Primer on Semiconductors

Unit 3: Equilibrium Carrier Concentrations

Lecture 3.6: Unit 3 Recap

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Fermi function

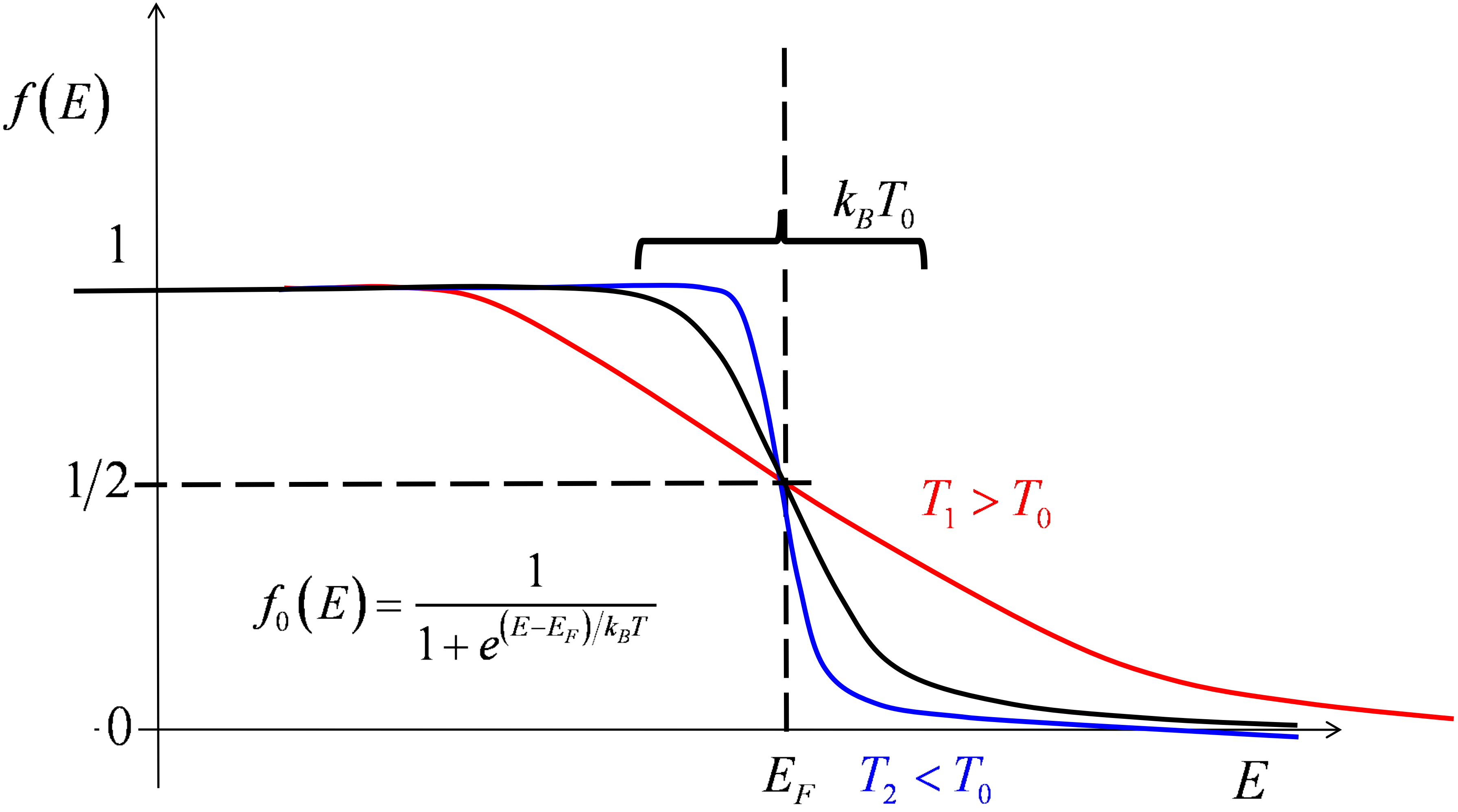
The Fermi function gives the probability that a state (if it exists) is occupied in equilibrium.

