Extrinsic Semiconductors

Impurities make Significant Contribution

$n_c(T) > p_v(T)$ ⇒ n-type

⇑

donors ⇐ impurities

$n_c(T) < p_v(T)$ ⇒ p-type

⇑

acceptors ⇐ impurities

Doping of Semiconductors

$\sigma = ne\mu$ ⇨ the conductivity depends linearly upon the doping

A typical metal has $n_{metal} \sim 10^{23}/(cm)^3$ whereas we have seen that a typical semiconductor has

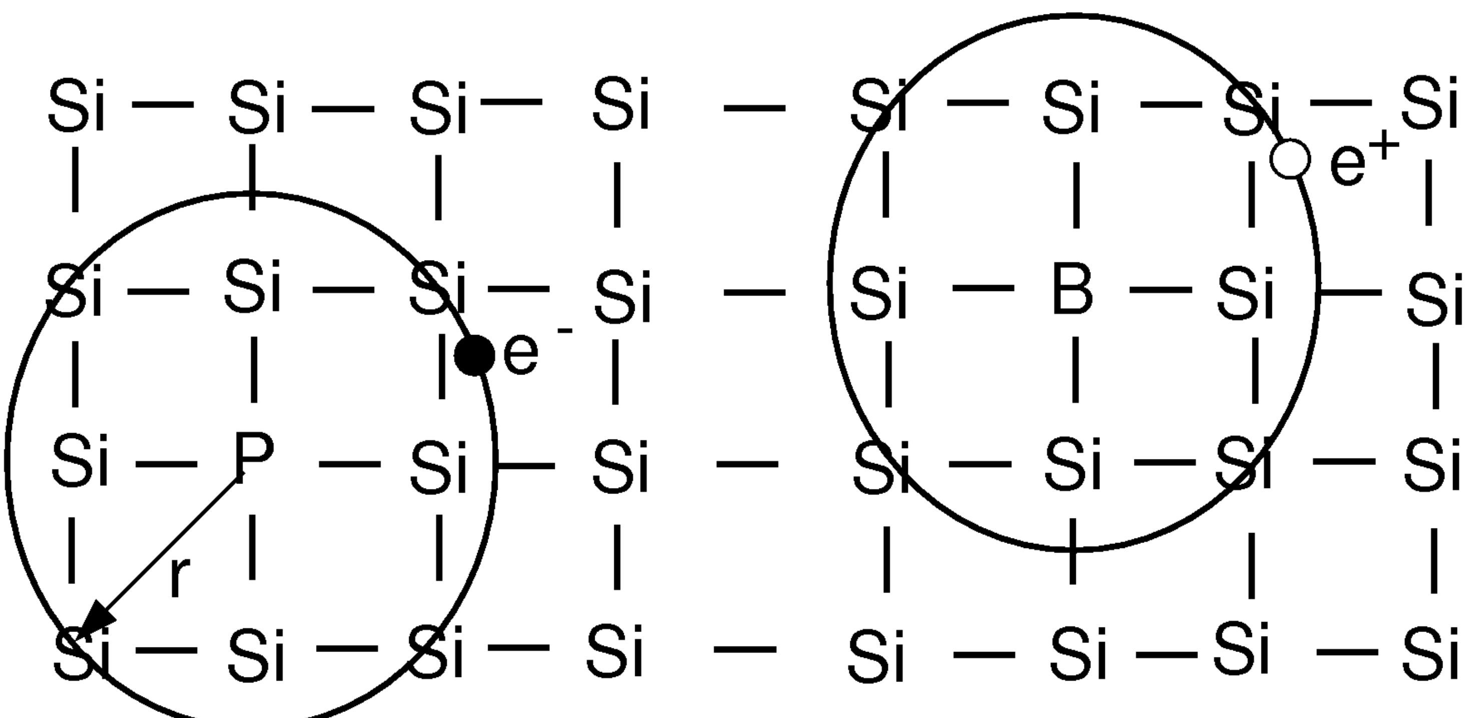
$$n_{i_{SeC}} \sim \frac{10^{10}}{cm^3} \qquad \text{at} T \simeq 300^\circ K$$

To increase n (or p) to $\sim 10^{18}$ or more, dopants are used.

Additional impurity charges will be localized around the FIXED donor or acceptor ion (may be treated as having infinite mass).

The binding energy is given by $E = \dfrac{m^* e^4}{2\epsilon^2 \hbar^2 n^2}$

m^* = hole mass acceptor(B) OR electron mass donor(P)



