7

pn junctions

November 5th, 2025

7

pn junctions

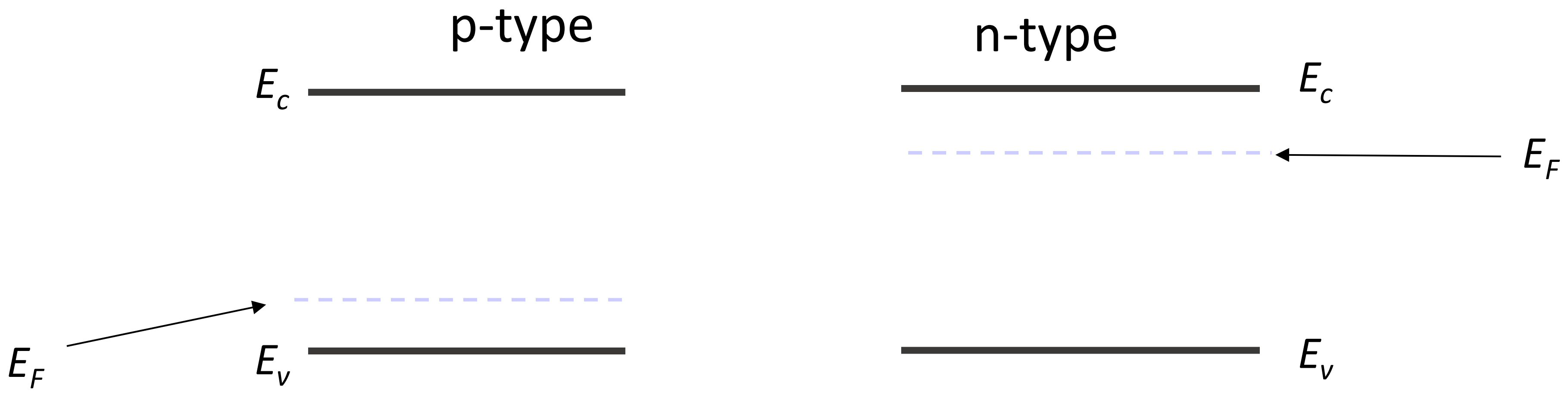
diodes
solar cells
LEDs

insulation

JFET
MOSFET
bipolar transitors

pn junction

isolated semiconductors



$$E_F = E_v + k_B T \ln\left(\frac{N_v}{N_A}\right)$$

$$E_F = E_c - k_B T \ln\left(\frac{N_c}{N_D}\right)$$

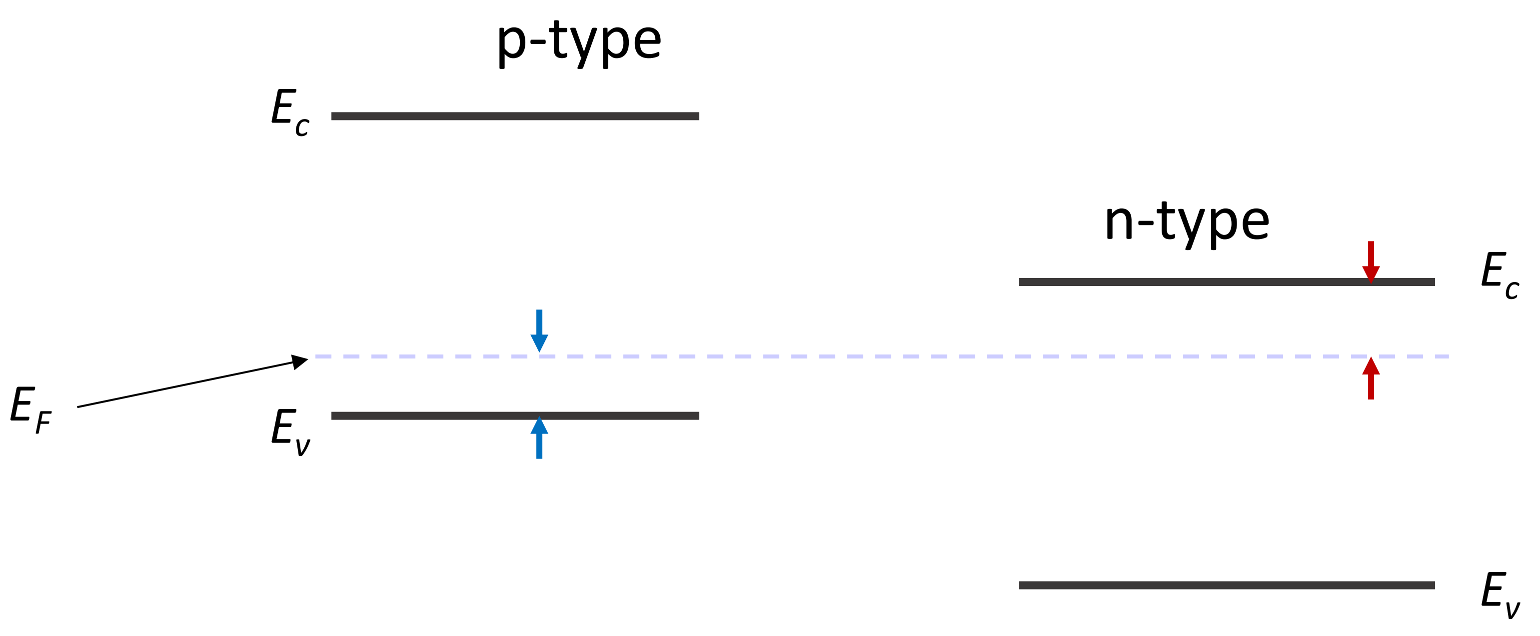
$$p = N_v \exp\left(\frac{E_v - E_F}{k_B T}\right)$$

