Unit 3: Equilibrium Carrier Concentrations

Lecture 3.5: Carrier concentration vs. temperature

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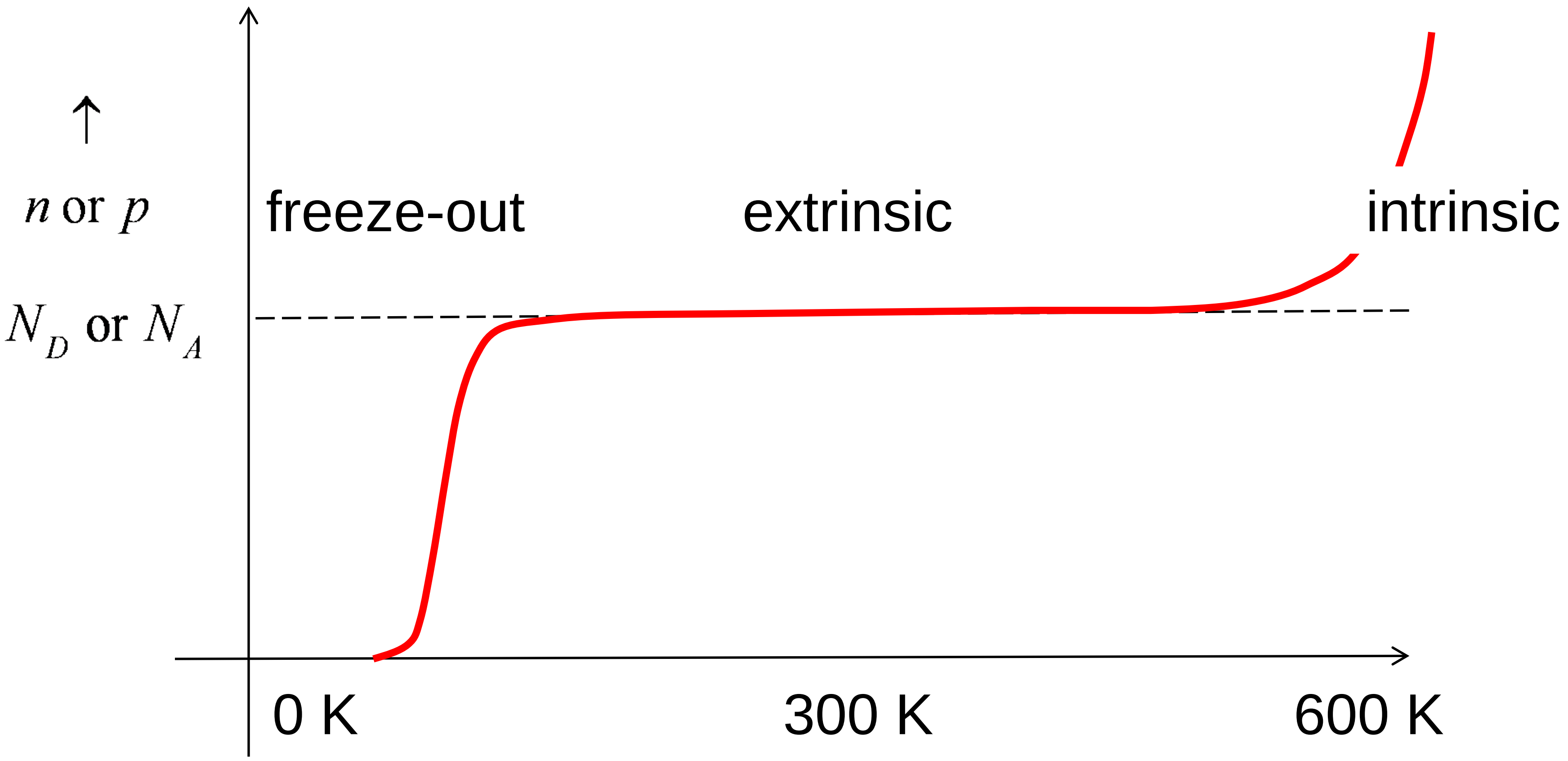
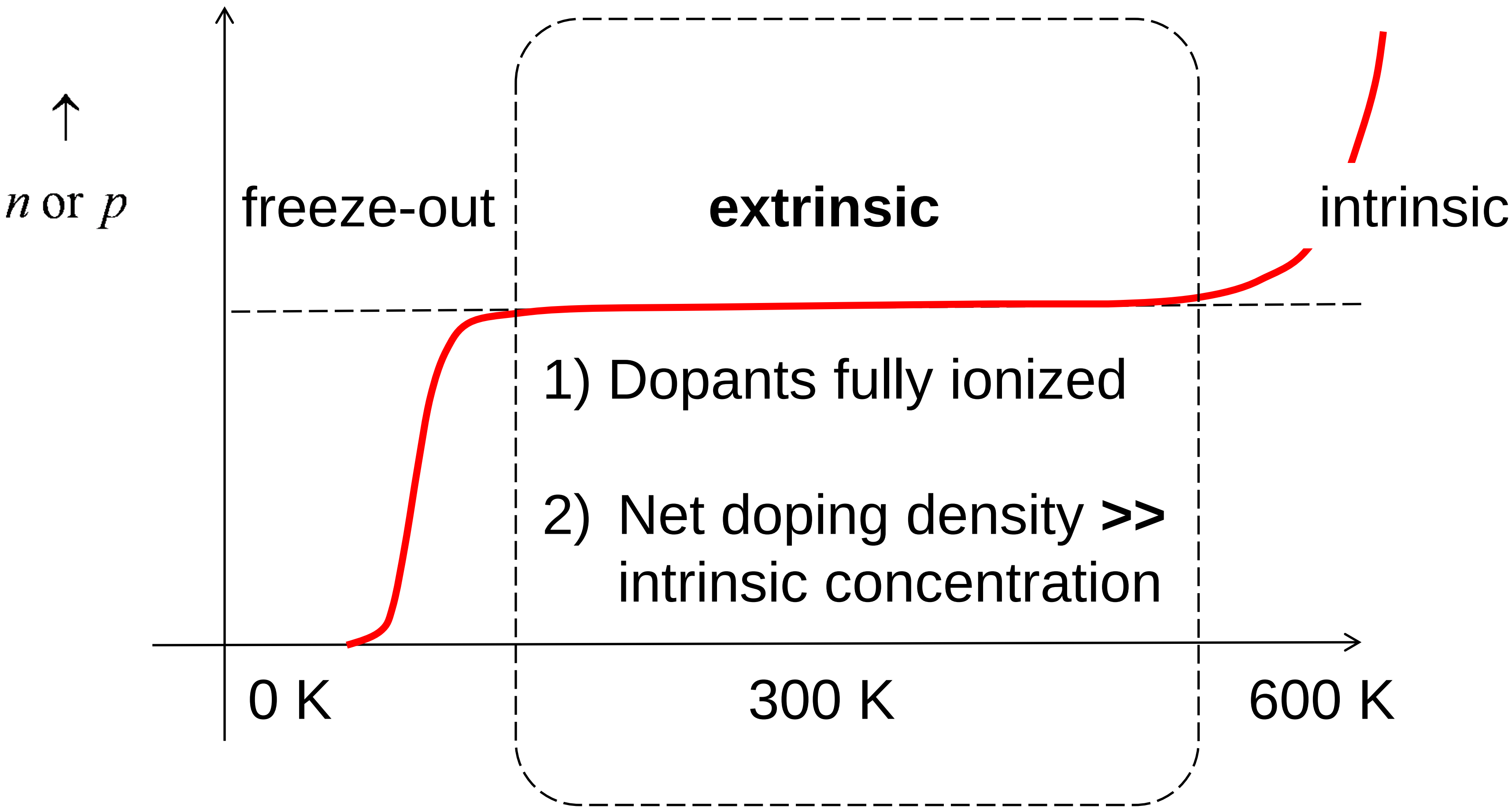
Carrier concentration vs. temperature



