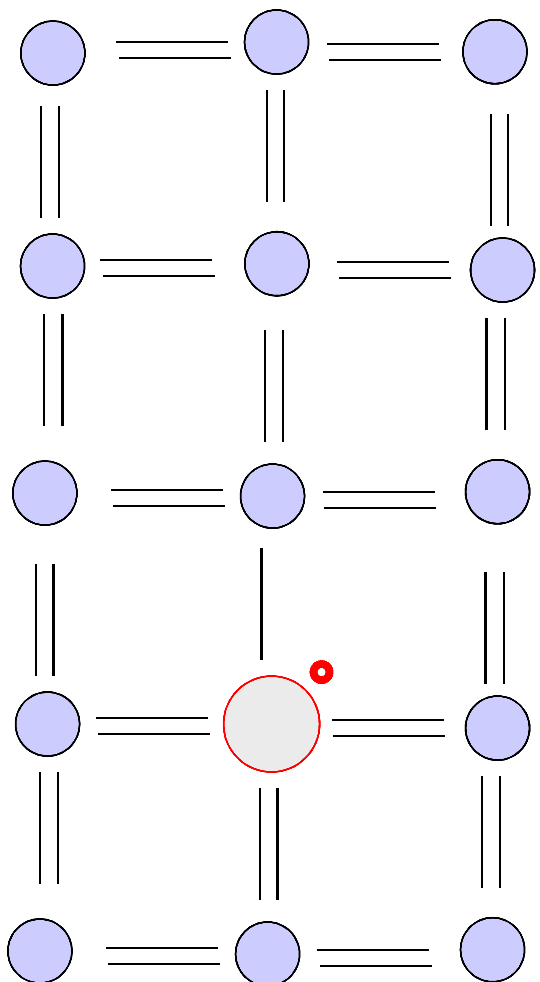
$$n \approx N_D^+ = 10^{18}\text{ cm}^{-3}$$

p-type doping



Gallium or boron

Acceptor Atoms



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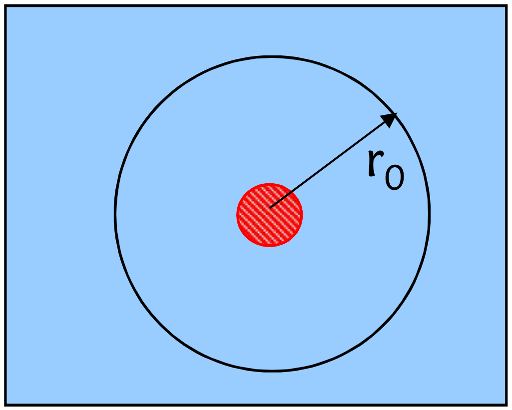
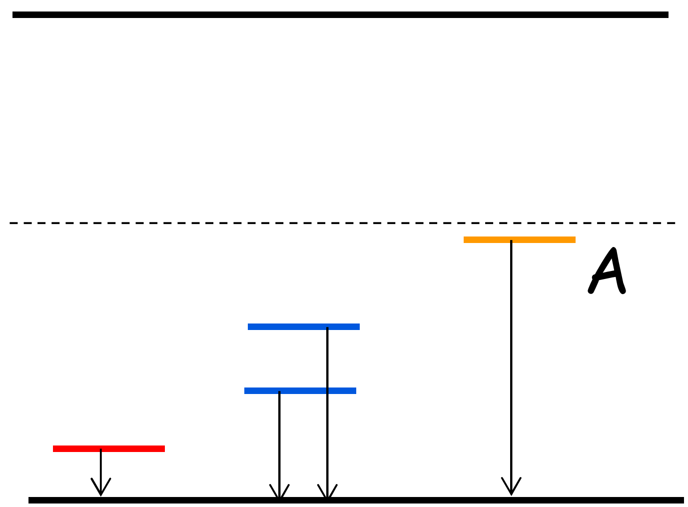
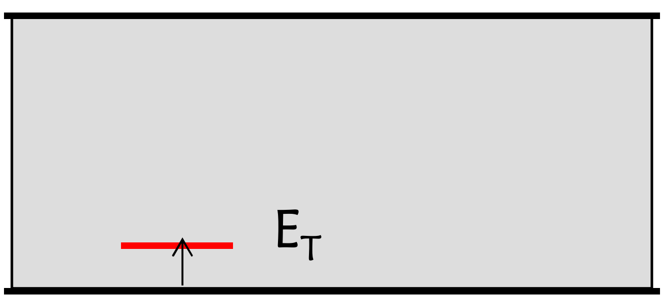
Even with acceptor, material is charge neutral