$$n = N_c \exp\left(\frac{E_F - E_c}{k_B T}\right)$$

pn junction

semiconductors in contact

electrons flow from n to p

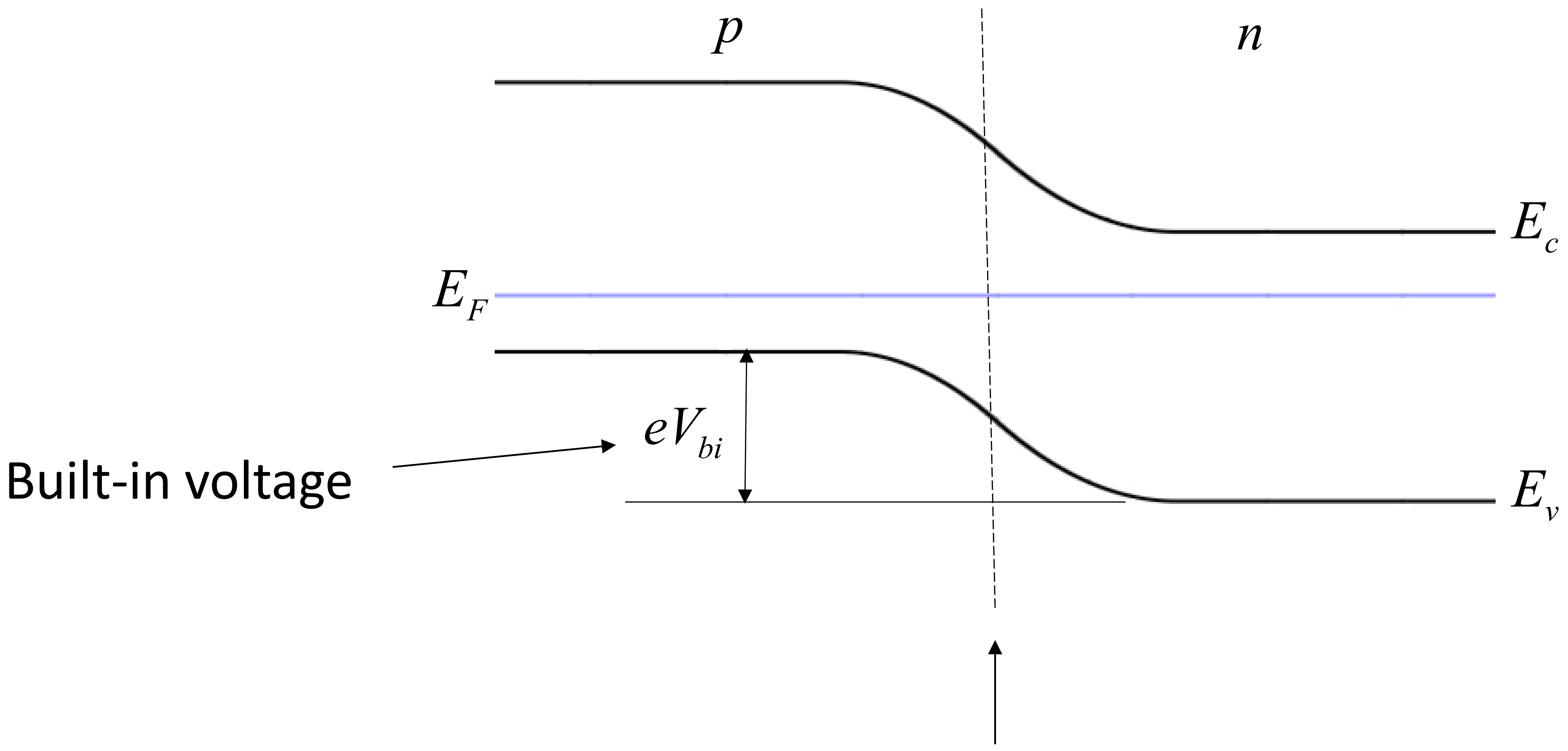


$$p = N_v \exp\left(\frac{E_v - E_F}{k_B T}\right) \approx N_A$$

$$n = N_c \exp\left(\frac{E_F - E_c}{k_B T}\right) \approx N_D$$

pn junction

semiconductors in contact

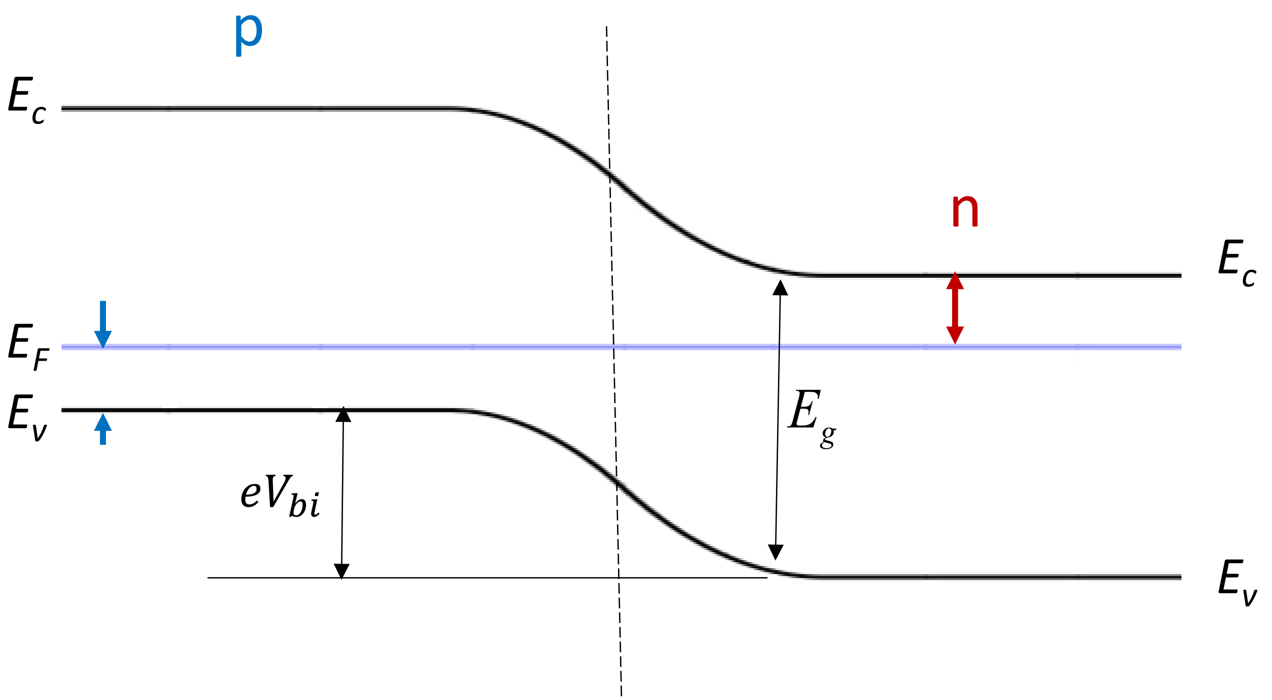


Abrupt junction: the doping changes abruptly from p to n

Built-in voltage V_{bi}

E_v in p-region

$$E_F - E_{vp} = k_B T \ln\left(\frac{N_v}{N_A}\right)$$



E_c in n-region

$$E_{cn} - E_F = k_B T \ln\left(\frac{N_c}{N_D}\right)$$

$$eV_{bi} = E_g - k_B T \ln\left(\frac{N_c}{N_{D,n} - N_{A,n}}\right) - k_B T \ln\left(\frac{N_v}{N_{A,p} - N_{D,p}}\right)$$

$$eV_{bi} = E_g - k_B T \ln\left(\frac{N_c N_v}{(N_{D,n} - N_{A,n})(N_{A,p} - N_{D,p})}\right)$$