The extrinsic region



The extrinsic region

N-type

$$N_D - N_A >> n_i$$

$$n_0 = N_D - N_A$$

$$p_0 = \frac{n_i^2}{n_0}$$

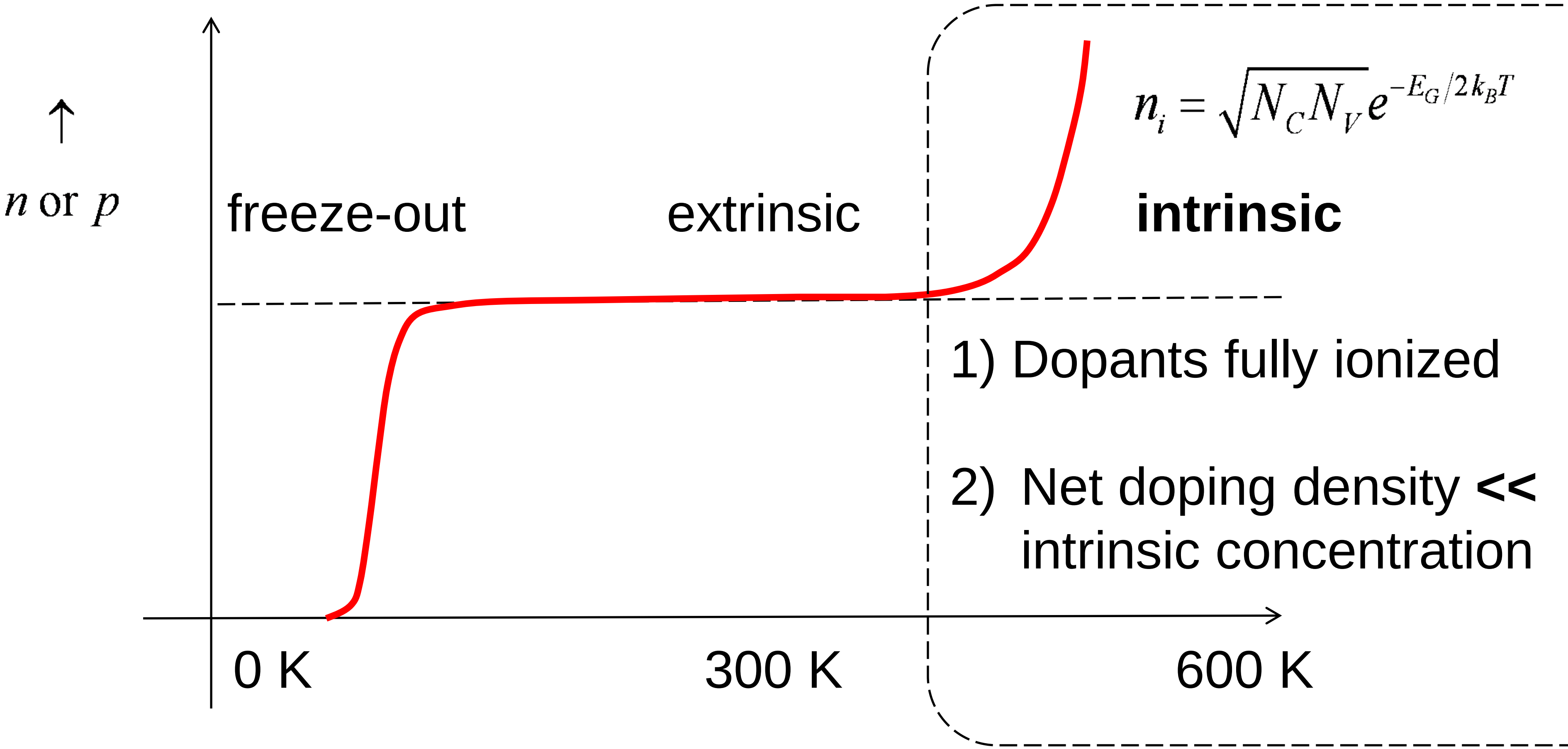
P-type

$$N_A - N_D >> n_i$$

$$p_0 = N_A - N_D$$

$$n_0 = \frac{n_i^2}{p_0}$$

The intrinsic region



$$n_i = \sqrt{N_C N_V} e^{-E_G/2k_BT}$$

1) Dopants fully ionized

2) Net doping density **<<** intrinsic concentration

Result: N-type

$$\frac{n_i^2}{n_0} - n_0 + N_D - N_A = 0$$

$$n_0 = \frac{N_D - N_A}{2} + \left[\left(\frac{N_D - N_A}{2} \right)^2 + n_i^2 \right]^{1/2}$$

$$p_0 = \frac{n_i^2}{n_0}$$

cannot be neglected

Result: P-type

$$p_0 - \frac{n_i^2}{p_0} + N_D - N_A = 0$$

$$p_0 = \frac{N_A - N_D}{2} + \left[\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2\right]^{1/2}$$

$$n_0 = \frac{n_i^2}{p_0}$$

cannot be neglected

Example 3

Consider Si doped with phosphorus at $N_D = 2.00 \times 10^{15}$ cm^{-3}
The temperature is **600 K**. What are *n* and *p*?

Recall that at 300 K in Si, $n_i = 1.00 \times 10^{10}$ cm^{-3}

$$n_i = \sqrt{N_C N_V}\, e^{-E_G/2k_BT}$$

$$N_C = 2\left[\frac{\left(m_n^* k_B T\right)}{2\pi\hbar^2}\right]^{3/2}$$

Computing n_i requires a careful treatment of the temperature dependent of the band gap and effective masses.

$$N_V = 2\left[\frac{\left(m_p^* k_B T\right)}{2\pi\hbar^2}\right]^{3/2}$$

Example 3 (cont.)