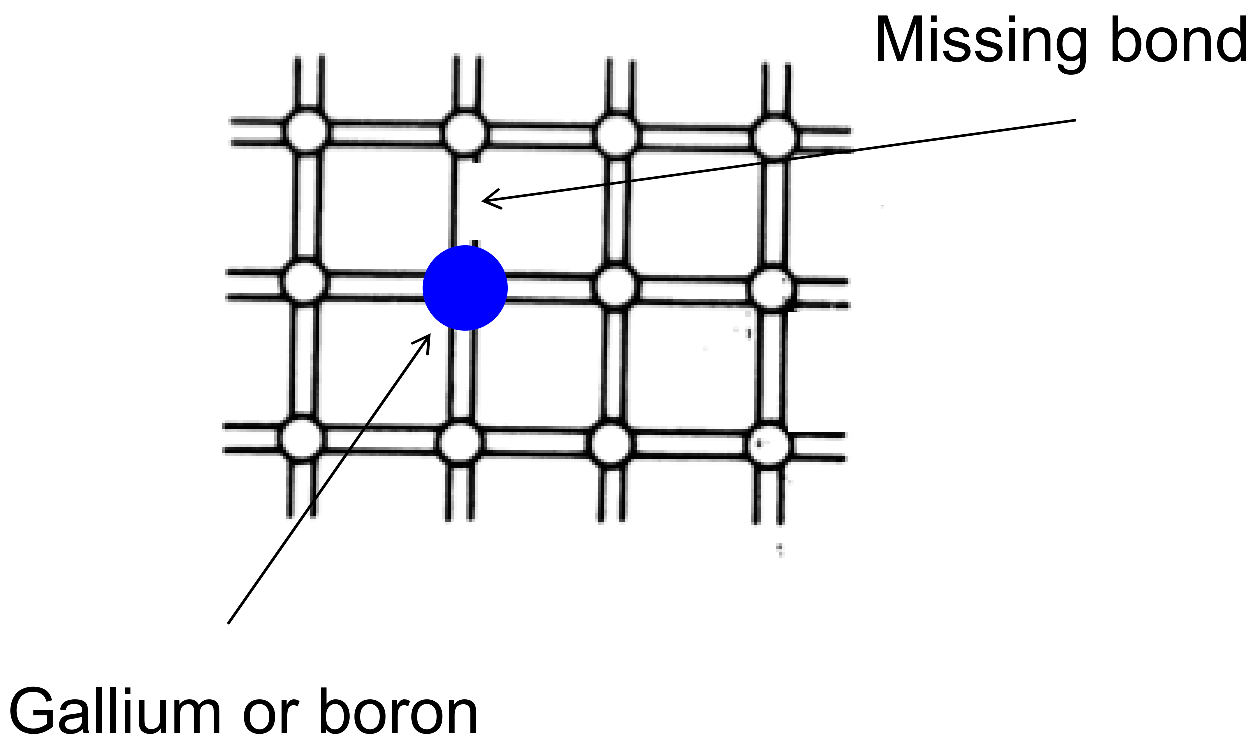
Characteristics of Acceptor Atoms



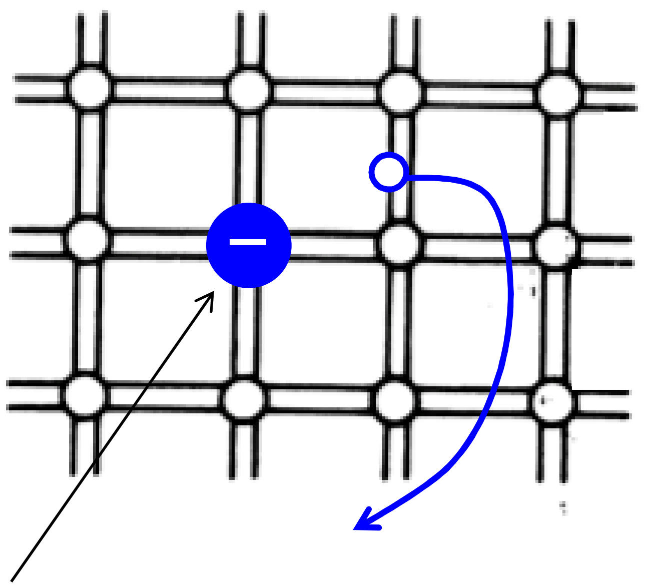




p-type doping



p-type doping



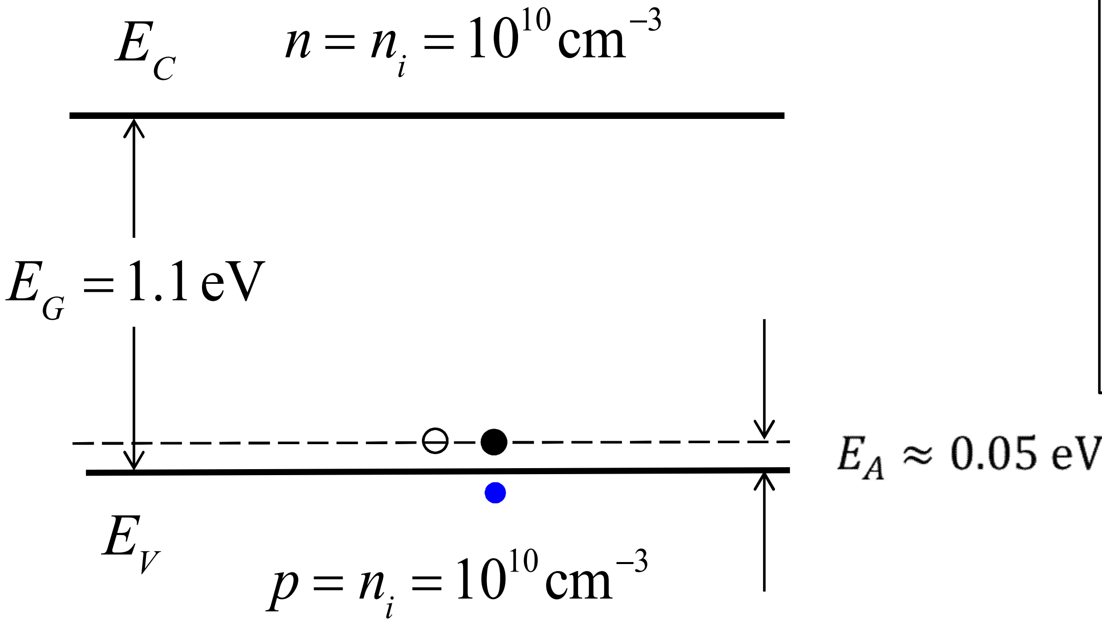
Gallium or boron

Ionized acceptor

$$N_A^- \approx p$$

energy band view (p-type)