Si $3s^2 3p^2$

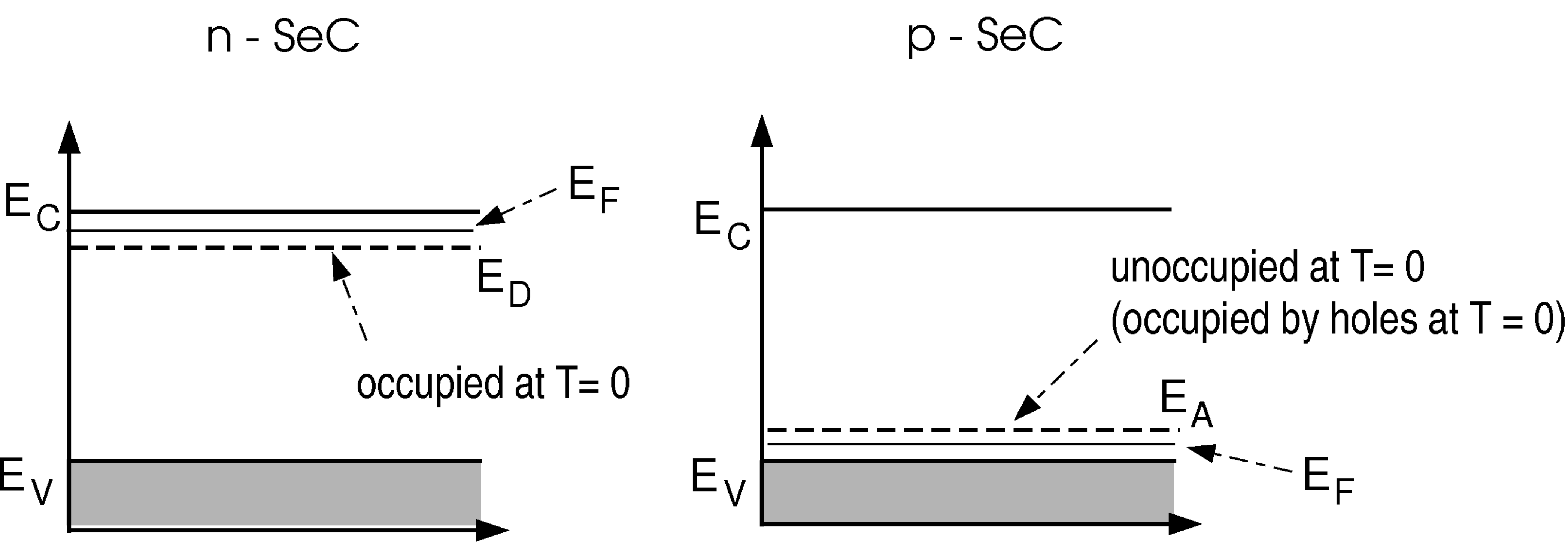
P $3s^2 3p^3$

B $3s^2 3p^1$

$r = \dfrac{\hbar^2 \varepsilon}{m^* e^2}$ big!

Since $m^*/m < 1$ and $\varepsilon \sim 10$ these energies are often much less than 13.6eV c.f. in Si E ~ 30M eV ~ 300°K or in Ge E ~ GMeV ~ 60°K

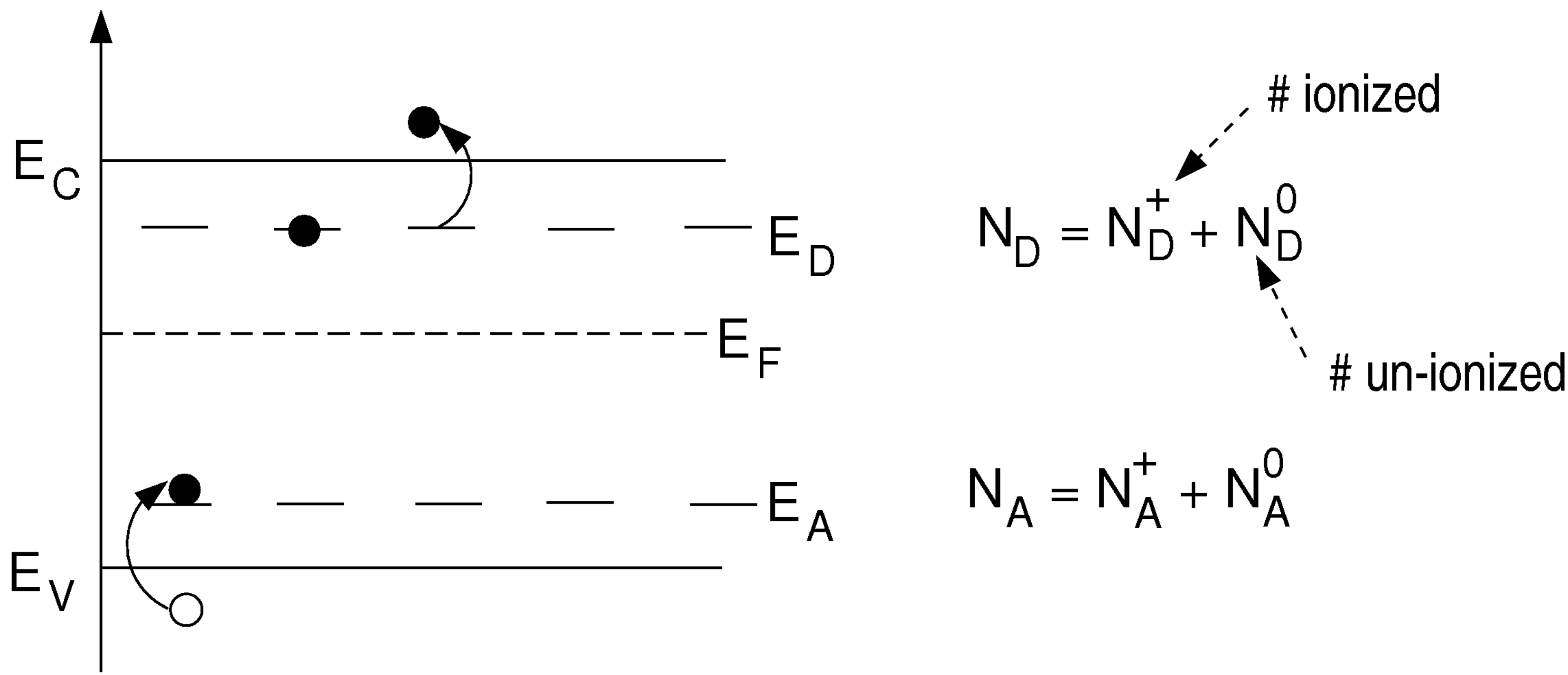
→ thermal excitations will often ionize these dopant sites!