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

(Fermi function)

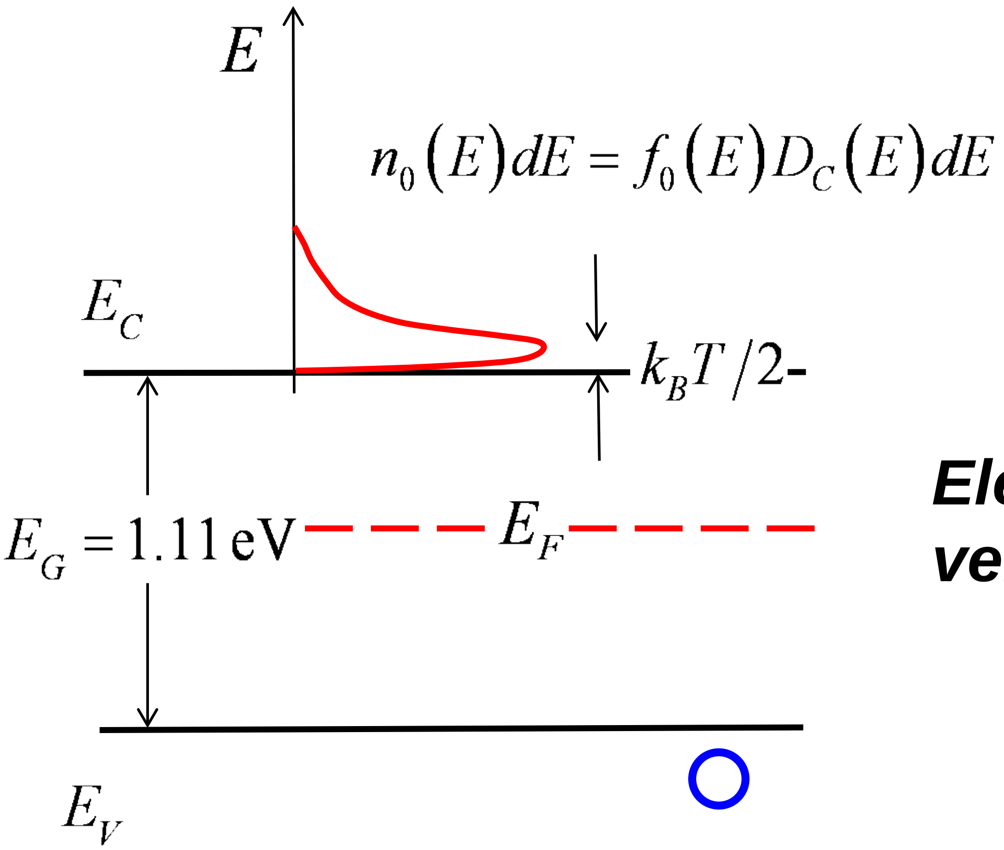
The two key parameters in the Fermi function are the Fermi level and the temperature.

Fermi level and temperature



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

Distribution of carriers in the bands



Electrons and holes are very near the band edges.