p-doped Si

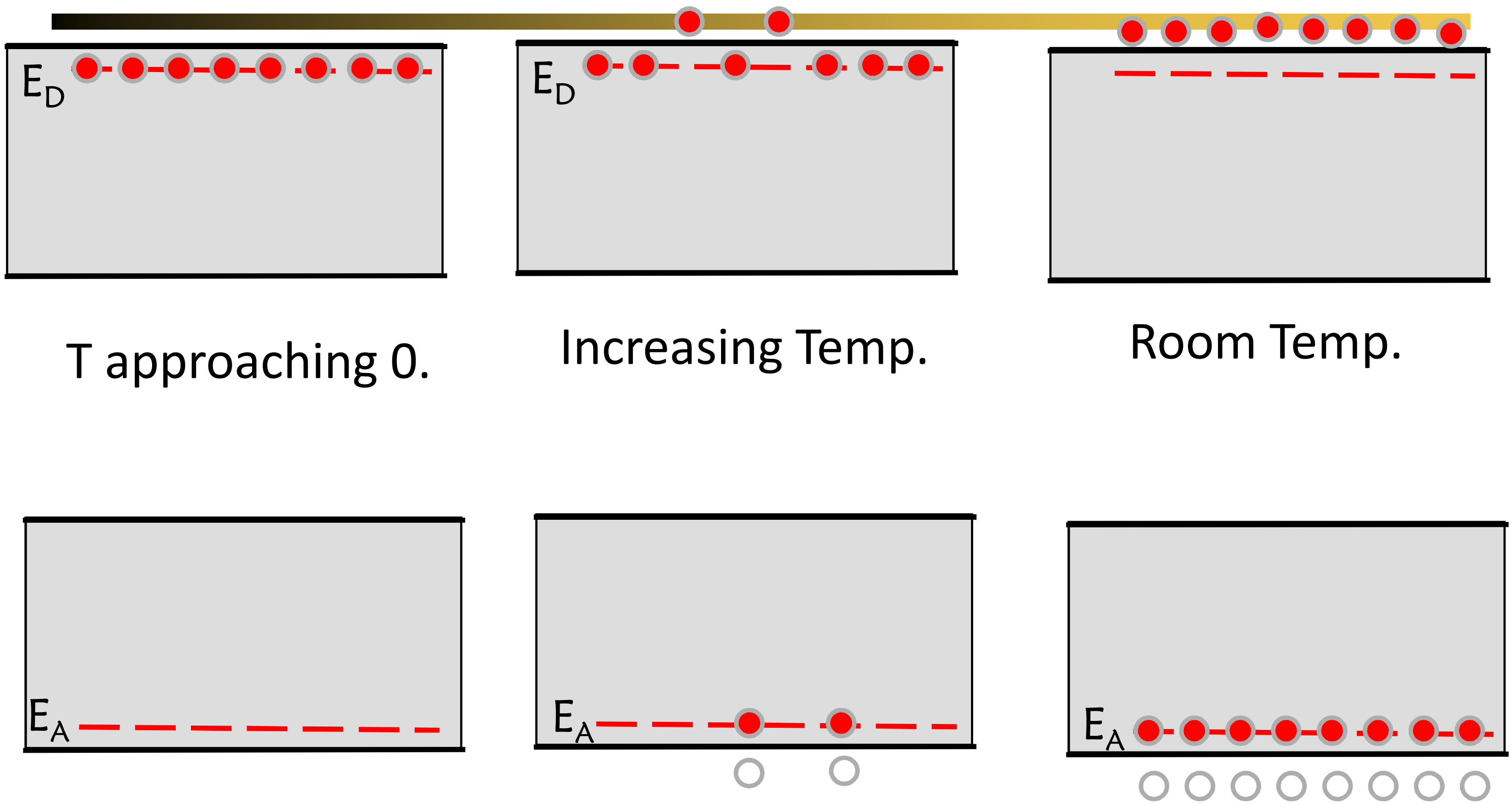


$$N_A = 10^{18}\,\mathrm{cm}^{-3}$$

$$N_A^- = 10^{18}\,\mathrm{cm}^{-3}$$

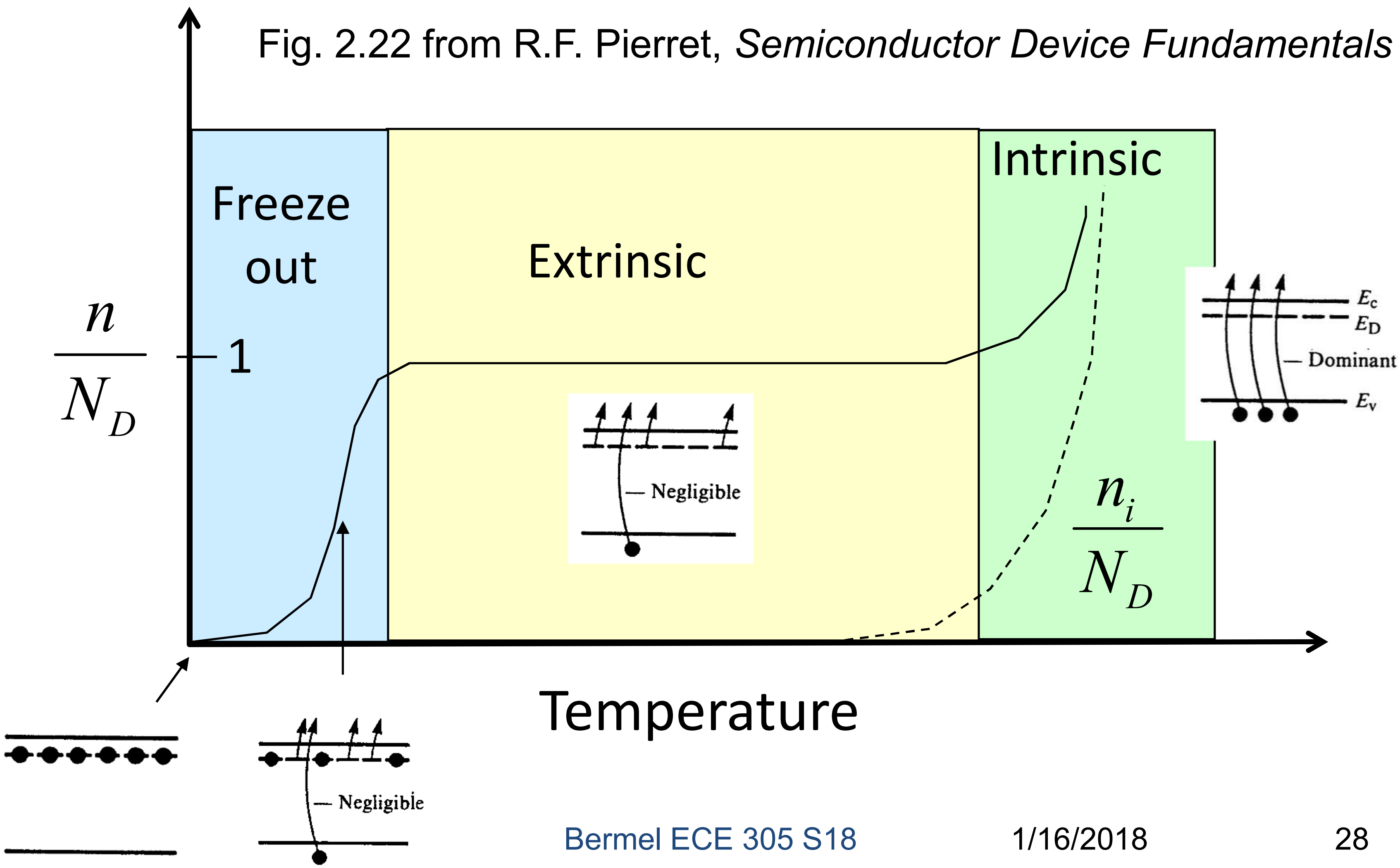
$$p \approx N_A^- = 10^{18}\ \mathrm{cm}^{-3}$$

Temperature-dependent ionization



Pierret, SDF, Fig. 2.13

Carrier concentration vs. temperature



Amphoteric Dopants

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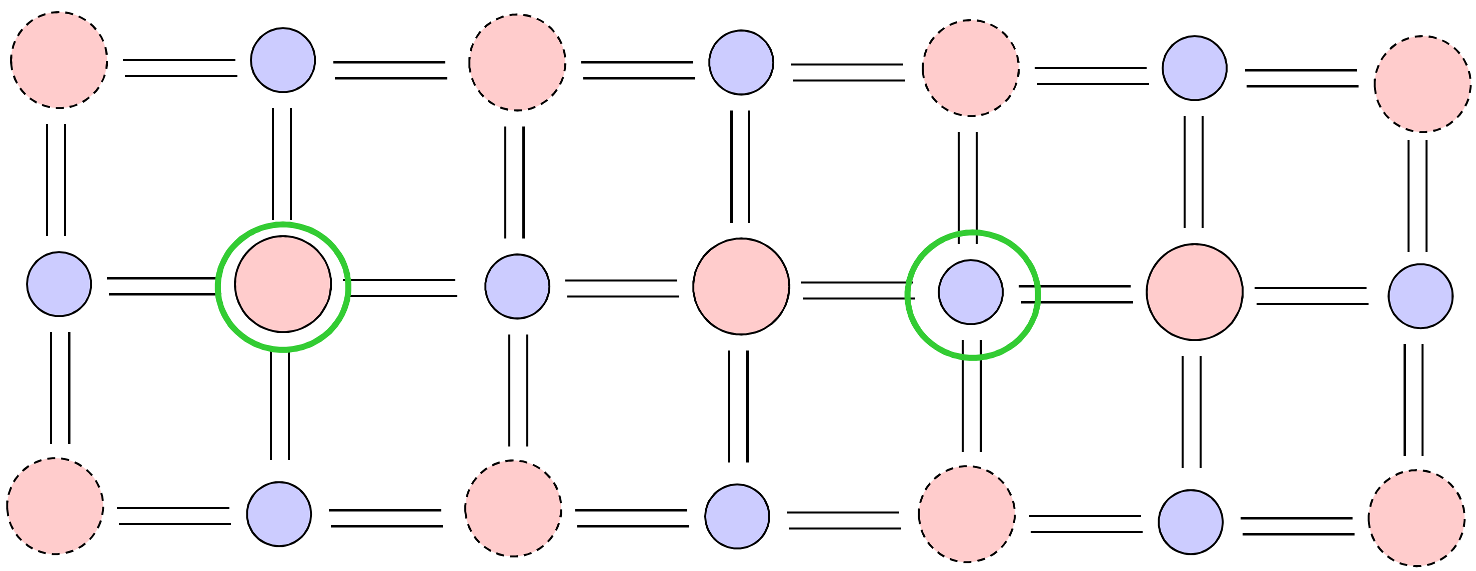
Donor-type

acceptor-type



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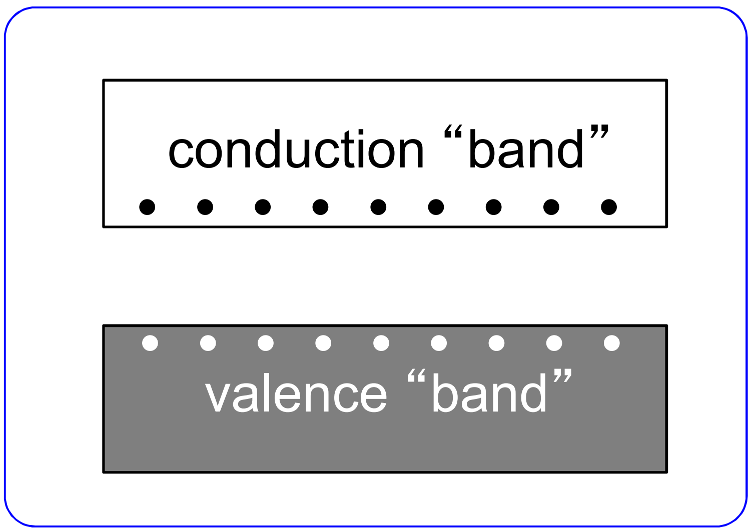
DOS



4N_a states / band

N_a = 5 x 10^{22} /cm^3

How are the energy levels distributed with the bands?