Carrier Densities in Doped semiconductor

The law of mass action remains valid so long as the use of Boltzmann statistics is valid i.e., if the degeneracy is small!

$$np = N^C_{eff} N^V_{eff} e^{-\beta E_g} = n_i^2 = p_i^2$$



In equilibrium, the semiconductor is charge neutral so that

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

The probability that a donor/acceptor is occupied by an electron is determined by Fermi statistics

$$n_D = N_D^0 = N_D \frac{1}{1 + e^{\beta(E_D - E_F)}}$$

$$p_A = N_A^0 = N_A(1 - f(E_A)) = N_A \frac{1}{1 + e^{\beta(E_F - E_A)}}$$

Imagine that we have an *n*-type semiconductor (no *p*-type dopants) so that $N_A = N^0_A = N^+_A = 0$, then

$$n = N_{eff}^C e^{-\beta(E_C - E_F)}$$

$$N_D = N_D^0 + N_D^+$$

$$N_D^0 = N_D \frac{1}{e^{\beta(E_D - E_F)} + 1}$$

Furthermore, charge neutrality requires that

$$n = p + N_D^+$$

An excellent approximation is to assume that for a (commercially) doped semiconductor

$$N_D^+ \gg n_i \quad \Longrightarrow \quad N_D^+ \gg p$$

$$\begin{aligned} n &\approx N_D^+ = N_D - N_D^0 \\ n &\approx N_D \left(1 - \frac{1}{e^{\beta(E_D - E_F)} + 1}\right) \end{aligned}$$

Thermally induced carriers satisfy the Boltzmann equation,

$$n = N_{eff}^C e^{\beta(E_F - E_C)}$$

$$n = \frac{N_D}{1 + e^{\beta E_d} n/(N_{eff}^C)}$$ where $$E_d = E_c - E_D$$

Which has only one meaningful solution

$$n = \frac{2N_D}{1 + \sqrt{1 + 4\left(N_D/N_{eff}^C\right) e^{\beta E_d}}}$$

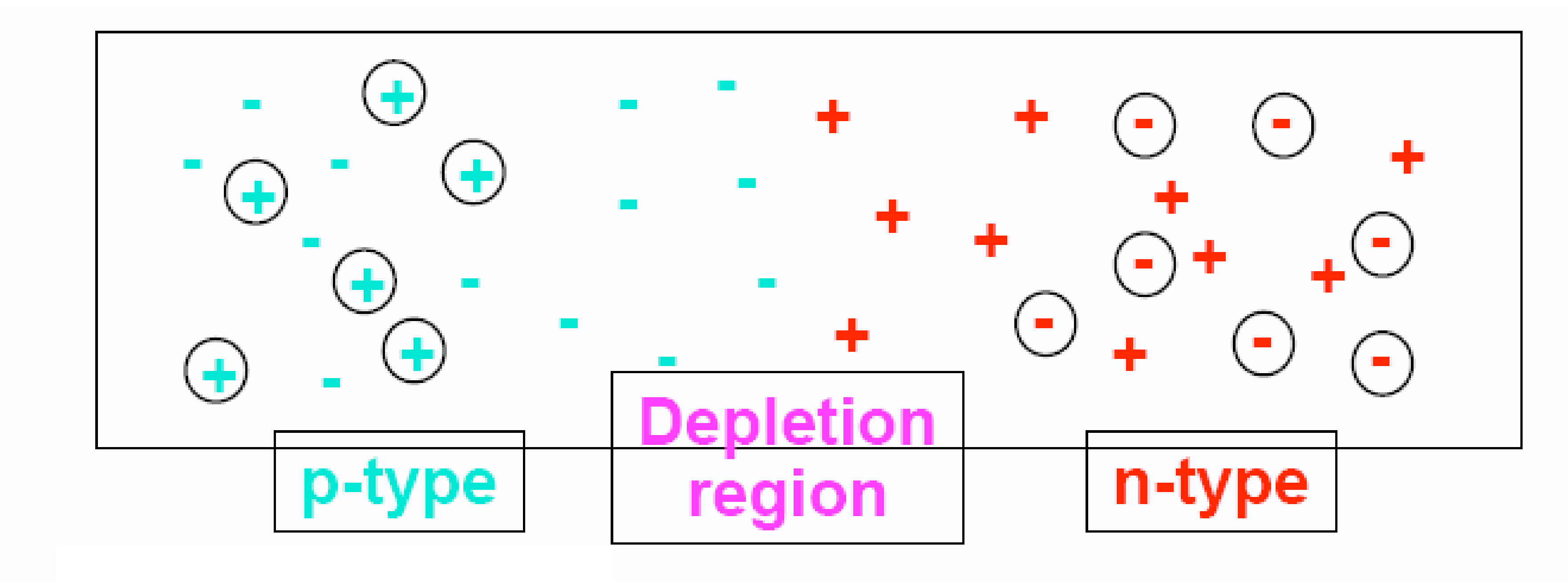
At low $T \ll \frac{E_d}{k_B}$ $\Rightarrow$ $n \simeq \sqrt{N_D N_{eff}^C} e^{-\beta E_d}$

and at higher $T \gg \frac{E_d}{k_B}$ $\Rightarrow$ $n = N_D$

At still higher T our approximation breaks down that $N_D \gg n$ since thermally excited carriers will dominate.