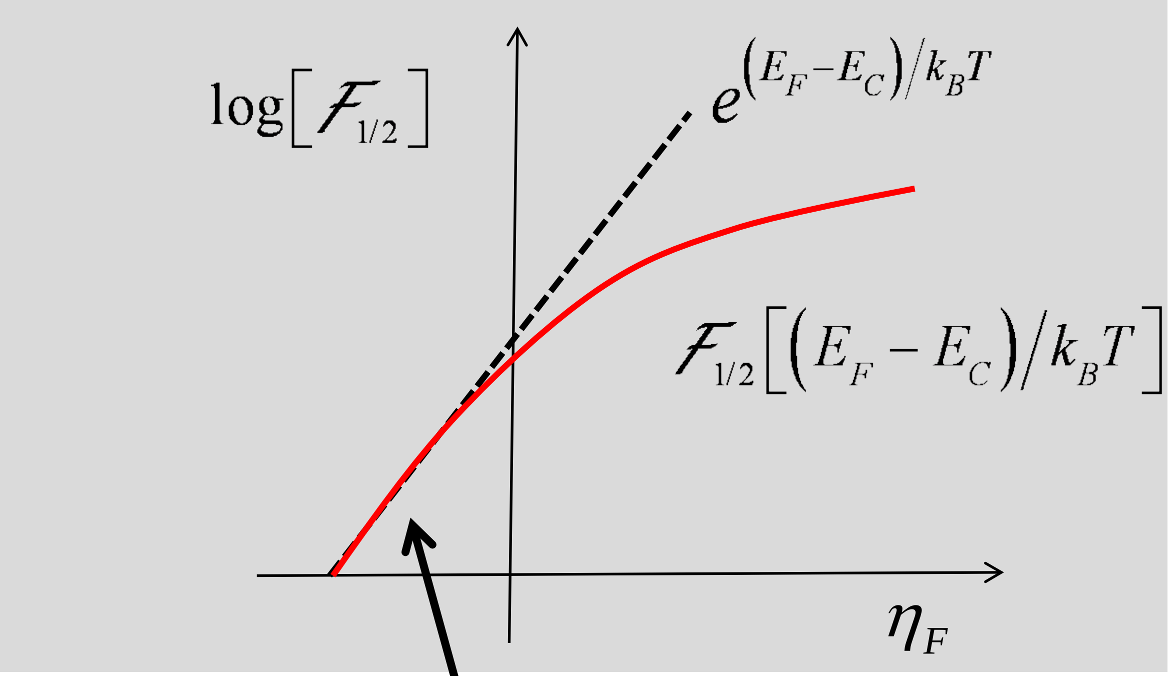
Fermi-Dirac integrals

$$n_0 = \int_{E_C}^{\infty} n_0(E)\,dE = \int_{E_C}^{\infty} f_0(E) D_C(E)\,dE$$

$$n_0 = N_C \mathcal{F}_{1/2}\left[\left(E_F - E_C\right)/k_B T\right] \text{cm}^{-3}$$

$$N_C = \frac{1}{4}\left(\frac{2m^* k_B T}{\pi\hbar^2}\right)^{3/2}$$

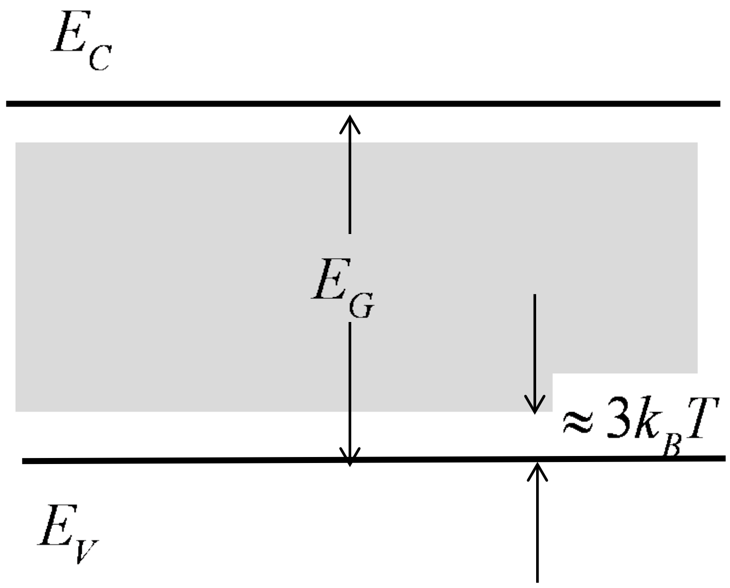
FD integrals and exponentials



$$E_F < E_C \quad \mathcal{F}_{1/2}\left(E_F - E_C\right)/k_B T \rightarrow e^{(E_F - E_C)/k_B T}$$

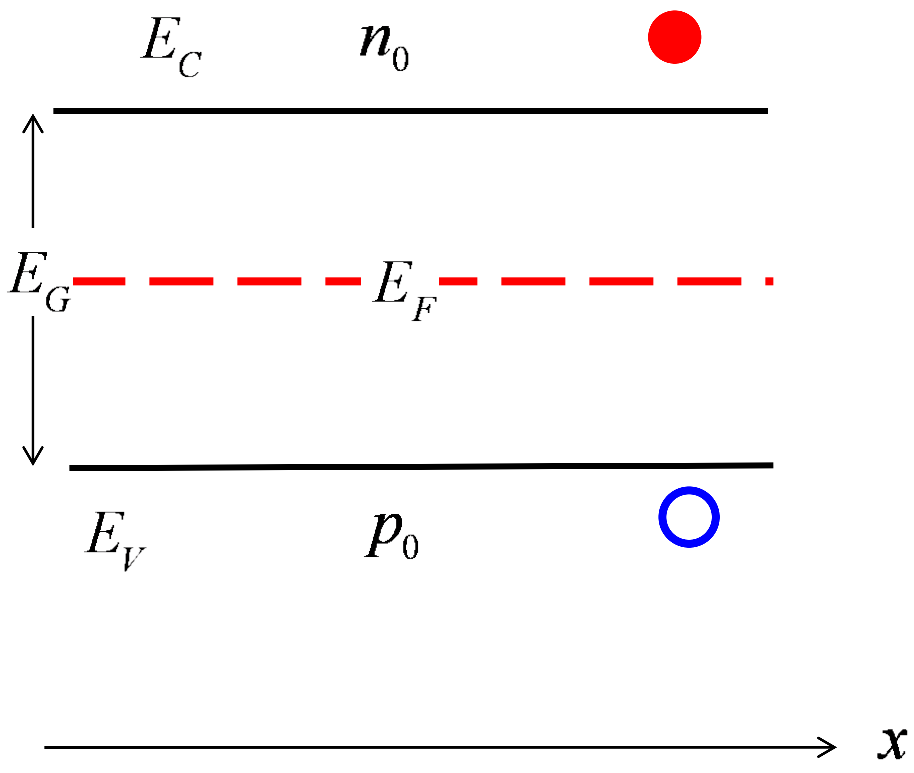
(nondegenerate semiconductor)

Nondegenerate semiconductors



In a nondegenerate semiconductor, the Fermi level is well below the bottom of the conduction band and well above the top of the valence band.