$$n_i\left(T = 600\text{ K}\right) = 4 \times 10^{15}\ \text{ cm}^{-3}$$

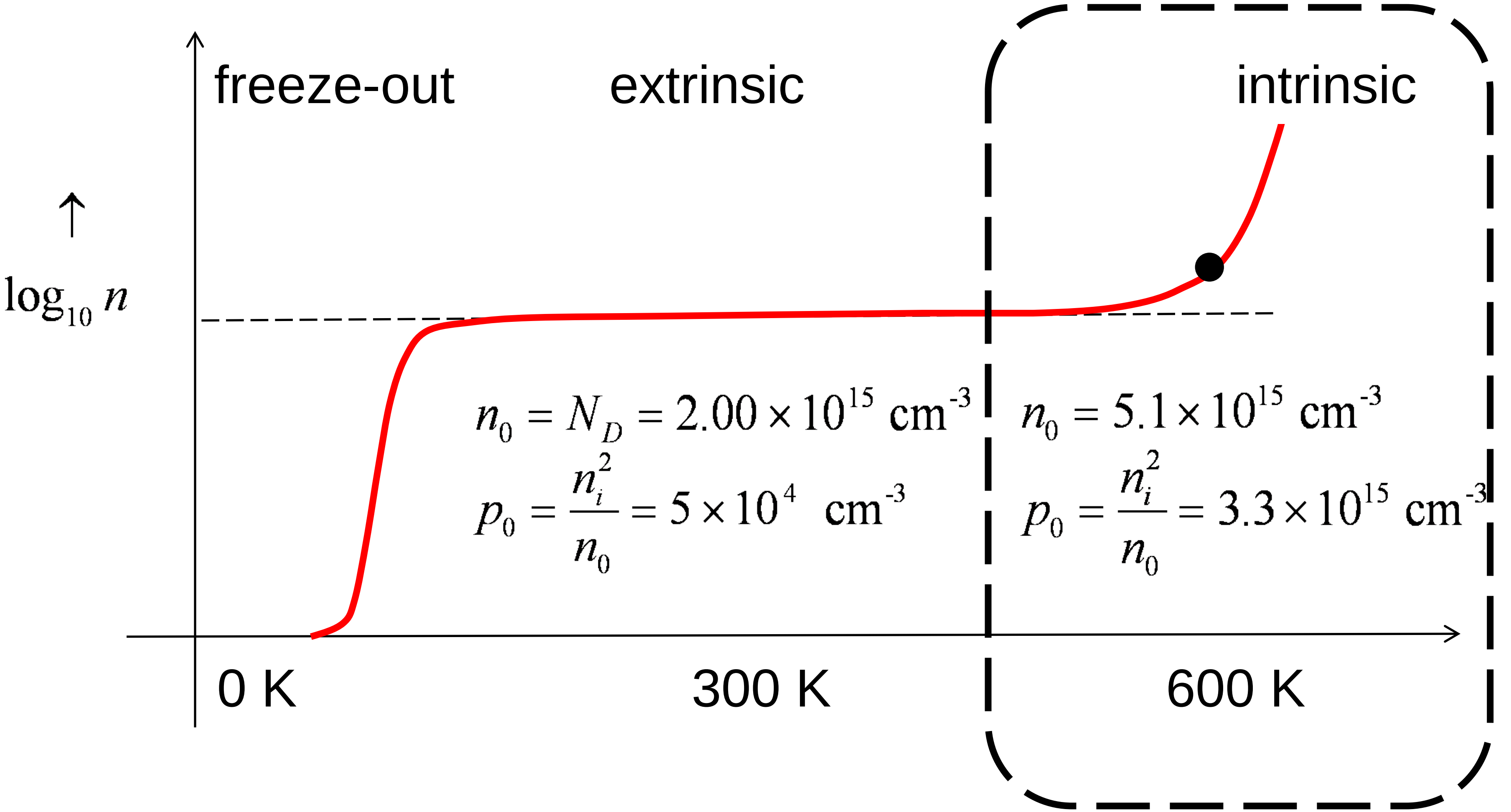
From Fig. 4.17, of R.F. Pierret, *Advanced Semiconductor Fundamentals*, 2nd Ed., Prentice Hall, 2003.

$$n_0 = \frac{N_D}{2} + \left[\left(\frac{N_D}{2}\right)^2 + n_i^2\right]^{1/2} \qquad N_D = 2 \times 10^{15}\text{ cm}^{-3}$$

$$n_0 = 1.0 \times 10^{15} + \left[\left(1.0 \times 10^{15}\right)^2 + \left(4.0 \times 10^{15}\right)^2\right]^{1/2} = 5.1 \times 10^{15}\text{ cm}^{-3}$$

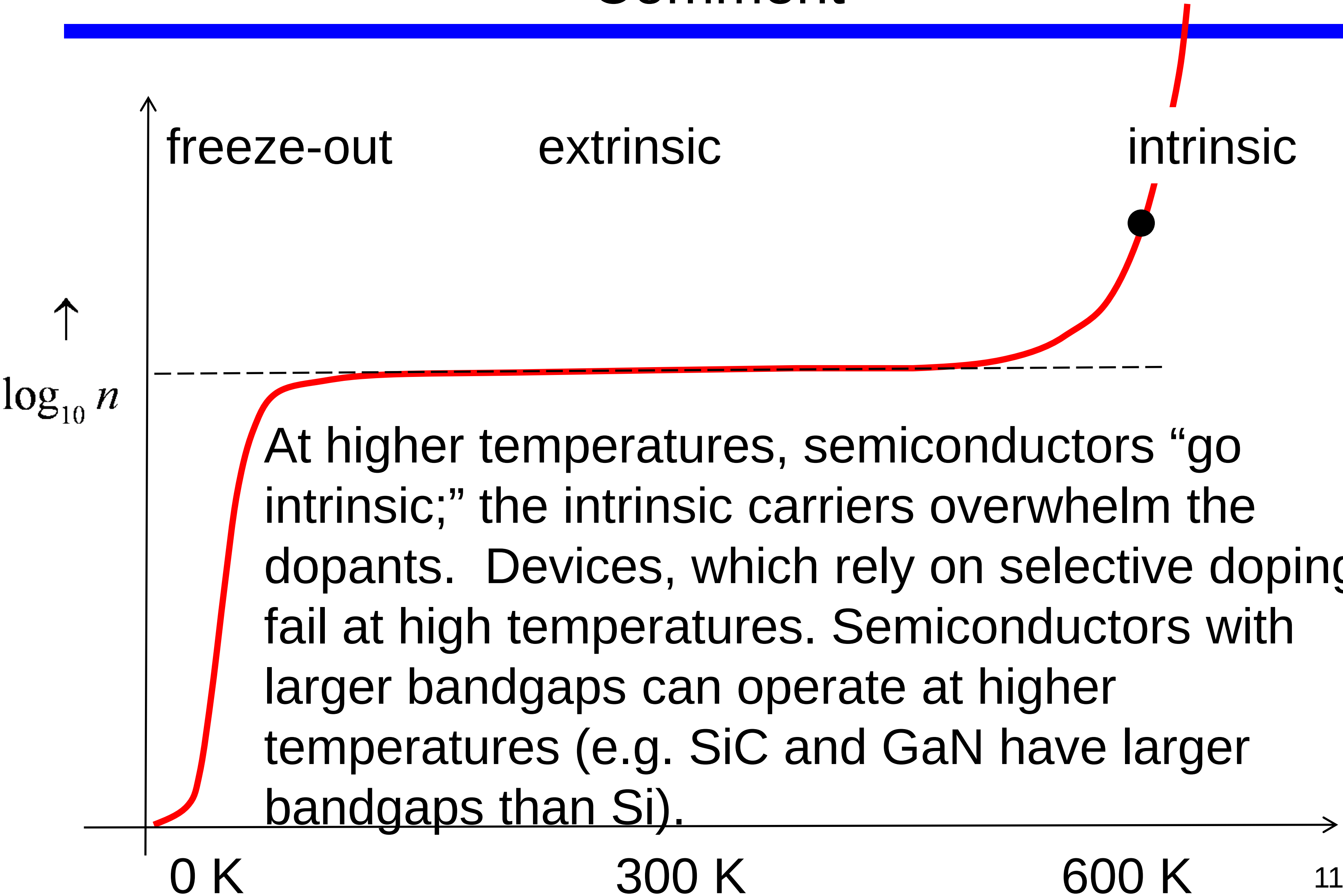
$$p_0 = \frac{n_i^2}{n_0} = \frac{\left(4.0 \times 10^{15}\right)^2}{5.1 \times 10^{15}} = 3.3 \times 10^{15}\text{ cm}^{-3}$$