Inhomogeneous Semiconductors

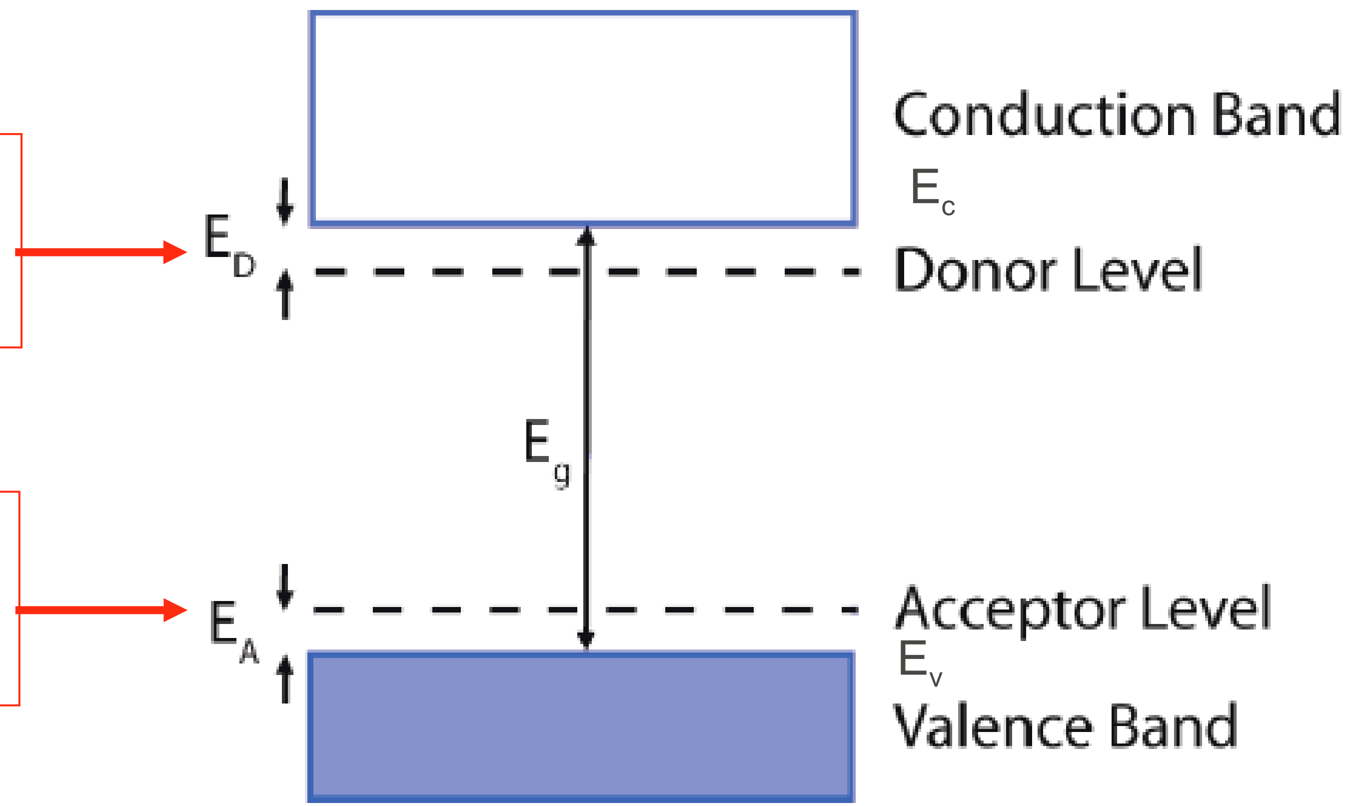
one material doped differently
in different regions