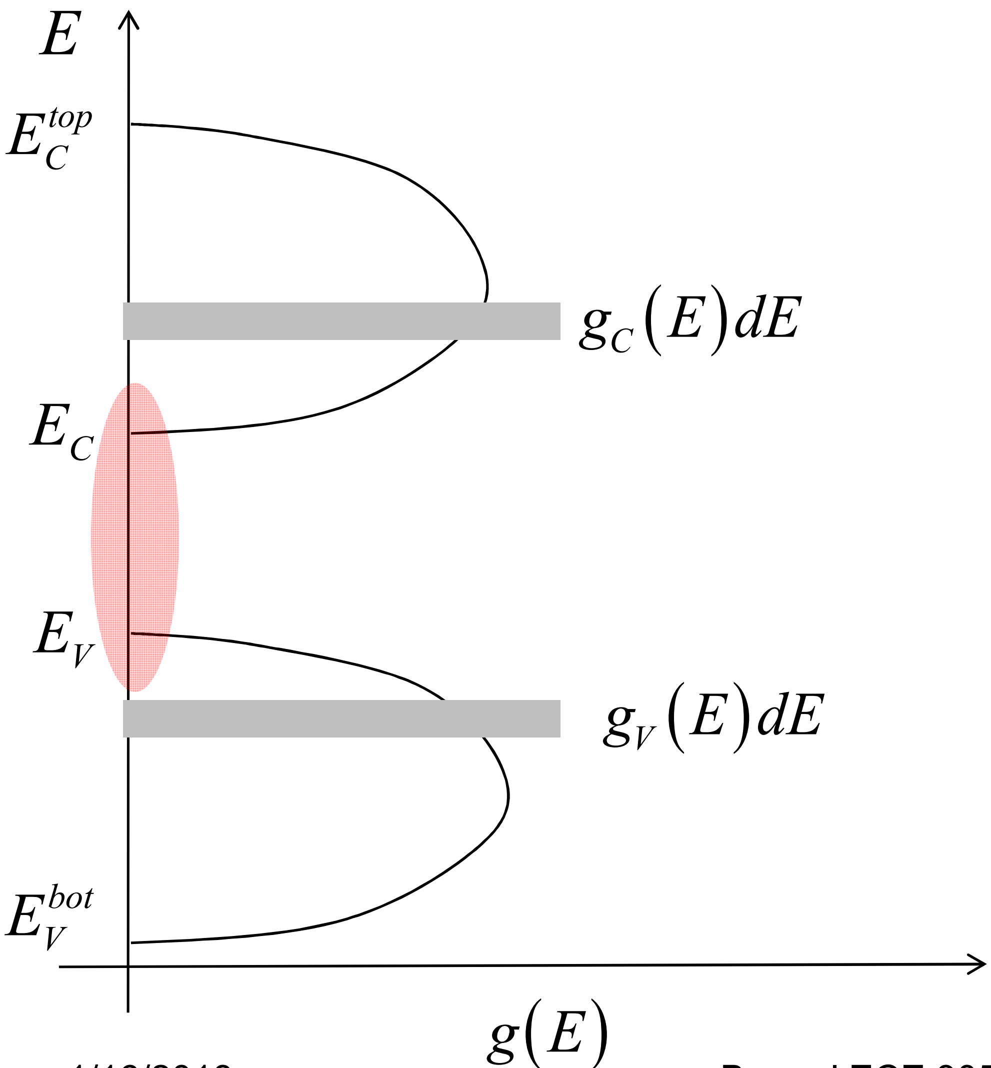
density-of-states

Number of states per unit energy per unit volume.
Units: (J-m^3)$^{-1}$

$$g(E)dE$$

Number of states in an energy range, *dE*, per m^3.