Example 3



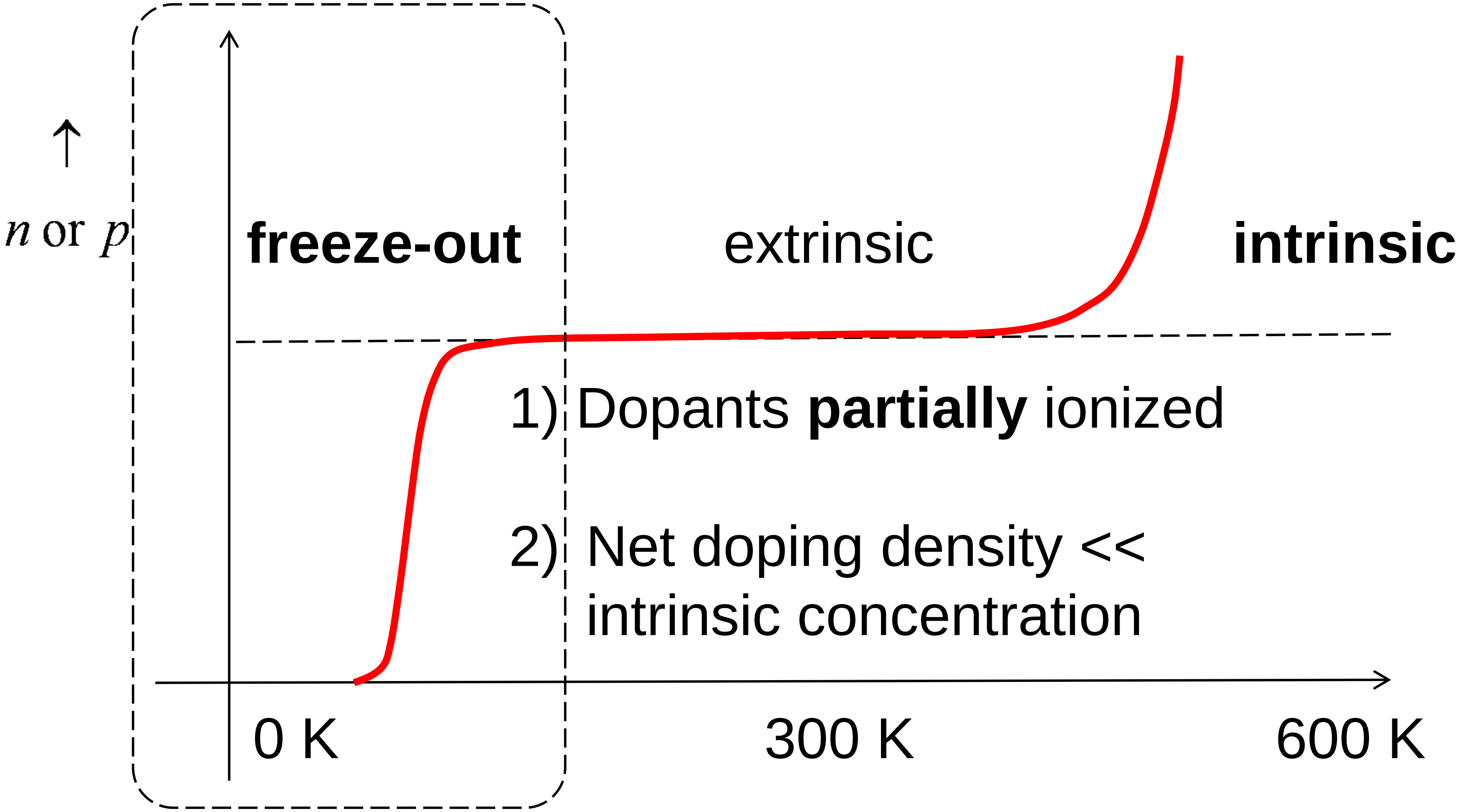
freeze-out
extrinsic
intrinsic
$\log_{10} n$
$n_0 = N_D = 2.00 \times 10^{15}\ \text{cm}^{-3}$
$p_0 = \dfrac{n_i^2}{n_0} = 5 \times 10^4\ \ \text{cm}^{-3}$
$n_0 = 5.1 \times 10^{15}\ \text{cm}^{-3}$
$p_0 = \dfrac{n_i^2}{n_0} = 3.3 \times 10^{15}\ \text{cm}^{-3}$
0 K
300 K
600 K

Comment



At higher temperatures, semiconductors "go intrinsic;" the intrinsic carriers overwhelm the dopants. Devices, which rely on selective doping, fail at high temperatures. Semiconductors with larger bandgaps can operate at higher temperatures (e.g. SiC and GaN have larger bandgaps than Si).

The freeze-out region



1) Dopants **partially** ionized

2) Net doping density << intrinsic concentration

Solving for the carrier density: N-type

1) charge neutrality: $p_0 - n_0 + N_D^+ - N_A^- = 0$

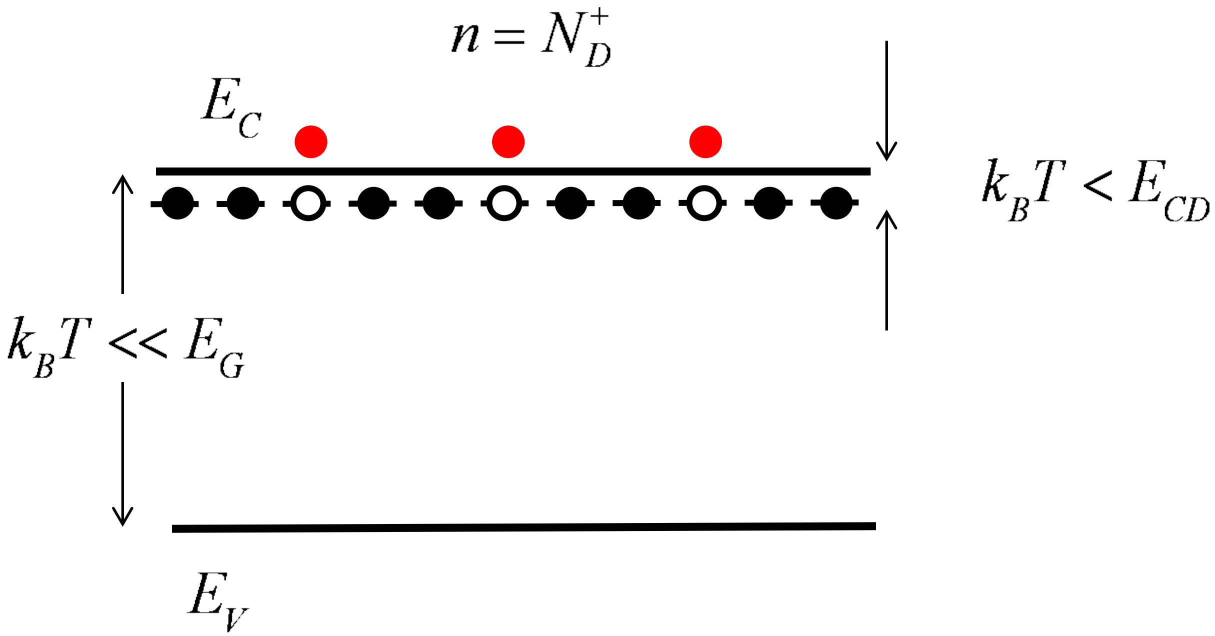
2) Neglect minority carriers: $n_0 p_0 = n_i^2 \rightarrow p_0 = n_i^2 / n_0 << n_0$

3) result: $n_0 = N_D^+ - N_A^-$

We just need to compute the net concentration of ionized dopants.

Low temperature

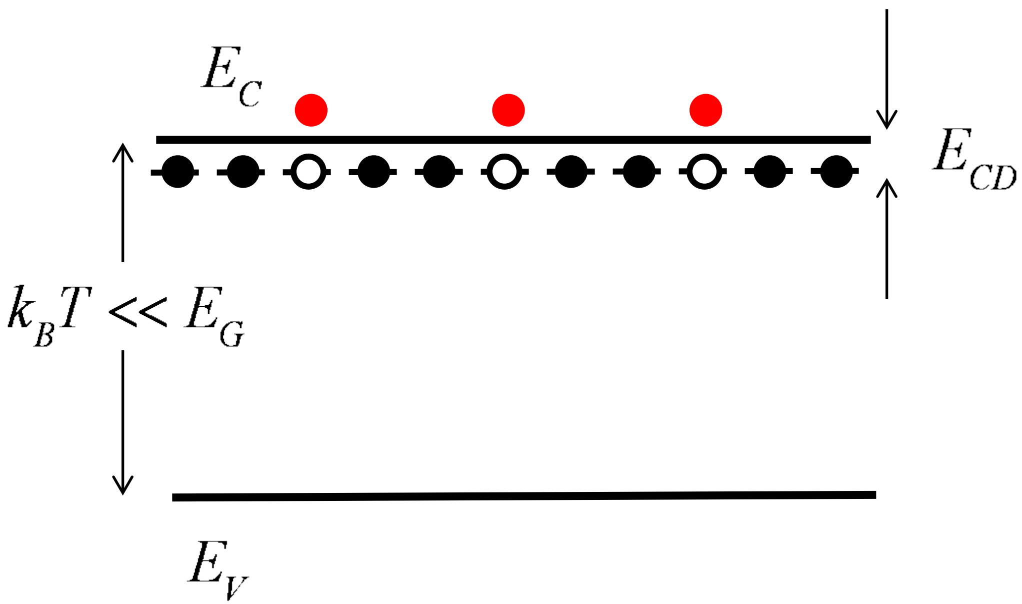
$T > 0$ K



A few extrinsic carriers due to doping, but no intrinsic carriers due to thermal excitation across the band gap.