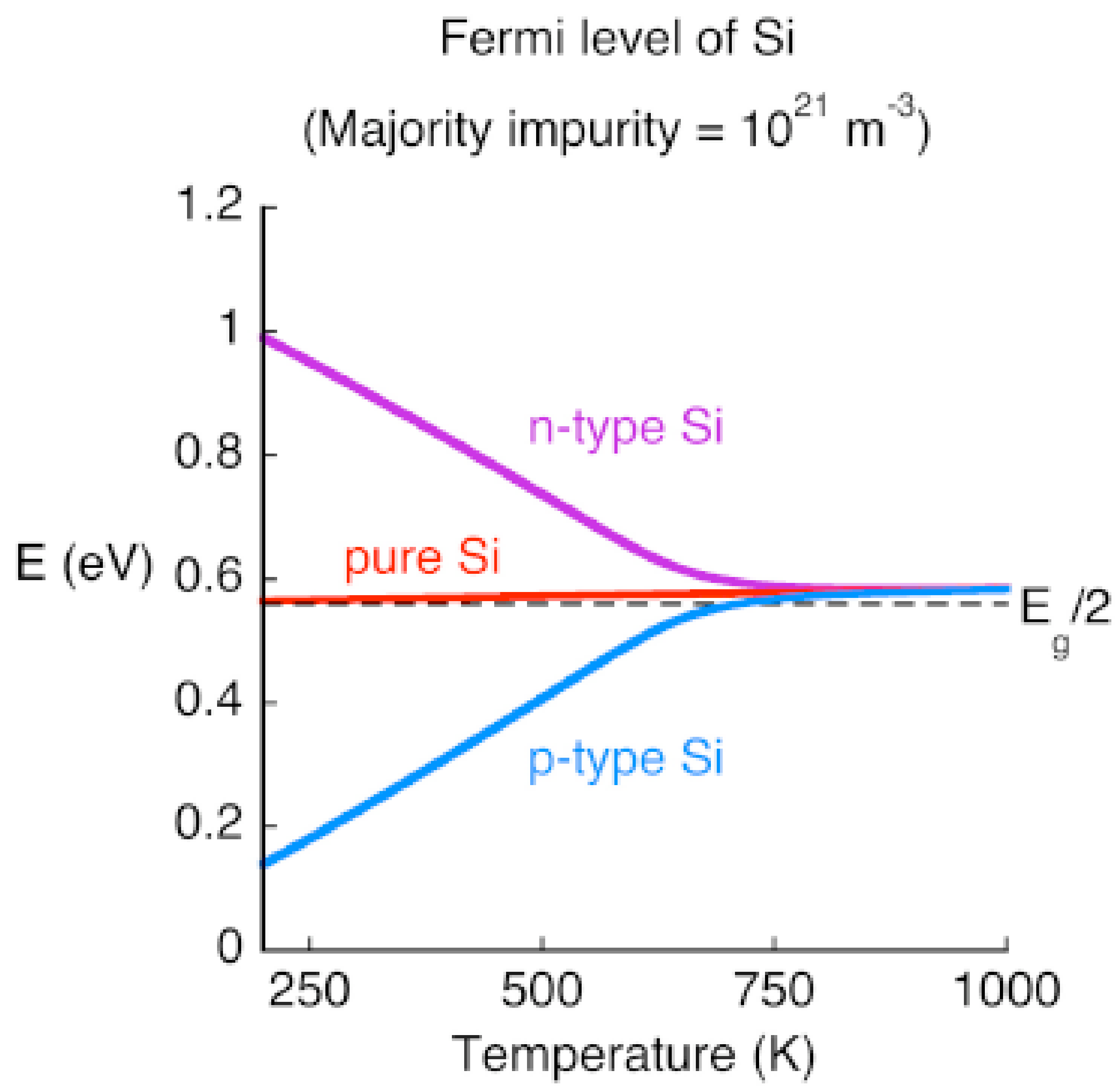


Doping Effects on the Band Structure

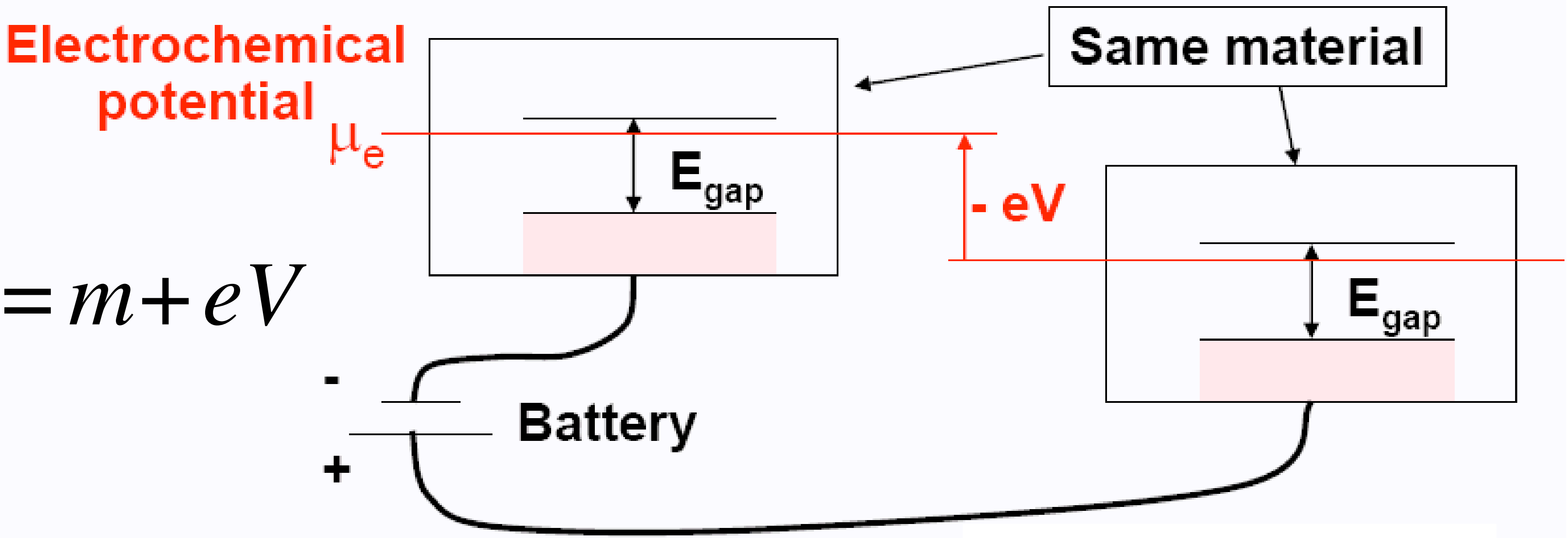
Donors lower down the conduction band level to E_c-E_D

Acceptors increase the valence band level to E_v+E_A




Fermi level of Si
(Majority impurity = 10^21 m^-3)
1.2
1
0.8
0.6
0.4
0.2
0
E (eV)
n-type Si
pure Si
p-type Si
E_g/2
250
500
750
1000
Temperature (K)

Electron Band Energies in a Macropotential V(x)



$$\mu_{ec} = m + eV$$

Poisson equation, the macropotential V(x) corresponds to a space charge ρ(x)

$$\frac{\partial^2 V(x)}{\partial x^2} = -\frac{\rho(x)}{\epsilon\epsilon_0}$$

For the concentration of majority carriers

$$n_i^2 = n_n p_n = N_{eff}^V N_{eff}^C e^{-\frac{E_C^n - E_V^n}{k_B T}}$$

The diffusion voltage V_D is the difference between the maximum and minimum of the macropotential V(x) which is built up in thermal equilibrium, is thus related to the carrier density by

$$eV_D = -(E_V^n - E_V^p) = k_B T \ln \frac{p_p n_n}{n_i^2}$$

The corresponding current densities

$$j^{\mathrm{diff}} = j_n^{\mathrm{diff}} + j_p^{\mathrm{diff}} = e\left(D_n \frac{\partial n}{\partial x} - D_p \frac{\partial p}{\partial x}\right)$$

$$j^{\mathrm{drift}} = j_n^{\mathrm{drift}} + j_p^{\mathrm{drift}} = e(n\mu_n + p\mu_p)E_x$$

In the p and n regions electron-hole pairs are continually created due to the finite temperature, and subsequently recombine. The total current density obeys

$$j^{\text{diff}} + j^{\text{drift}} = 0$$

and thus the separate contributions of the electrons and holes must vanish individually,