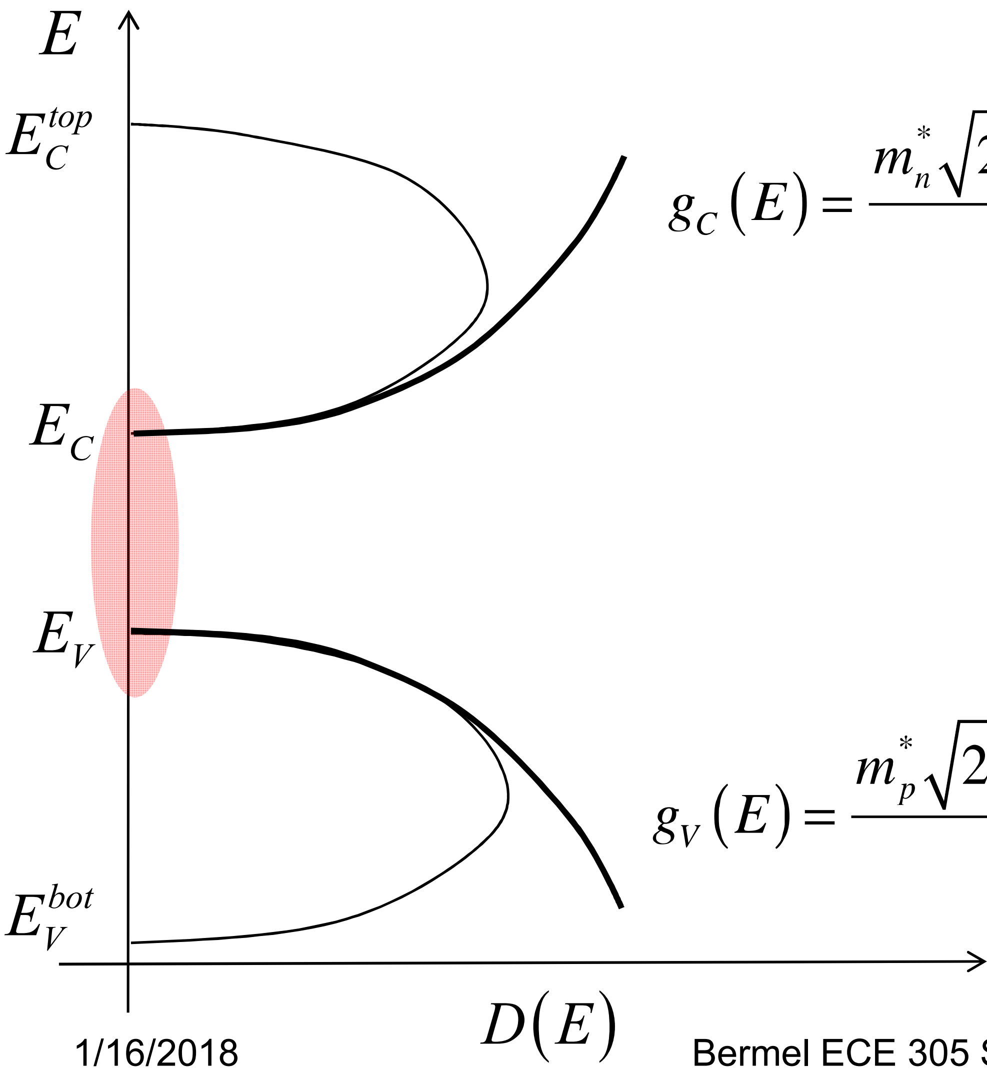
DOS



$$\int_{E_C}^{E_C^{top}} g_C(E)dE = 4N_a$$

$$\int_{E_V^{bot}}^{E_V} g_V(E)dE = 4N_a$$

density of states



$$g_C(E) = \frac{m_n^* \sqrt{2m_n^*(E - E_C)}}{\pi^2 \hbar^3}$$

$$g_V(E) = \frac{m_p^* \sqrt{2m_p^*(E_V - E)}}{\pi^2 \hbar^3}$$

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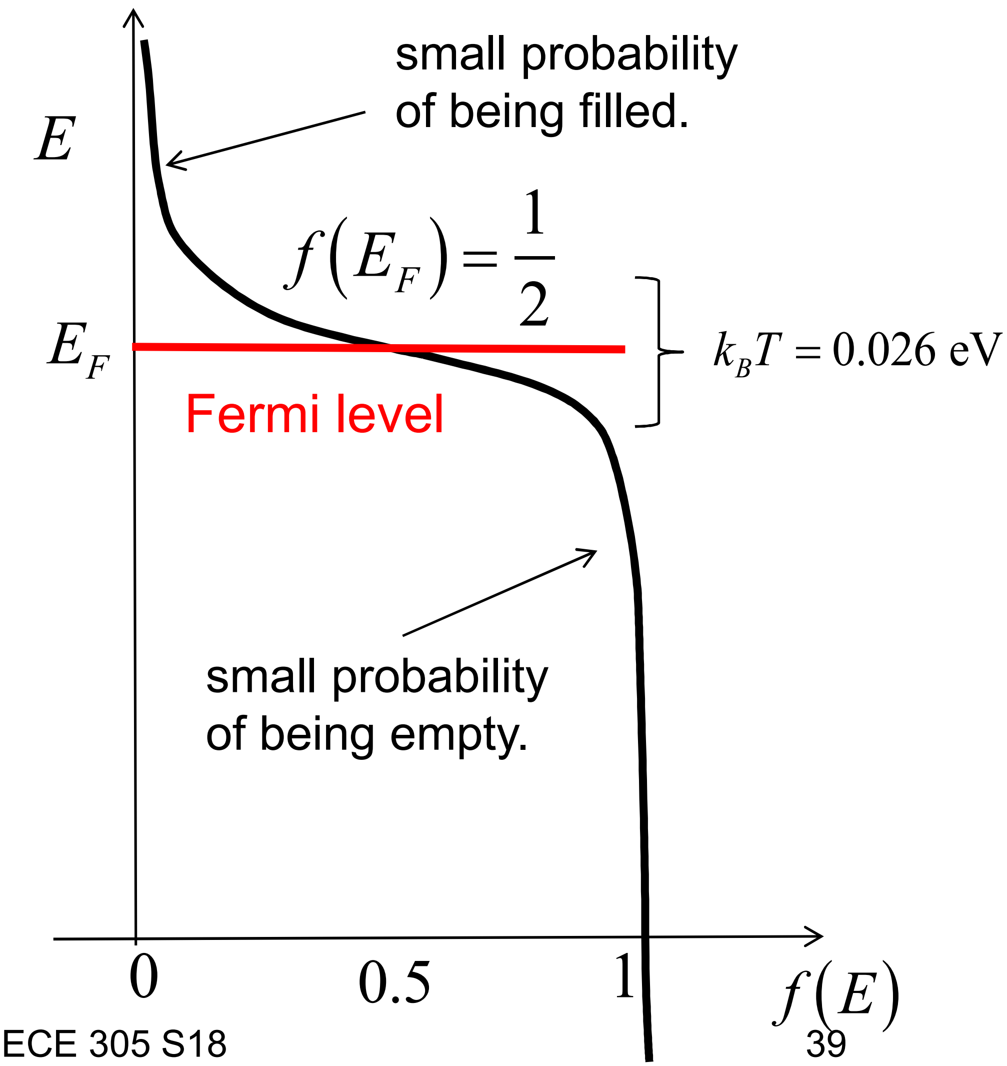
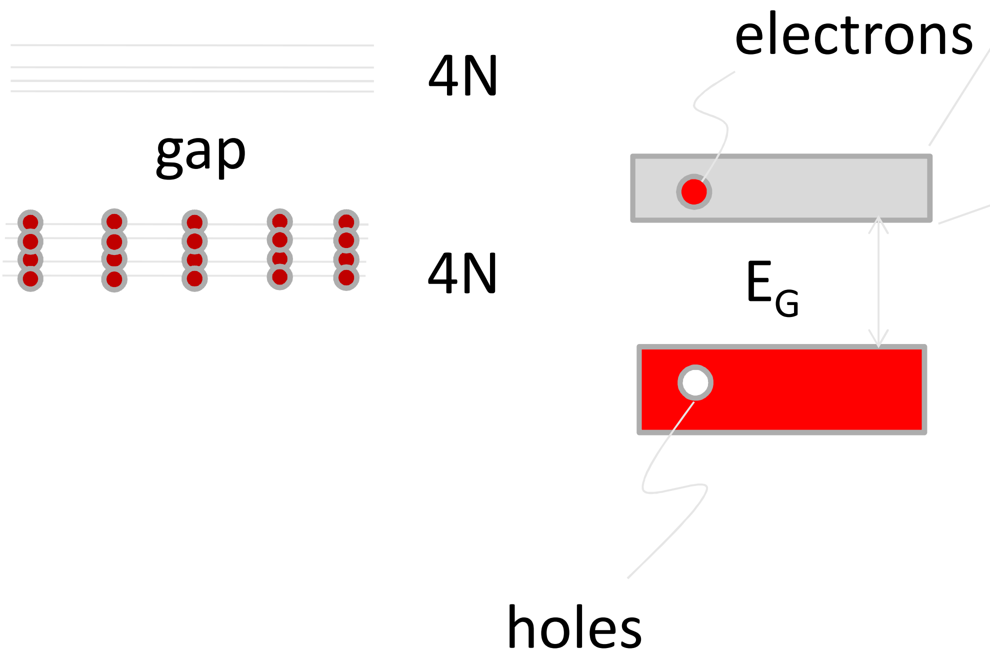
Fermi function

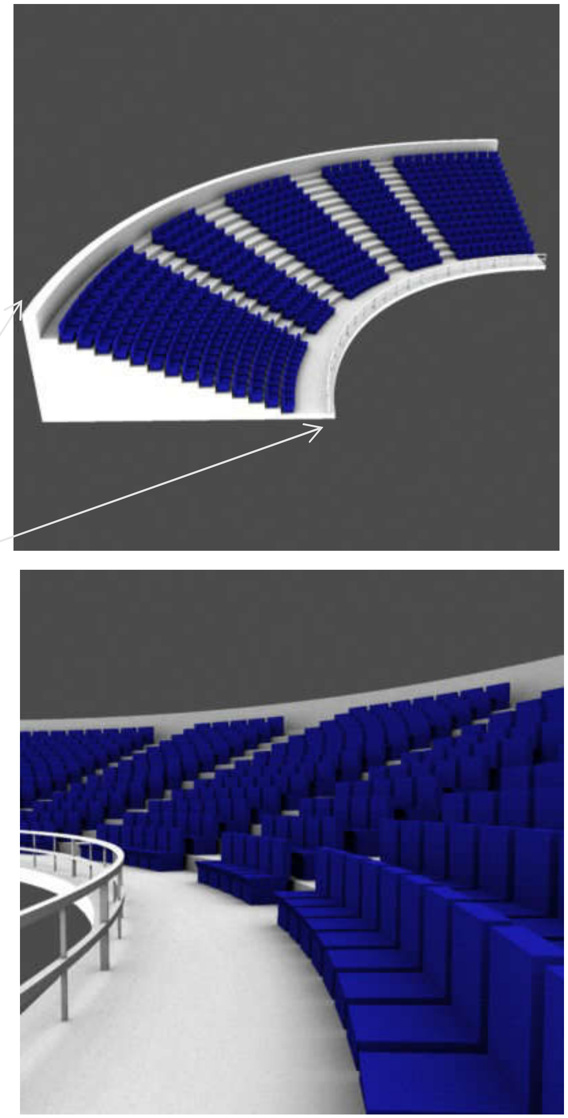
$$f(E) = \frac{1}{1 + e^{(E-E_F)/k_B T}}$$

Probability that a state at energy, E, is occupied <u>in equilibrium</u>.