Ionized donor concentration

$T > 0$ K



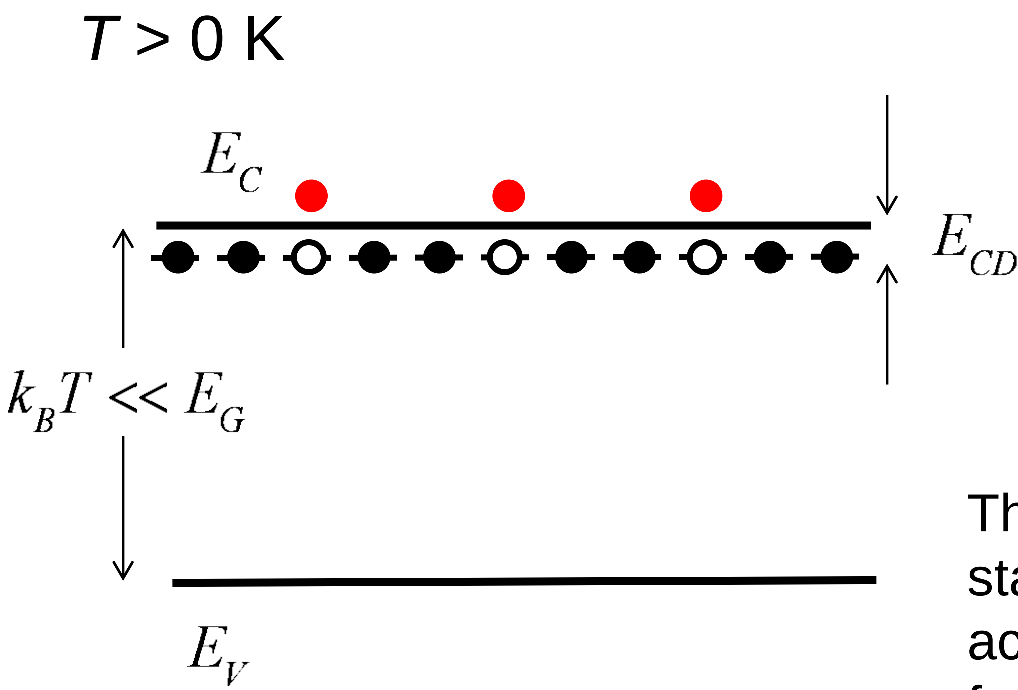
fraction of donor level occupied:

$$\frac{N_D^0}{N_D} = f_0(E_D)$$

$$\frac{N_D^+}{N_D} = 1 - \frac{N_D^0}{N_D} = 1 - f_0(E_D)$$

$$f_0(E_D) = \frac{1}{1 + e^{(E_D - E_F)/k_B T}}$$

Ionized donor concentration



$$\frac{N_D^+}{N_D} = 1 - f_0\left(E_D\right)$$

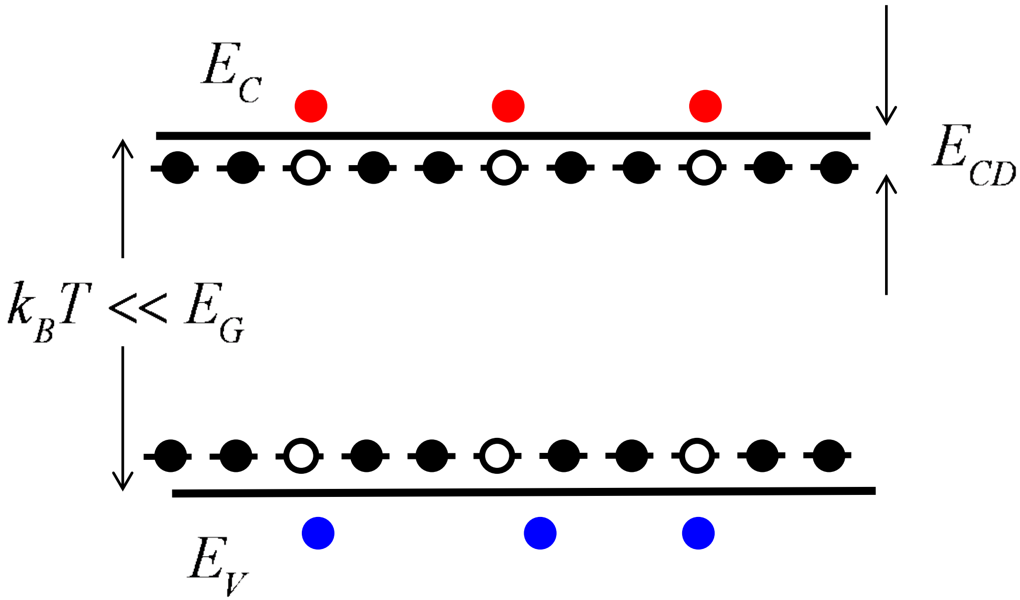
$$\frac{N_D^+}{N_D} = \frac{1}{1 + e^{\left(E_F - E_D\right)/k_B T}}$$

This is **almost correct**. The statistics of occupying donor (and acceptor) levels are a bit different from occupying band states.

$$\frac{N_D^+}{N_D} = \frac{1}{1 + g_D e^{\left(E_F - E_D\right)/k_B T}}$$

Ionized dopant concentration

T > 0 K



$$\frac{N_D^+}{N_D} = \frac{1}{1 + g_D e^{(E_F - E_D)/k_B T}}$$

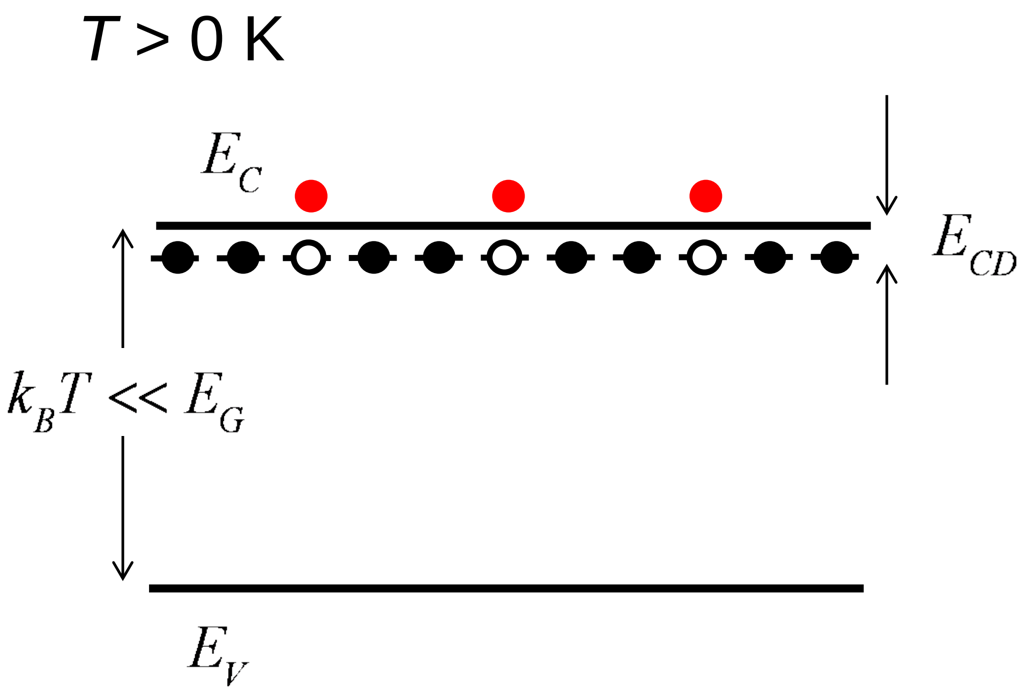
$g_D = 2$ (standard value)

$$\frac{N_A^-}{N_A} = \frac{1}{1 + g_A e^{(E_A - E_F)/k_B T}}$$

$g_A = 4$ (standard value)

See R.F. Pierret, *Advanced Semiconductor Fundamentals*, Sec. 4.4.4 for a discussion.