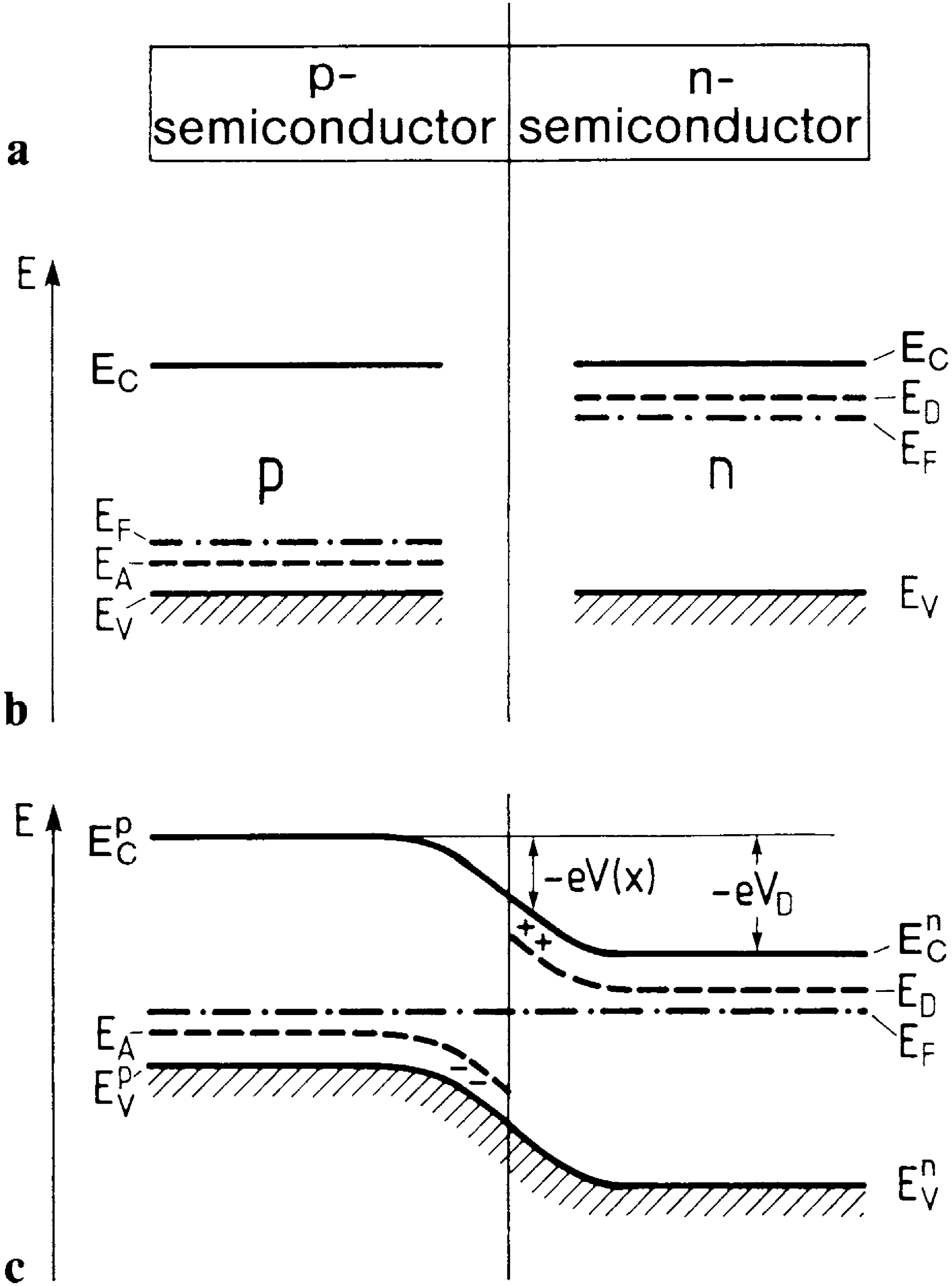
$$D_n \frac{\partial n}{\partial x} = n\mu_n \frac{\partial V(x)}{\partial x}$$

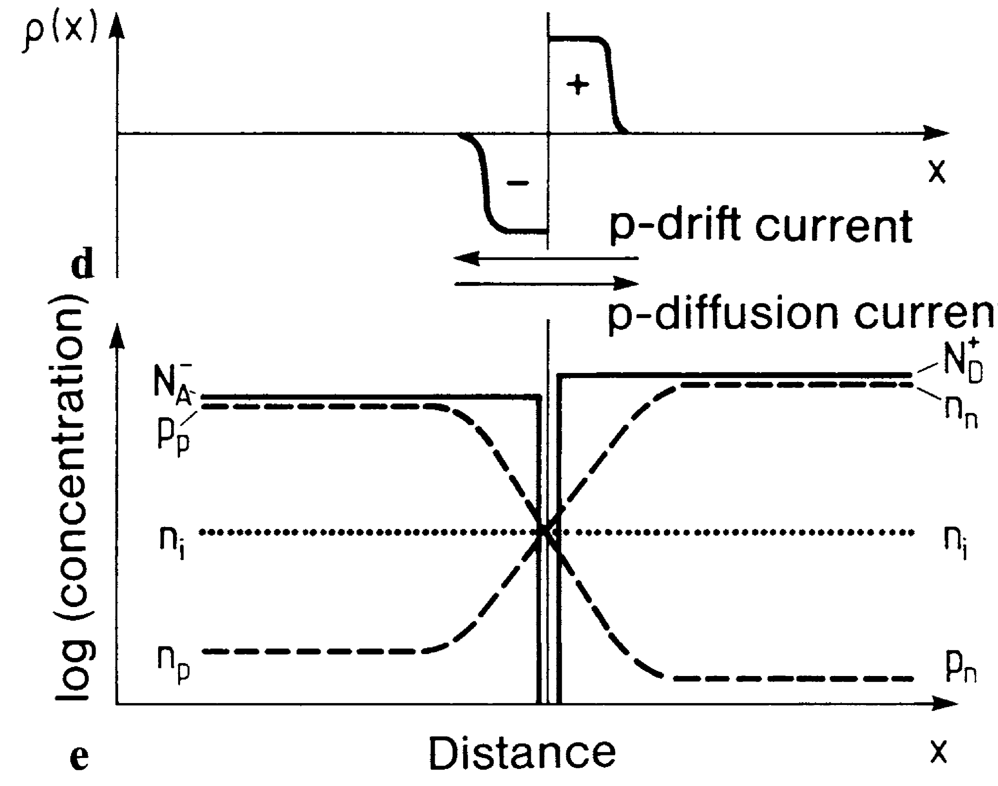
The concentration of the electrons is position dependent with

$$n(x) = N_{eff}^{C} e^{-\frac{E_C^p - eV(x) - E_F}{k_B T}}$$

$$\Rightarrow \quad \frac{\partial n}{\partial x} = n \frac{e}{k_B T} \frac{\partial V}{\partial x} \quad \text{or} \quad D_n = \frac{k_B T}{e} \mu_n$$