Carrier densities for nondegenerate semiconductors



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

$$p_0 = N_V e^{(E_V - E_F)/k_B T}$$

Nondegenerate semiconductor

np product

$$n_0 p_0 = n_i^2$$

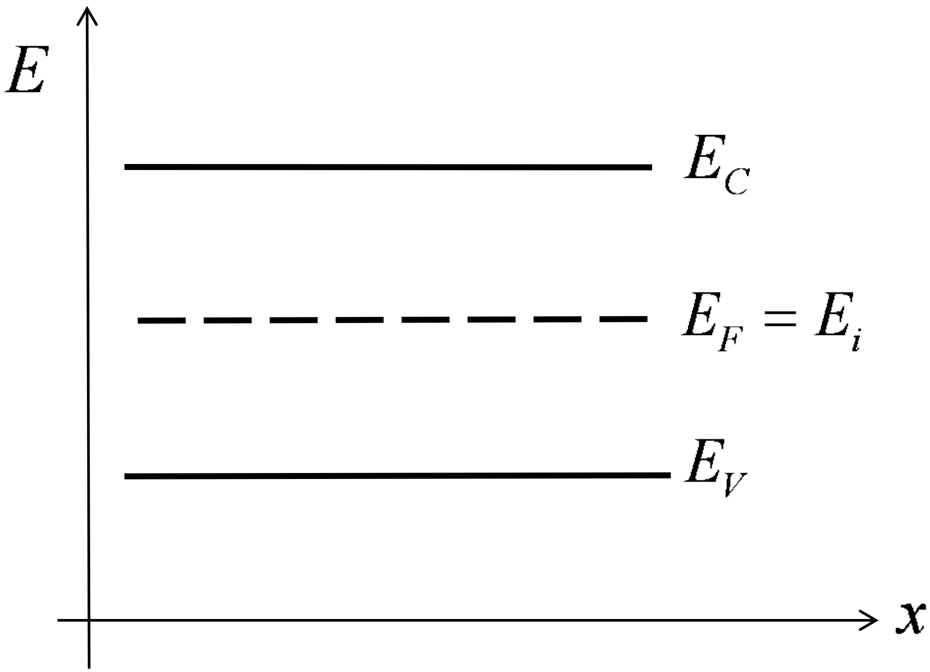
$$n_i = \sqrt{N_C N_V} e^{-E_G/2k_BT}$$

- Independent of Fermi level (for nondegenerate semiconductor)
- Depends exponentially on band gap
- Depends exponentially on temperature
- For Si at 300 K

$$n_i = 1.0 \times 10^{10}\ \text{cm}^{-3}$$

The intrinsic Fermi level

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



Carrier concentration relations (nondegenerate)