Example: N-type sample



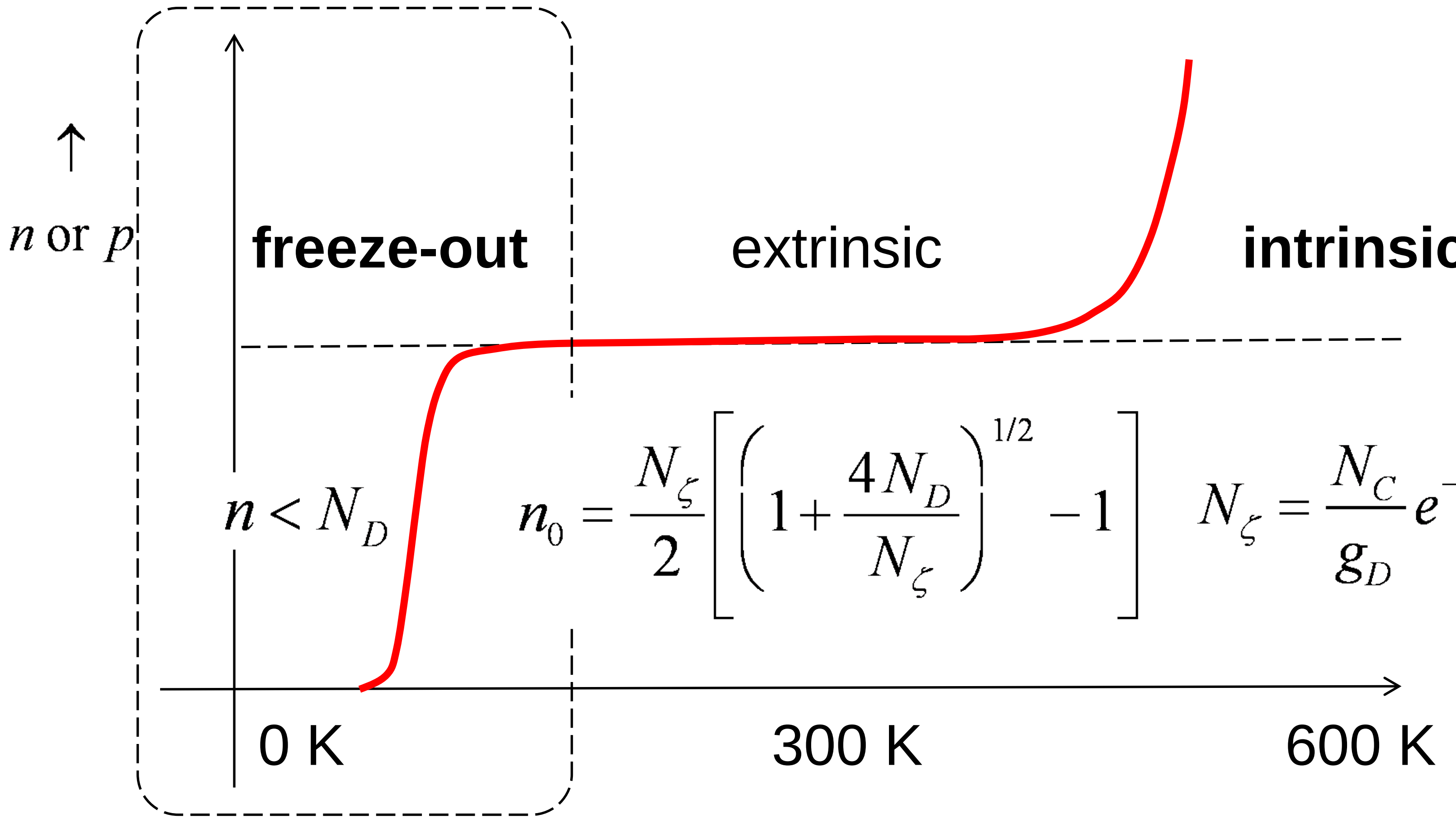
$$\frac{N_D^+}{N_D} = \frac{1}{1+g_D e^{(E_F-E_D)/k_BT}}$$

$$n_0 = N_D^+ = \frac{N_D}{1+g_D e^{(E_F-E_D)/k_BT}}$$

$$n_0 = N_C e^{(E_F-E_C)/k_BT}$$

These two equations can be solved for $n_0(T)$ – see R.F. Pierret, *Advanced Semiconductor Fundamentals*, 2nd Ed. Sec. 4.5.2.