p-n junction in thermal equilibrium



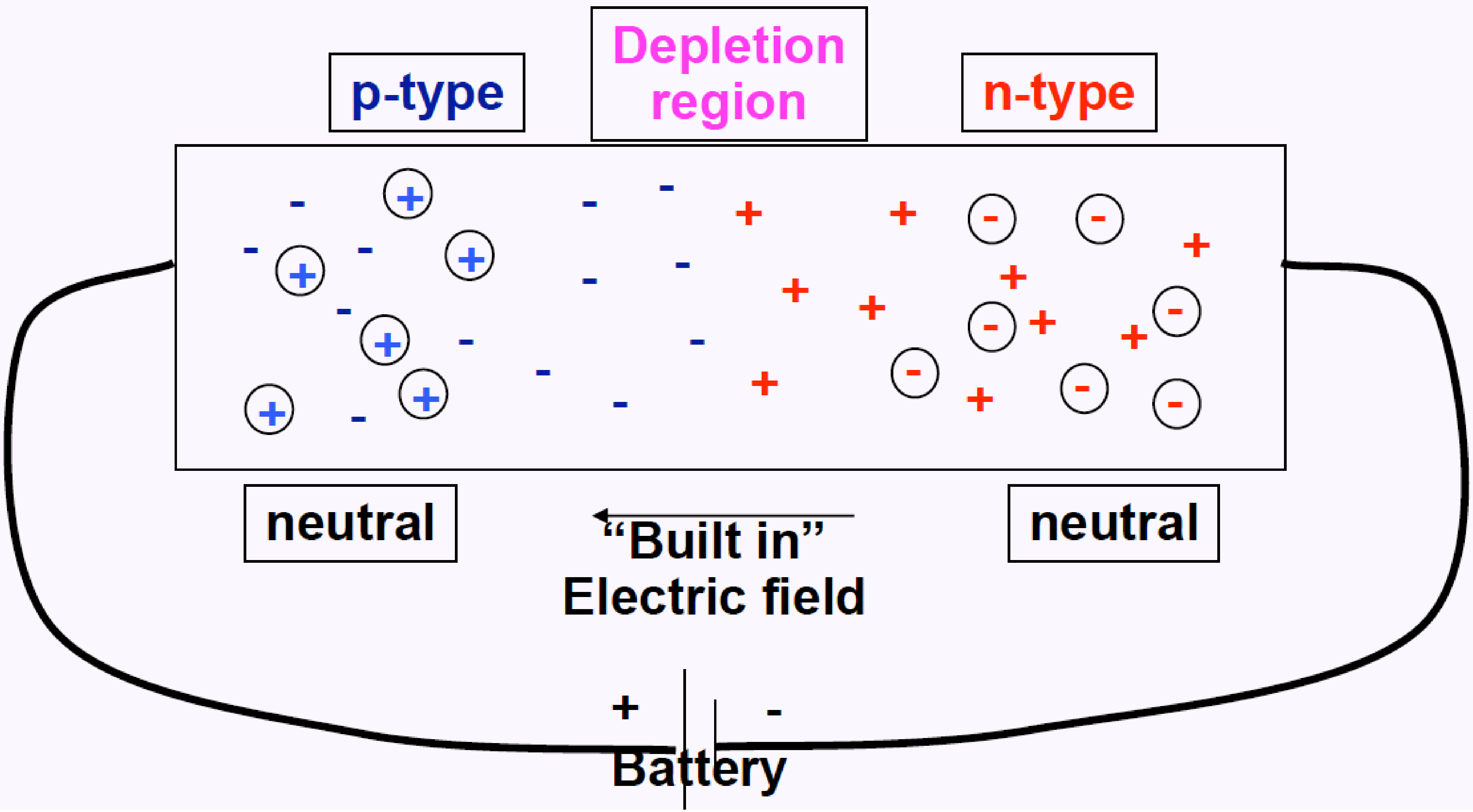


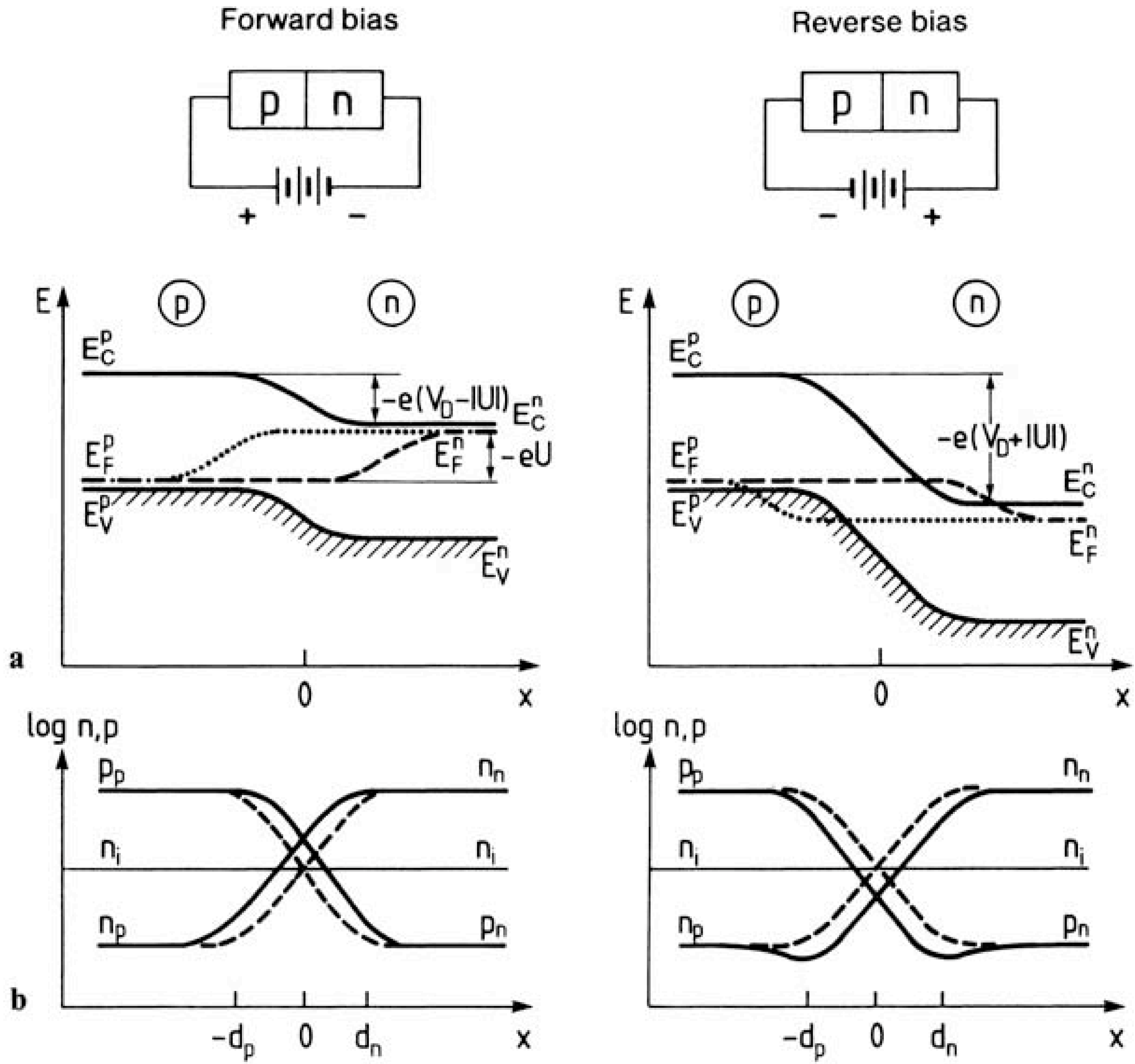
How can a p-n Junction be Used to Make a Diode?