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

$$n_0 = n_i e^{(E_F - E_i)/k_B T}$$

$$p_0 = N_V e^{(E_V - E_F)/k_B T}$$

$$p_0 = n_i e^{(E_i - E_F)/k_B T}$$

$$N_C = \frac{1}{4}\left(\frac{2m_n^* k_B T}{\pi \hbar^2}\right)^{3/2}$$

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

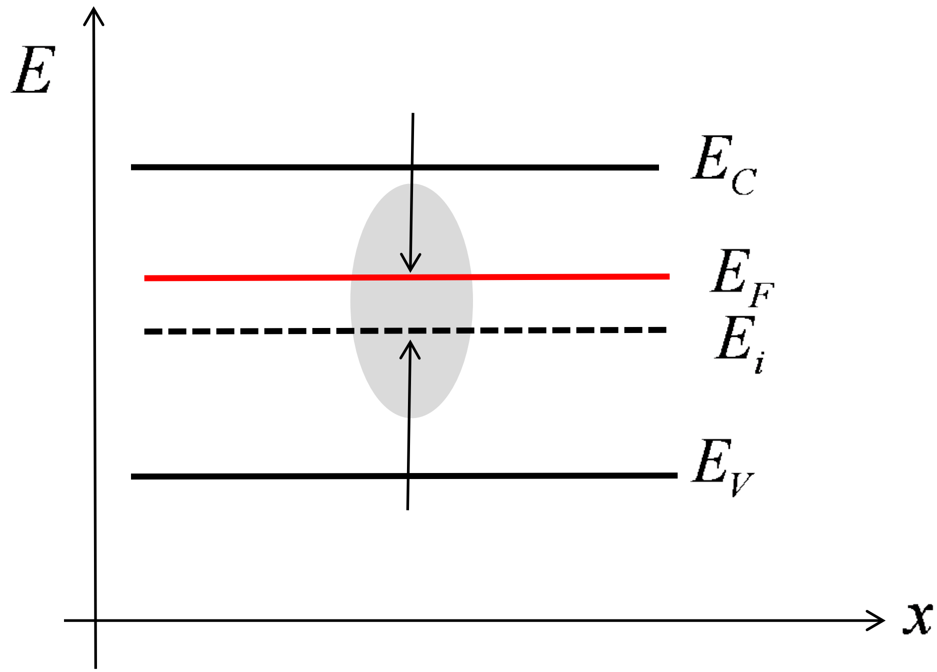
$$N_V = \frac{1}{4}\left(\frac{2m_p^* k_B T}{\pi \hbar^2}\right)^{3/2}$$