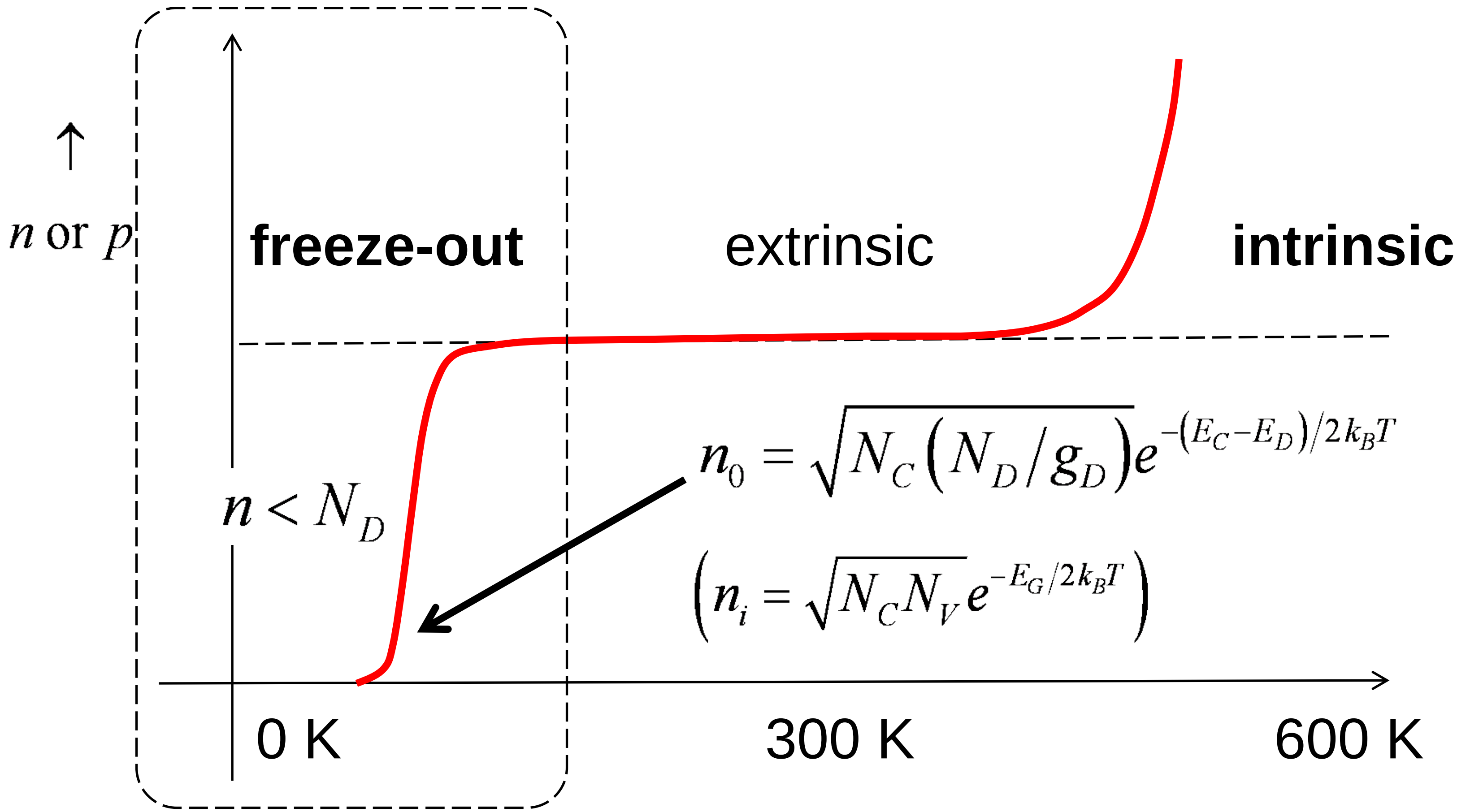
The freeze-out region



$$n < N_D$$

$$n_0 = \frac{N_\zeta}{2}\left[\left(1+\frac{4N_D}{N_\zeta}\right)^{1/2}-1\right] \qquad N_\zeta = \frac{N_C}{g_D}e^{-(E_C-E_D)/k_BT}$$

The freeze-out region



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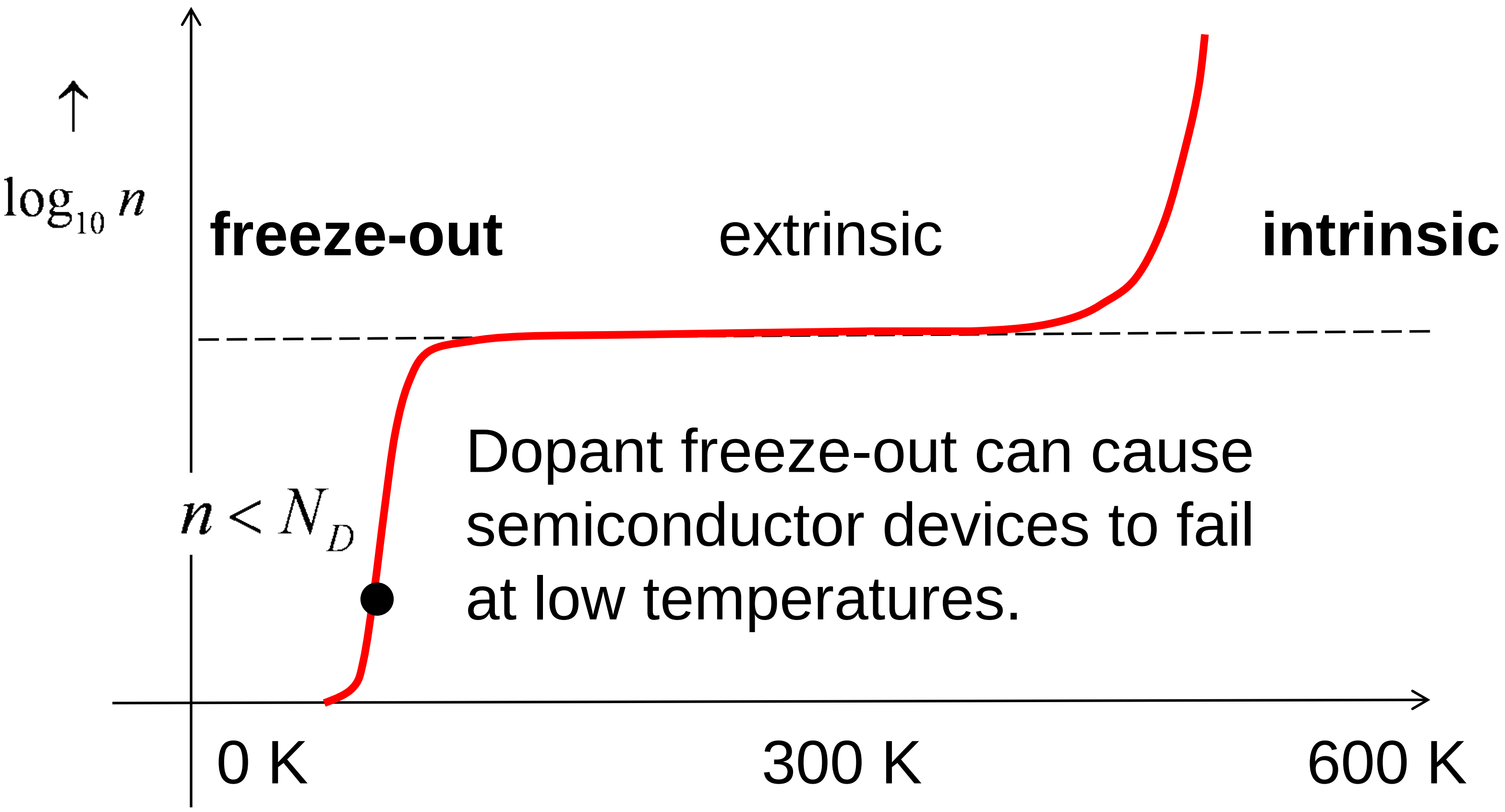
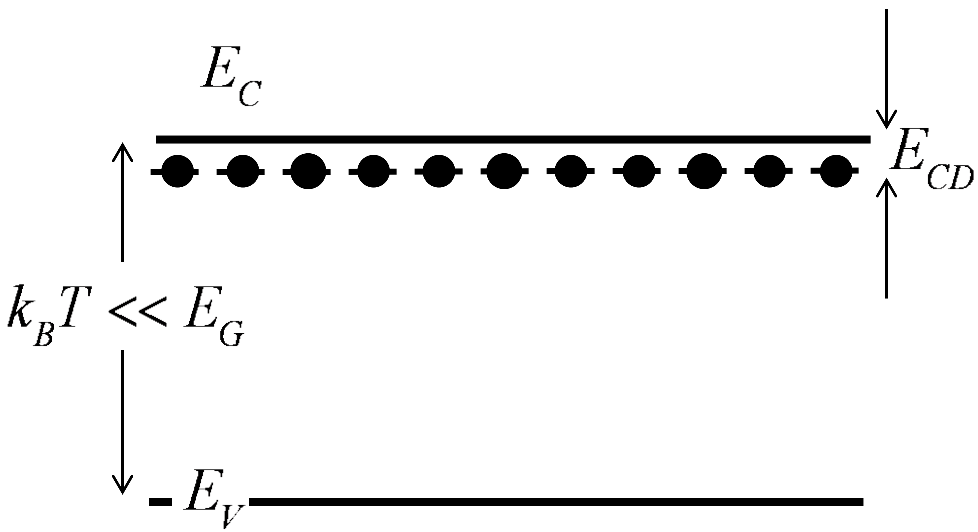


$\log_{10} n$
freeze-out
extrinsic
intrinsic
$n < N_D$
Dopant freeze-out can cause semiconductor devices to fail at low temperatures.
0 K
300 K
600 K

Metal-insulator transition

T = 0 K



***Freeze-out does not occur in heavily doped semiconductors*.**

Metals conduct electricity at 0 K.

Semiconductors become insulators at 0 K because of freeze-out.

Heavily doped semiconductors are different.