- A device that passes current easily in one direction
- Low resistance for voltage applied in one direction (the forward direction)
- High resistance for voltage applied in the other direction (the reverse direction)

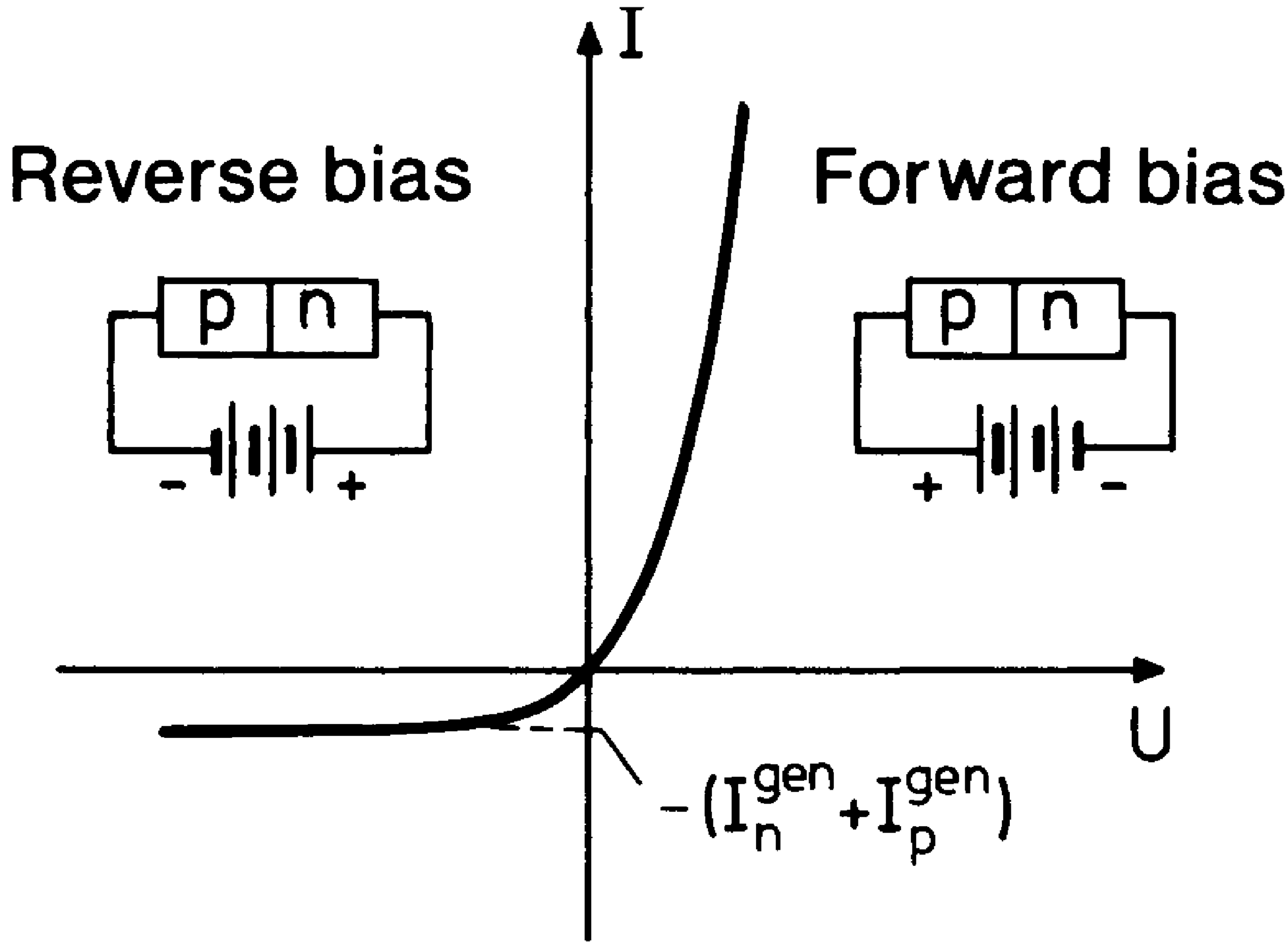
Forward Bias

Apply a voltage V to reduce the difference between the two sides to $\Delta E - e\Delta V$ ($\Delta V > 0$) ($\Delta E = E_L^0 - E_R^0$)





Forward bias
Reverse bias
p
n
+
−
E
E_C^p
$-e(V_D-|U|)$
E_C^n
E_F^p
E_F^n
$-eU$
E_V^p
E_V^n
$-e(V_D+|U|)$
a
0
x
log n, p
p_p
n_n
n_i
n_p
p_n
b
$-d_p$
d_n


I
Reverse bias
Forward bias
p
n
p
n
-
+
+
-
U
$-(I_n^{gen}+I_p^{gen})$

Homework
(due on 11/11/10)

Problem 6 (page 613)