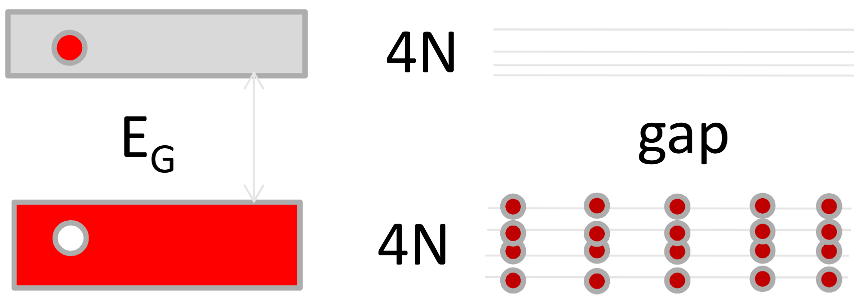
Analogy with stadium …

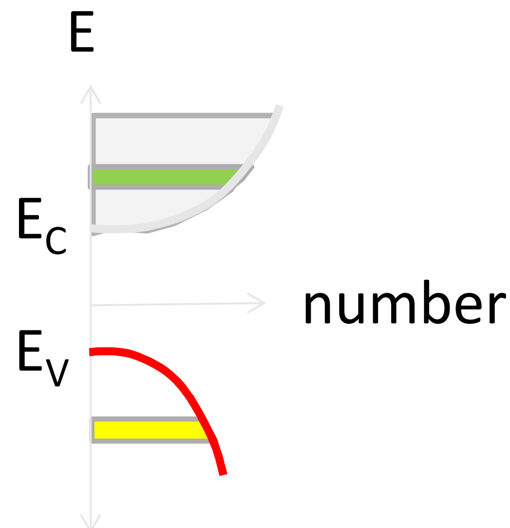




Floating around in the conduction band

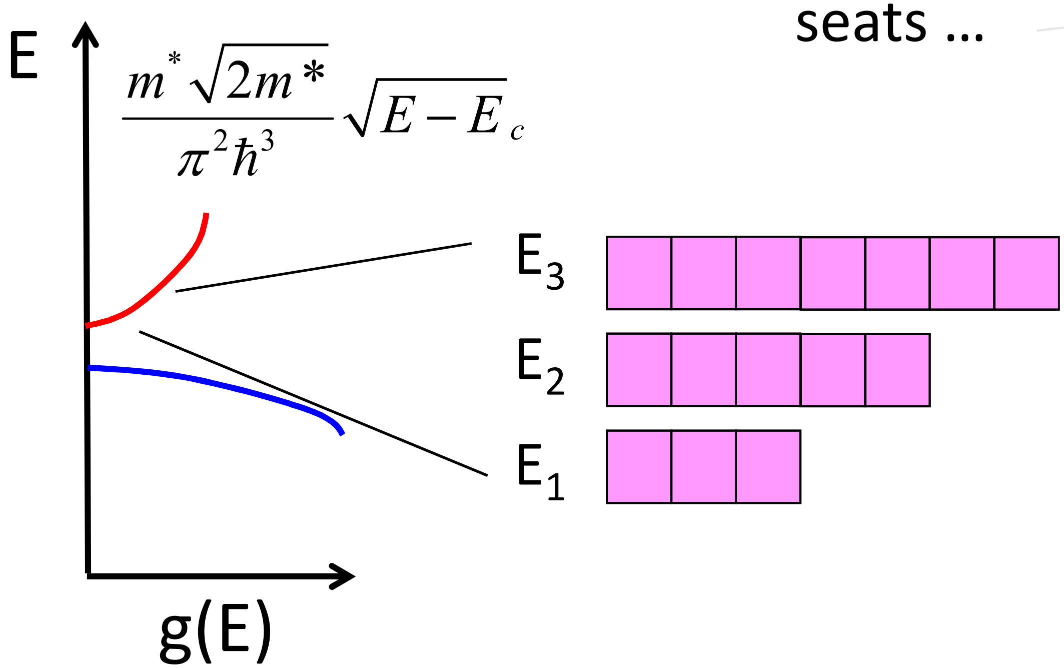
$$g_c(E) = \frac{m_n^* \sqrt{2m_n^*(E - E_c)}}{\pi^2 \hbar^3}$$



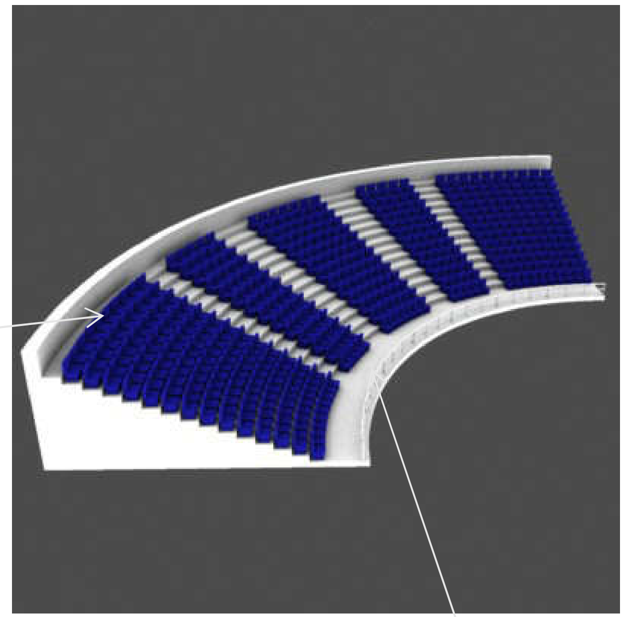


$$g_\upsilon(E) = \frac{m_h^* \sqrt{2m_h^*(E_V - E)}}{\pi^2 \hbar^3}$$

Density of States



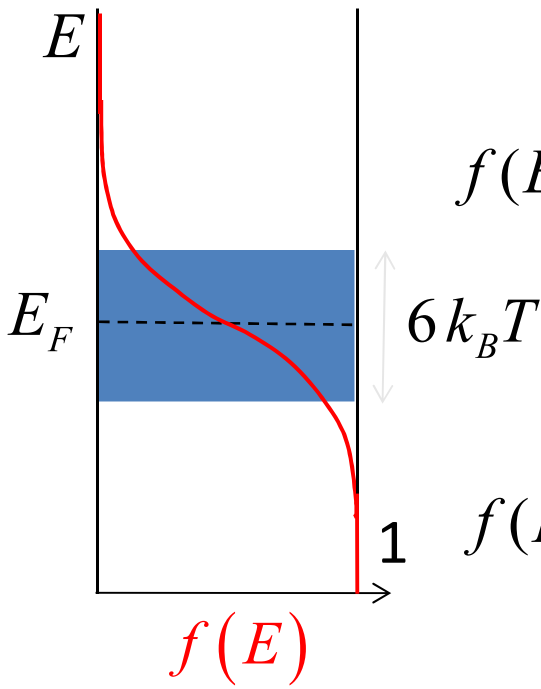
Lower priced seats …



Higher priced seats …

Distribution Functions

High Temp.

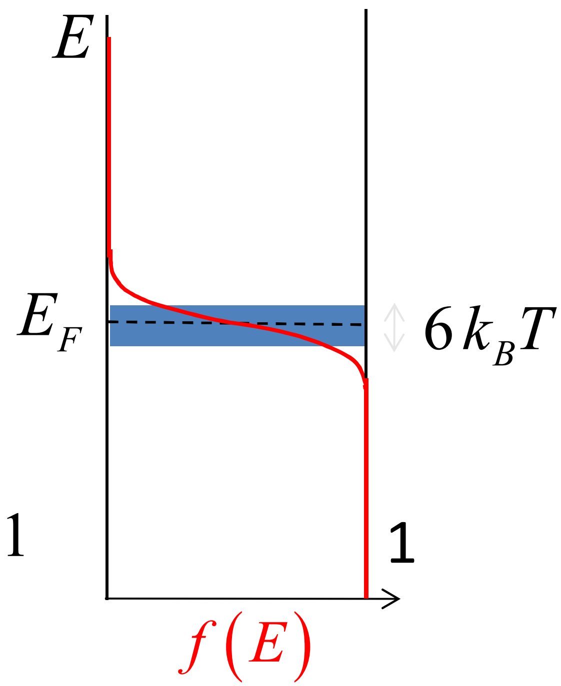


$$f(E) = \frac{1}{1+e^{(E-E_F)/k_BT}}$$

$$f(E\to\infty) = e^{-(E-E_F)/k_BT}$$

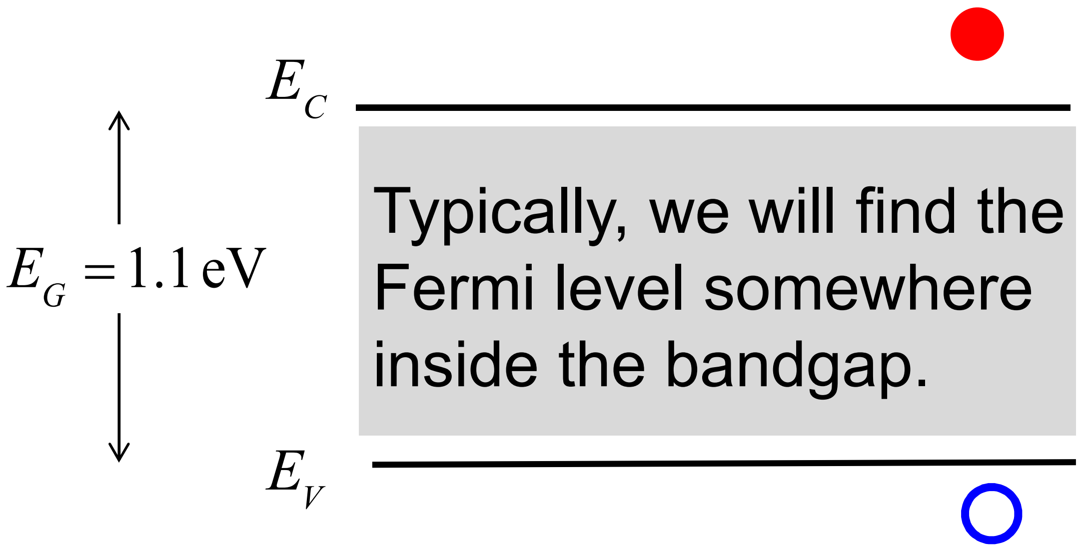
$$f(E\to E_F) \to 1 - e^{(E-E_F)/k_BT} \to 1$$

Low Temp.