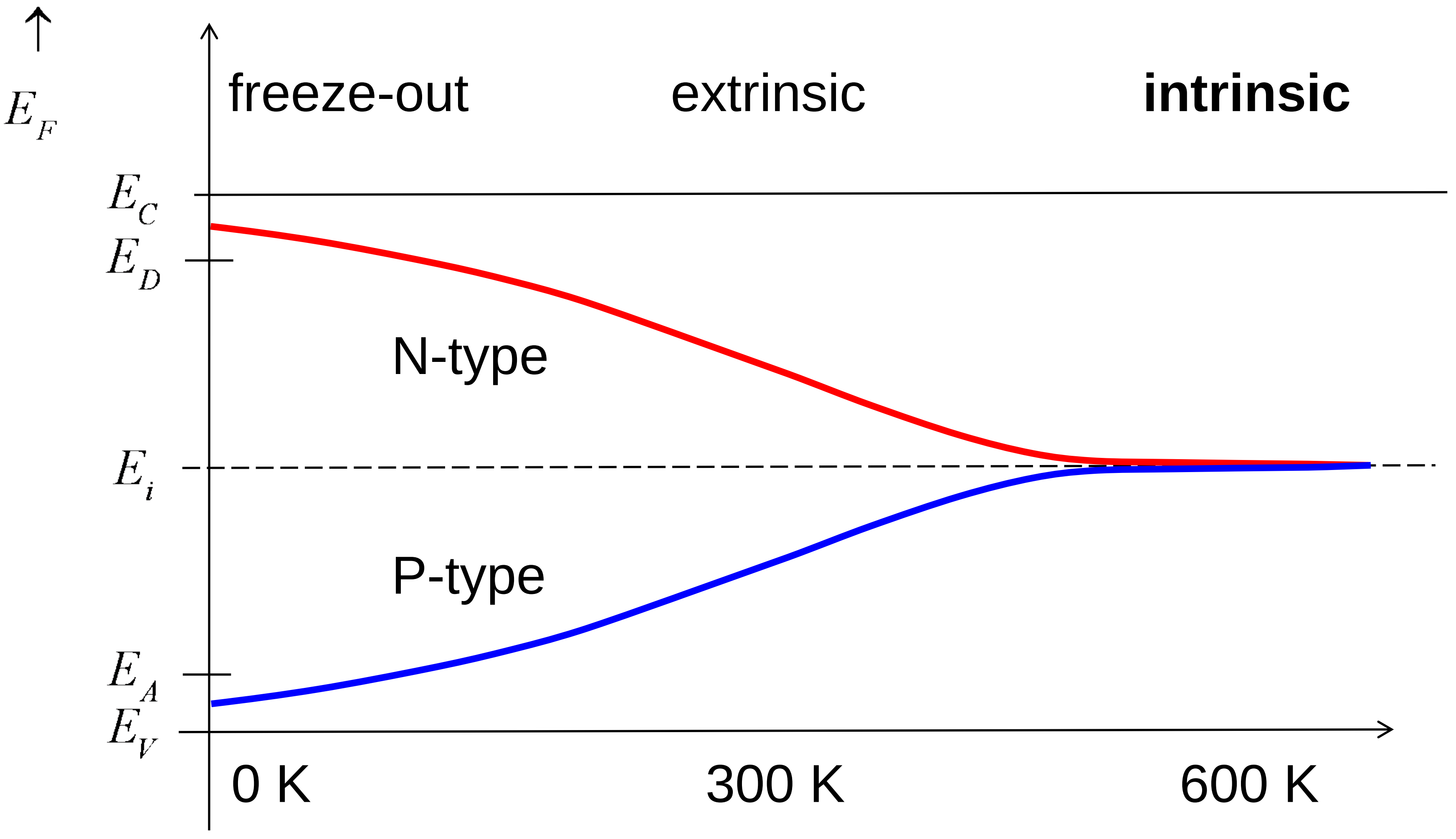
When the dopants are close to each other, their wave functions overlap. Impurity levels become impurity bands.

In Si, for $N_D > 10^{19}$ cm^{-3}, the impurity band merges with the conduction band.

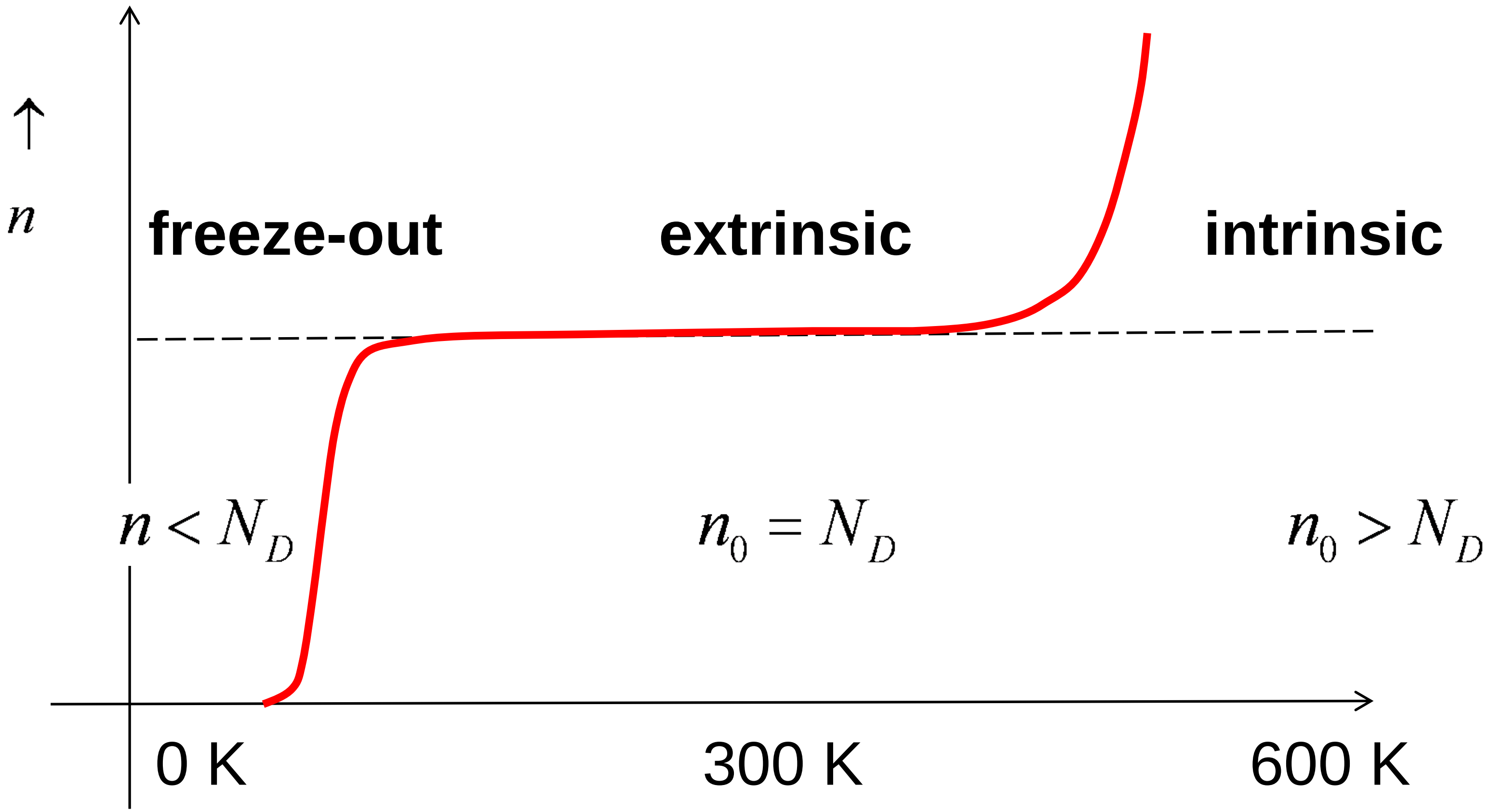
Question

We now understand how the carrier concentration varies with temperature. How does the Fermi level vary with temperature?

Fermi level vs. temperature



Summary



You should also understand E_F vs. T qualitatively.