$$n_0 p = n_i^2$$

Reading an e-band diagram

$$n_0 = n_i\, e^{(E_F - E_i)/k_B T}$$

$$p_0 = n_i e^{(E_i - E_F)/k_B T}$$



- Fermi level above E_i, n-type
- Fermi level below E_i, p-type

Carrier concentration vs. doping

$$p_0 - n_0 + N_D - N_A = 0 \quad \text{(SCN)}$$

$$n_0 p_0 = n_i^2$$

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

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

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

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

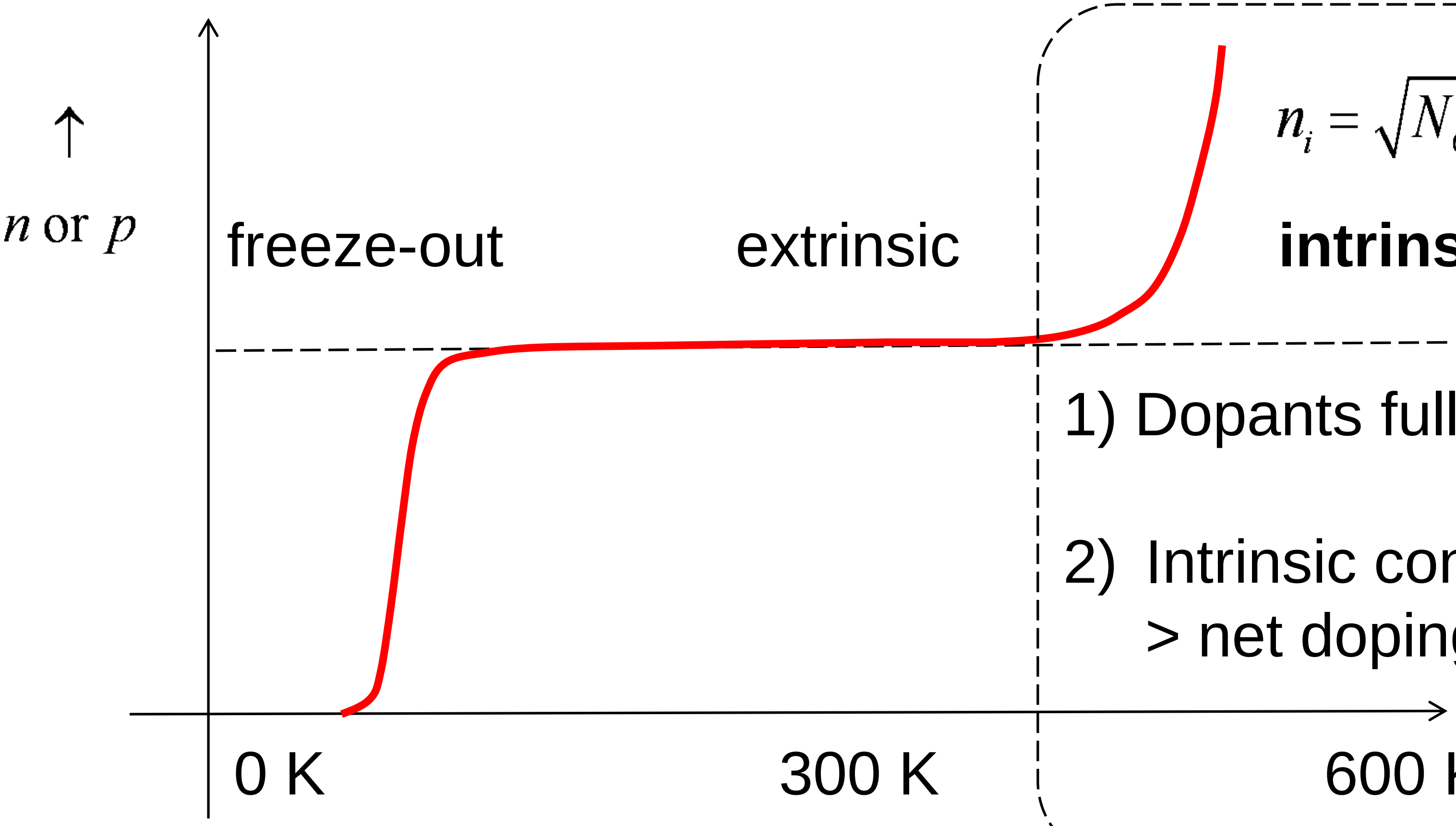
Extrinsic region

When the net doping density is much greater than the intrinsic carrier concentration and the dopants are fully ionized, then

$$n_0 = N_D - N_A \quad p_0 = n_i^2 / \left(N_D - N_A \right)$$ N-type $N_D > N_A$

$$p_0 = N_A - N_D \quad n_0 = n_i^2 / \left(N_A - N_D \right)$$ P-type $N_A > N_D$