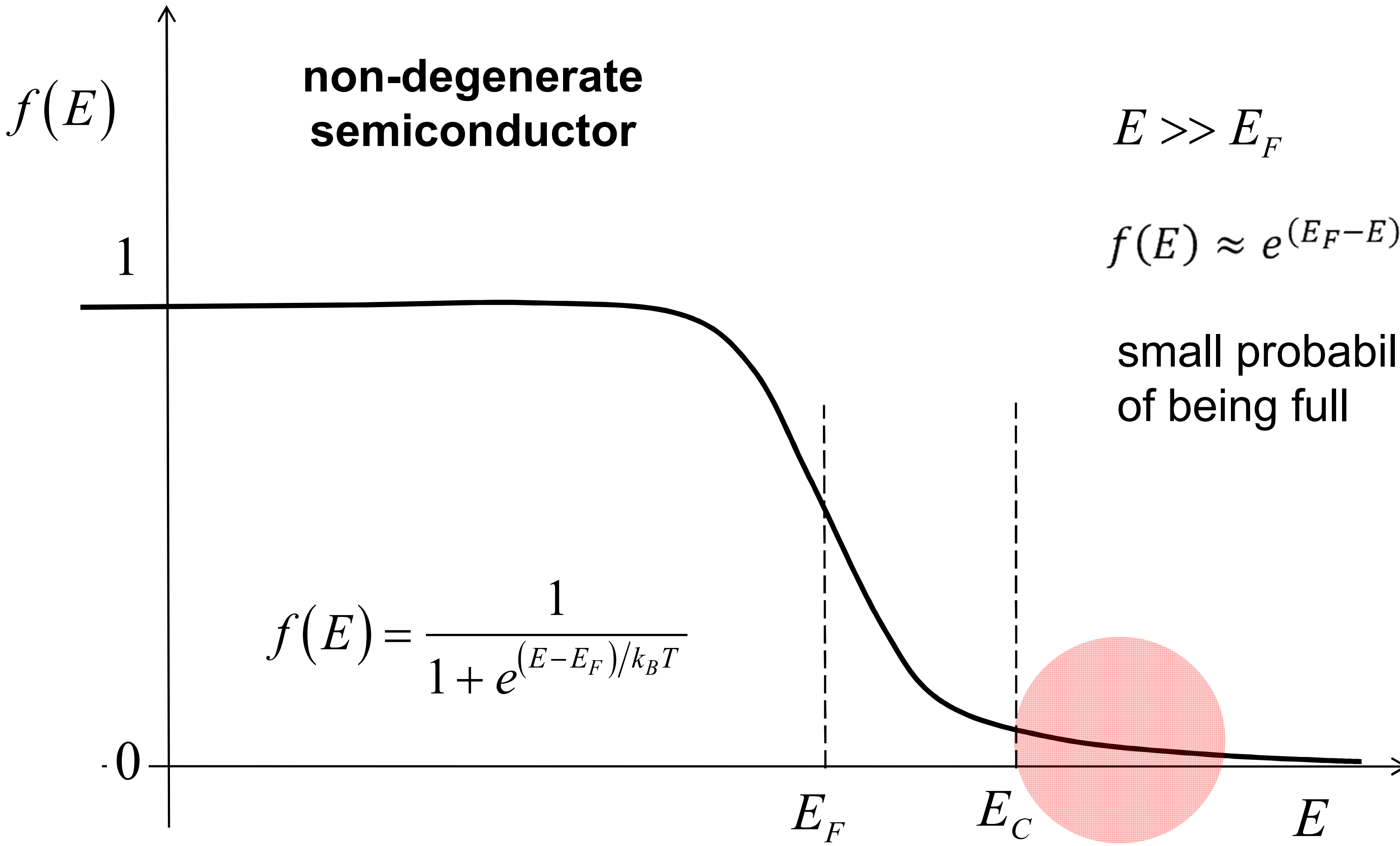
electrons and holes

These states are way above the Fermi level.



These states are way below the Fermi level.

conduction band



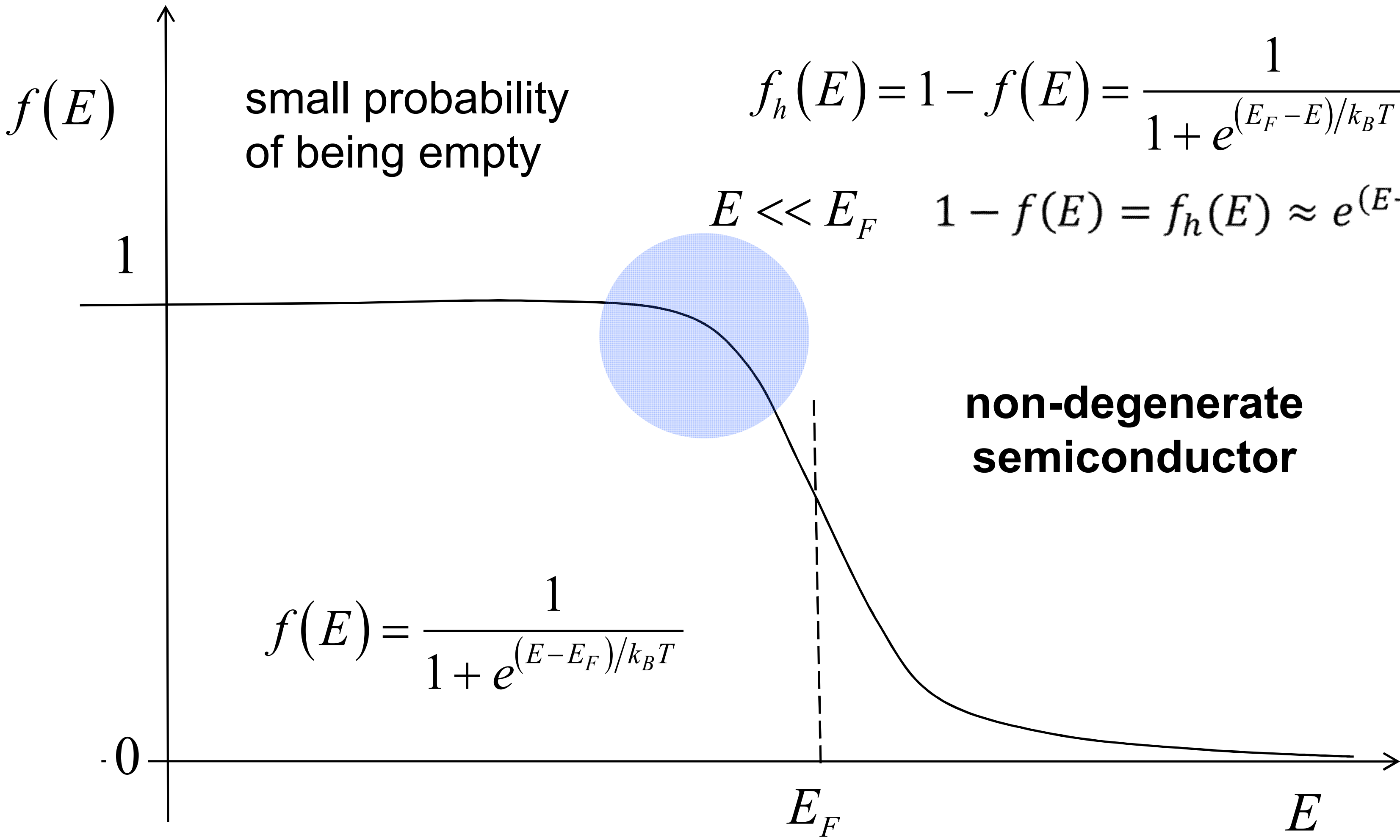
$$f(E) = \frac{1}{1 + e^{(E-E_F)/k_B T}}$$