The intrinsic region

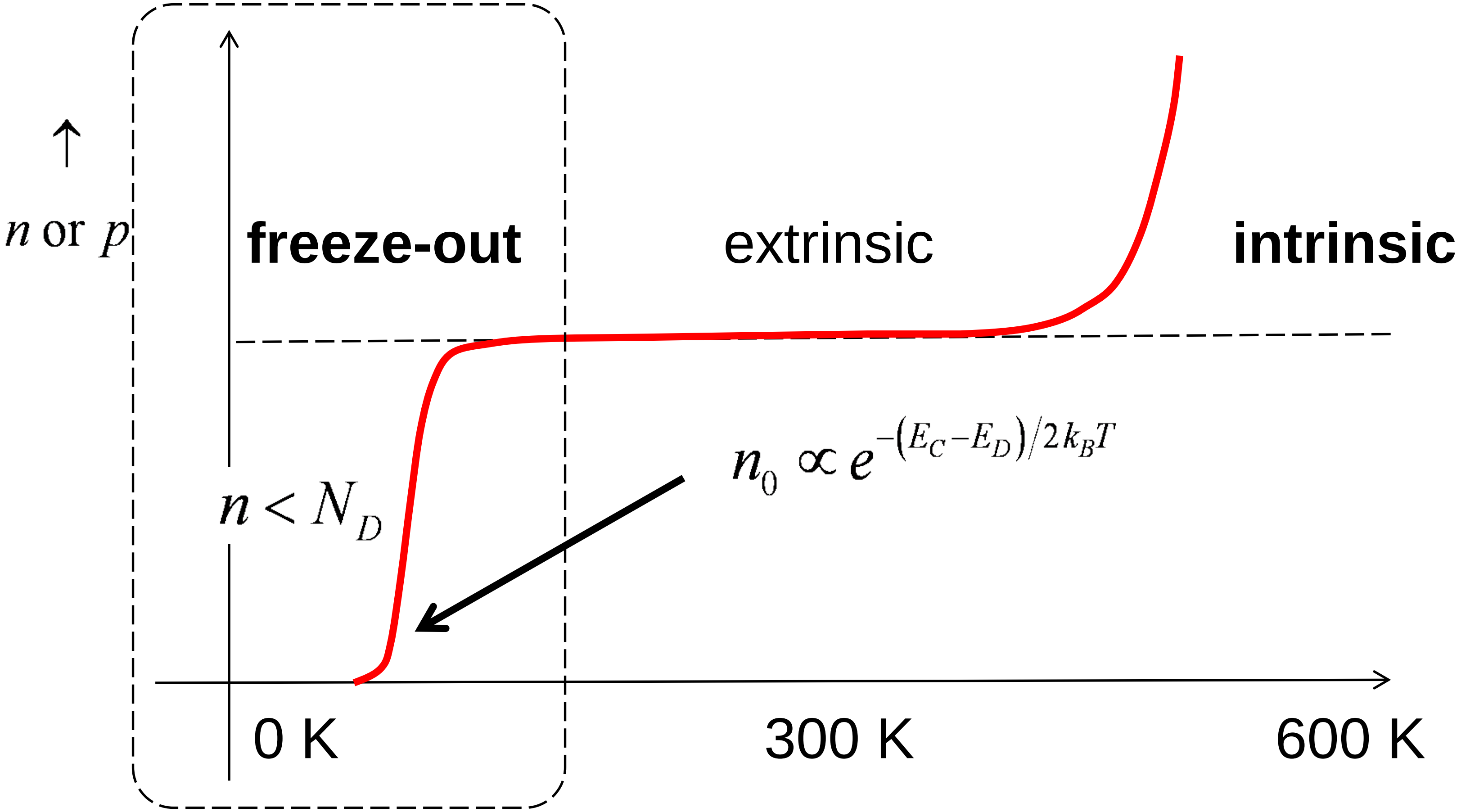


$$n_i = \sqrt{N_C N_V}\, e^{-E_G/2k_BT}$$

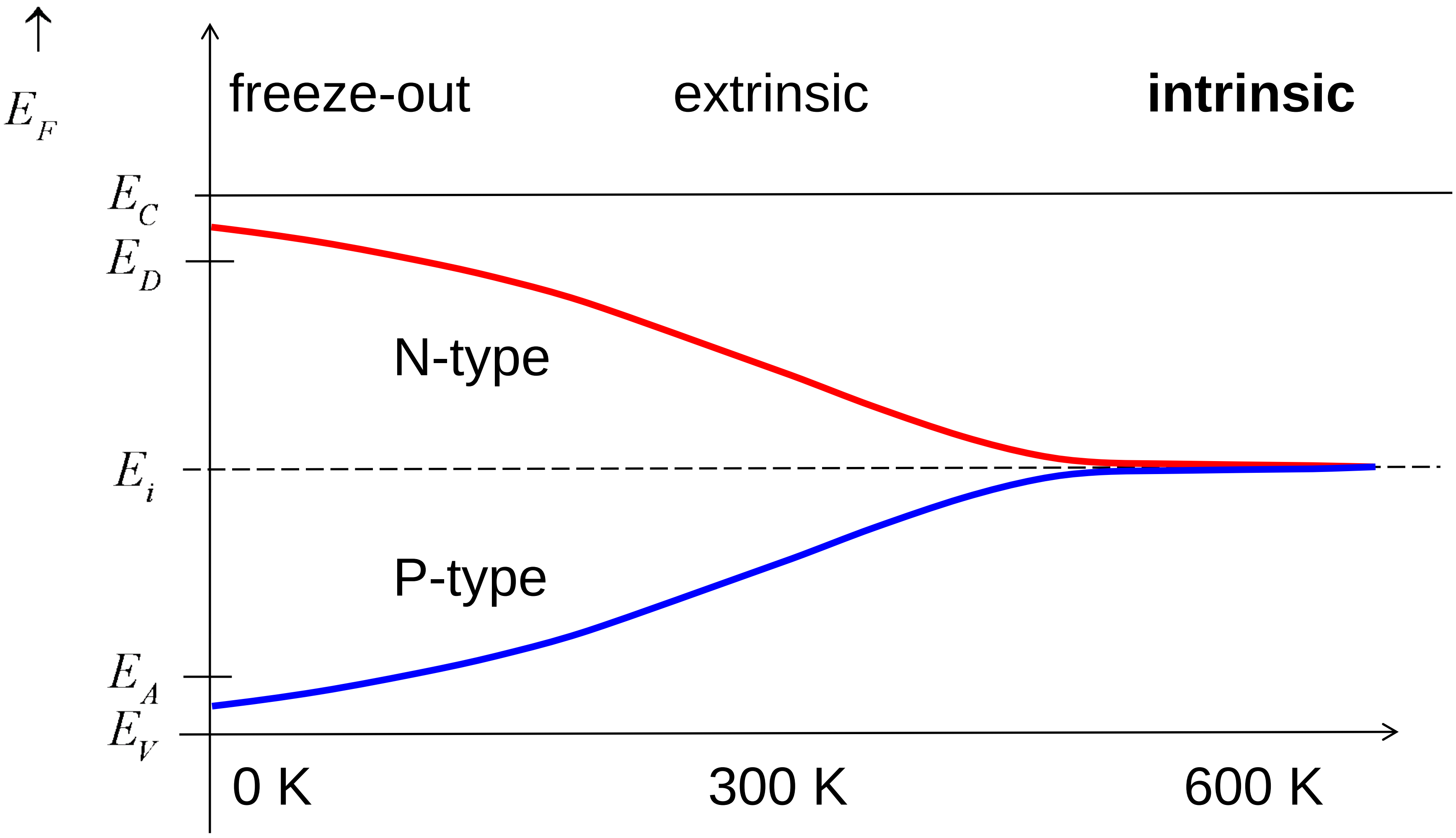
1) Dopants fully ionized

2) Intrinsic concentration > net doping density

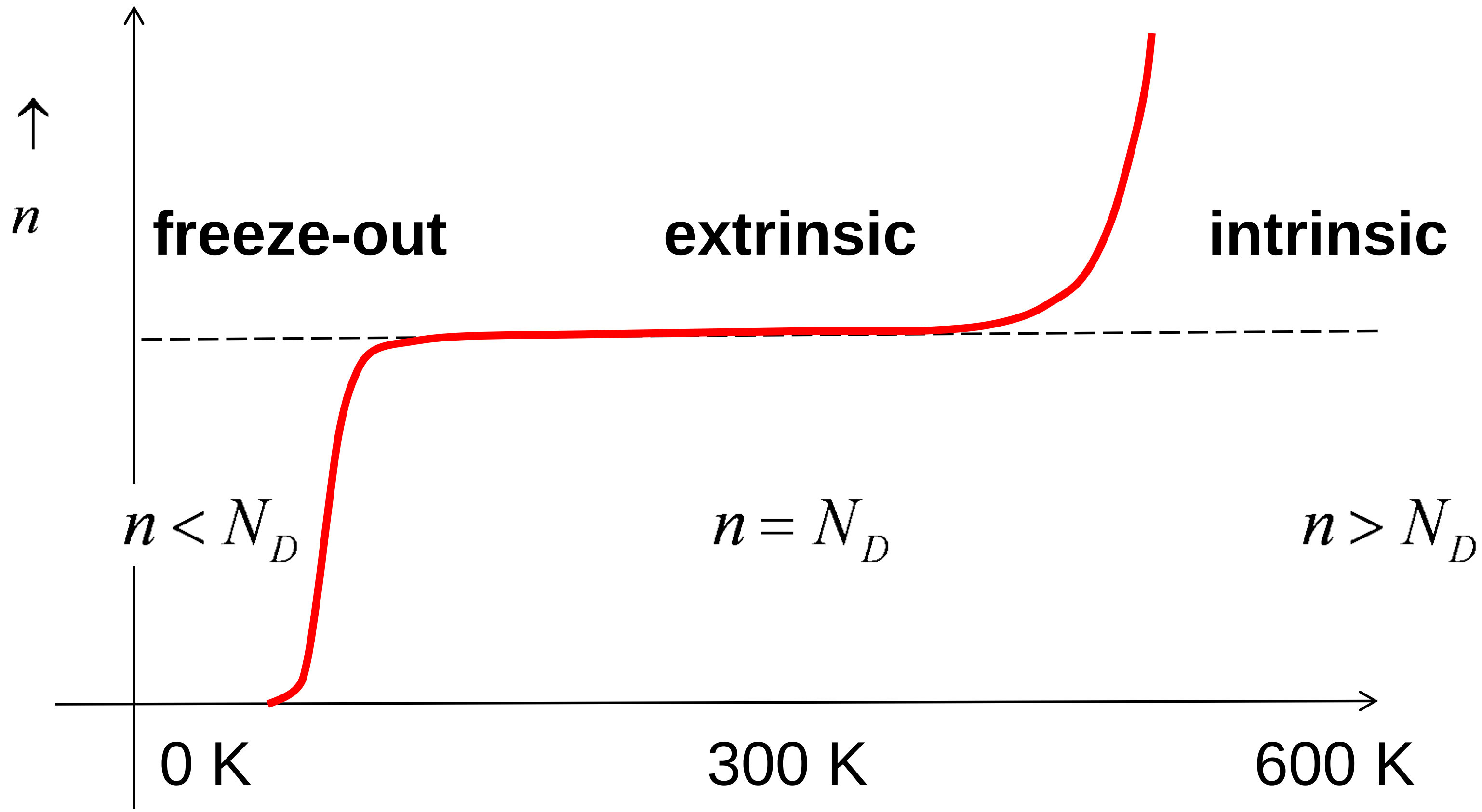
The freeze out region



Fermi level vs. temperature



Unit summary



You should understand this quantitatively and E_F vs. T qualitatively.

Vocabulary

1) Fermi level
2) Fermi function
3) Nondegenerate
4) Fermi-Dirac integral
5) Effective DOS
6) np product
7) Intrinsic concentration
8) Intrinsic Fermi level
9) Majority carrier
10) Minority carrier
11) Freeze-out
12) Extrinsic semiconductor
13) Intrinsic semiconductor
14) Donor degeneracy factor
15) Acceptor degeneracy factor
16) Metal-insulator transition