$E >> E_F$

$f(E) \approx e^{(E_F - E)/kT}$

small probability of being full

valence band



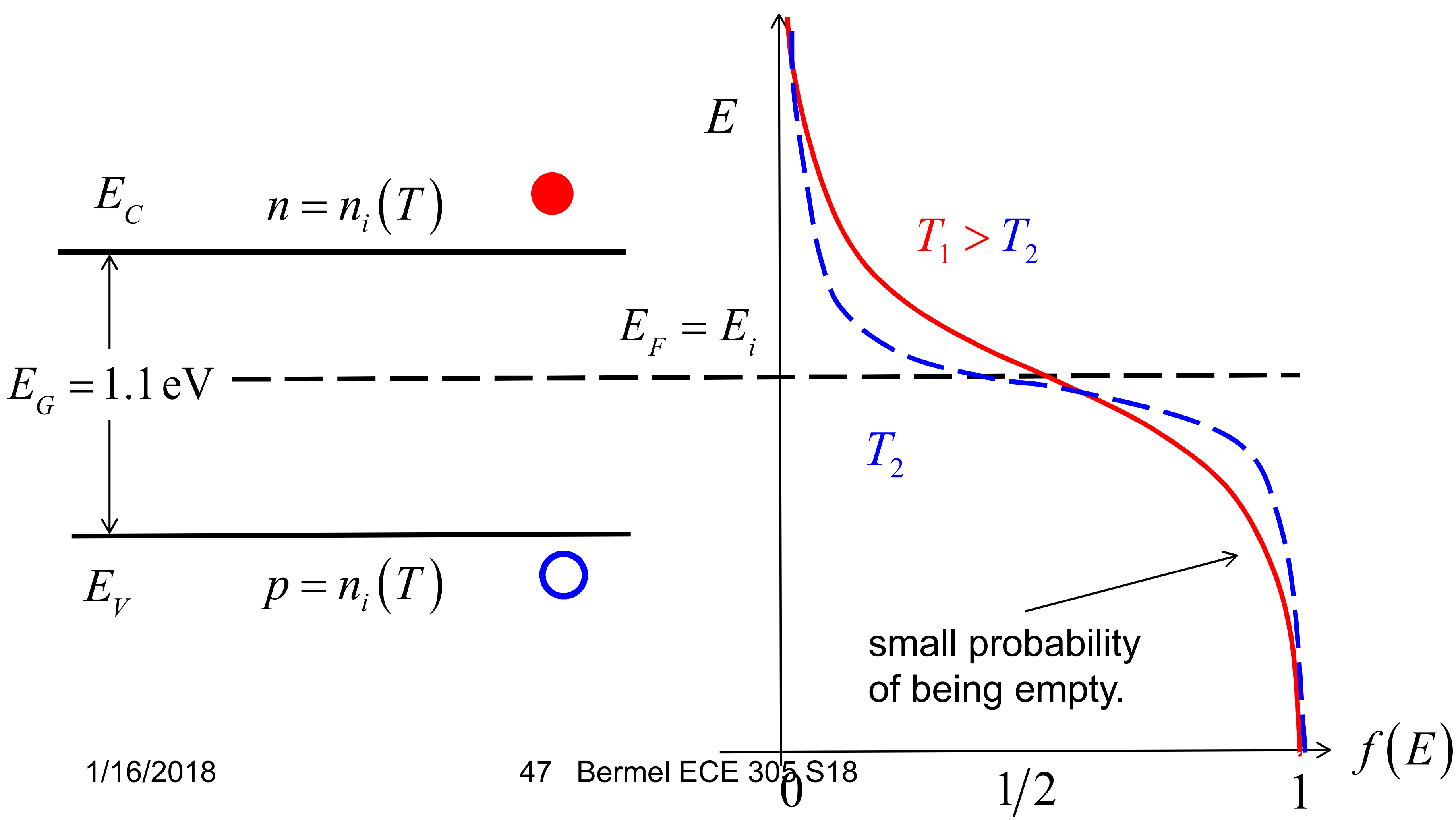
$$f_h(E) = 1 - f(E) = \frac{1}{1 + e^{(E_F - E)/k_B T}}$$

$$E \ll E_F \quad 1 - f(E) = f_h(E) \approx e^{(E - E_F)/kT}$$

$$f(E) = \frac{1}{1 + e^{(E - E_F)/k_B T}}$$

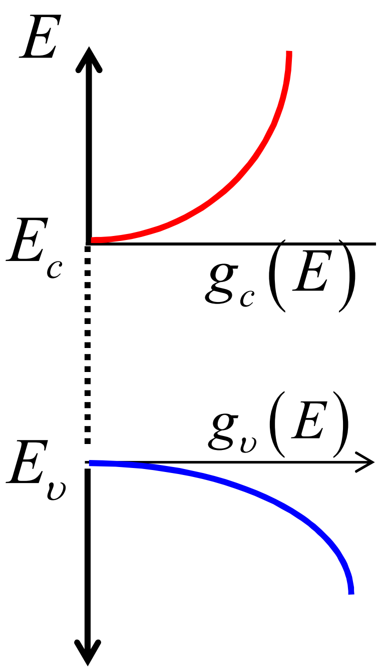
temperature dependence of intrinsic density

Fermi function

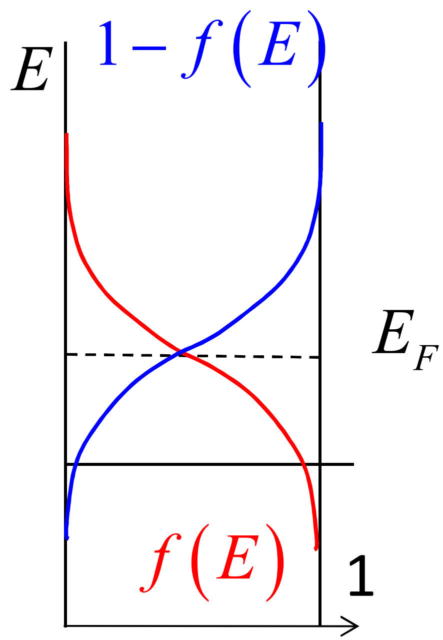


Carrier Distribution

DOS

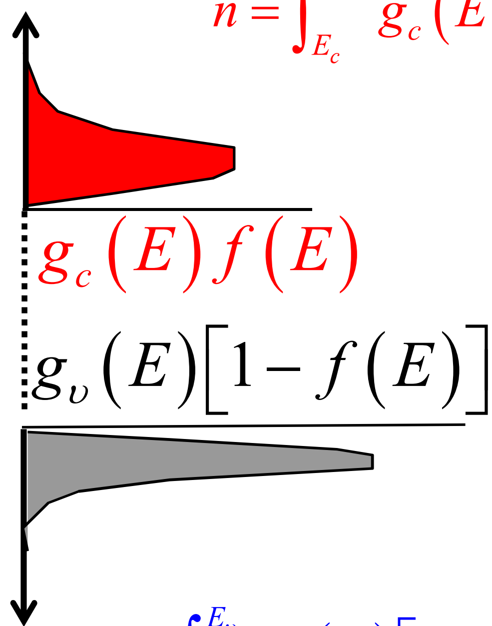


F-D



concentration

$$n = \int_{E_c}^{E_{top}} g_c(E) f(E)\, dE$$



$$p = \int_{E_{bot}}^{E_\upsilon} g_\upsilon(E)\left[1-f(E)\right] dE$$

Conclusions

- Two types of carriers, electrons and holes, move within conduction and valence bands, respectively
- Temperature creates intrinsic carriers, but extrinsic doping is main control knob in semiconductors
- Doping affects the Fermi level for both donor-like (n-type) and acceptor-like (p-type) dopants
- The density of states increases with distance away from the conduction band minimum and valence band maximum
- The Fermi-Dirac distribution $f(E) = \frac{1}{1 + e^{(E-E_F)/k_B T}}$ reflects the Pauli exclusion principle + thermal spreading
- Combining these factors yields carrier distributions for semiconductors in equilibrium