V_{bi}

$$eV_{bi} = E_g - k_BT\ln\left(\frac{N_cN_v}{(N_{D,n}-N_{A,n})(N_{A,p}-N_{D,p})}\right)$$

$$n_i^2 = N_vN_c\exp\left(\frac{-E_g}{k_BT}\right)$$

$$E_g = -k_BT\ln\left(\frac{n_i^2}{N_vN_c}\right)$$

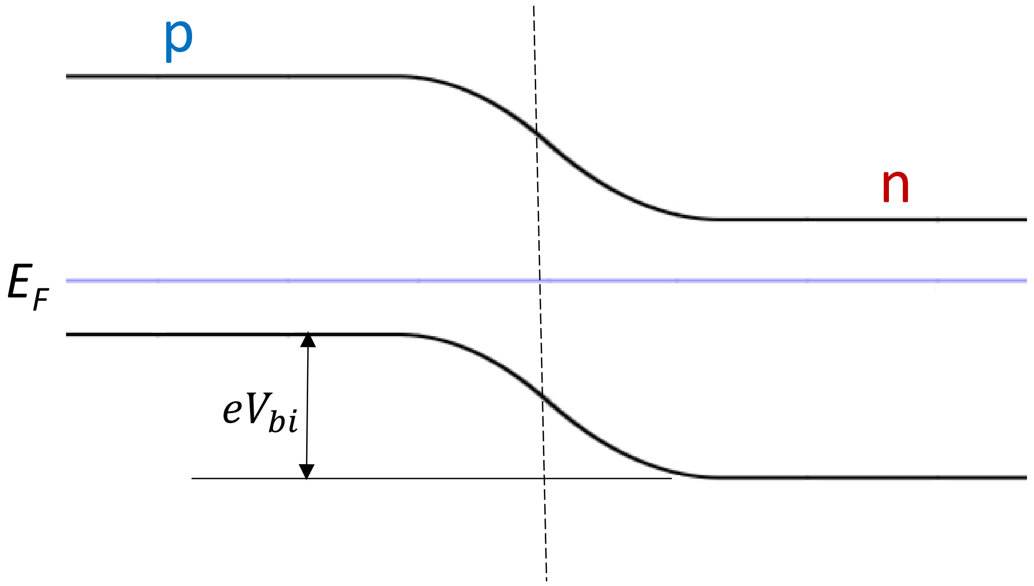
$$eV_{bi} = k_BT\ln\left(\frac{(N_{D,n}-N_{A,n})(N_{A,p}-N_{D,p})}{n_i^2}\right)$$

for $N_{D,n} - N_{A,n} = N_D$ and $N_{A,p} - N_{D,p} = N_A$

$$eV_{bi} = k_BT\ln\left(\frac{N_DN_A}{n_i^2}\right)$$

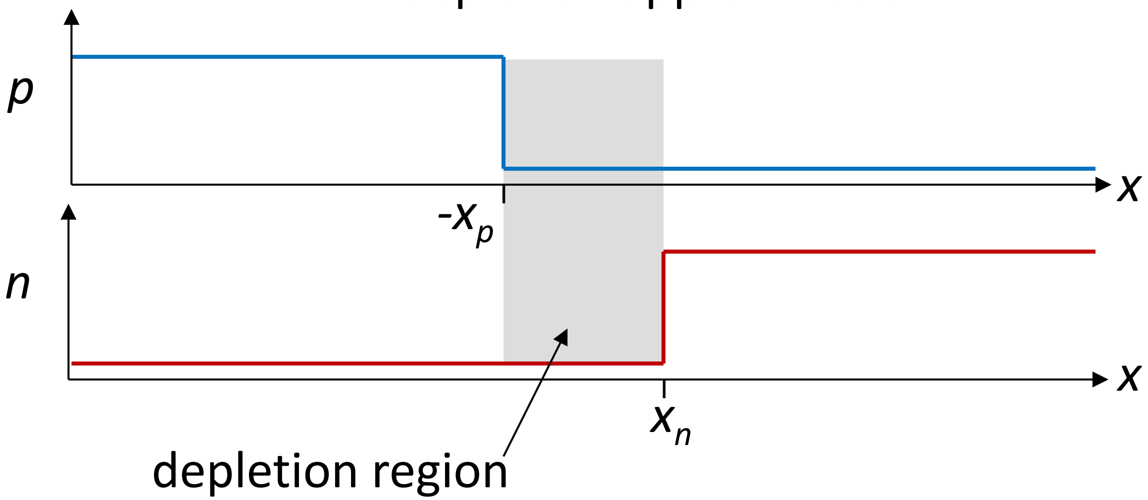
https://lampz.tugraz.at/~hadley/psd/L6/Vbi.html

p and n profiles



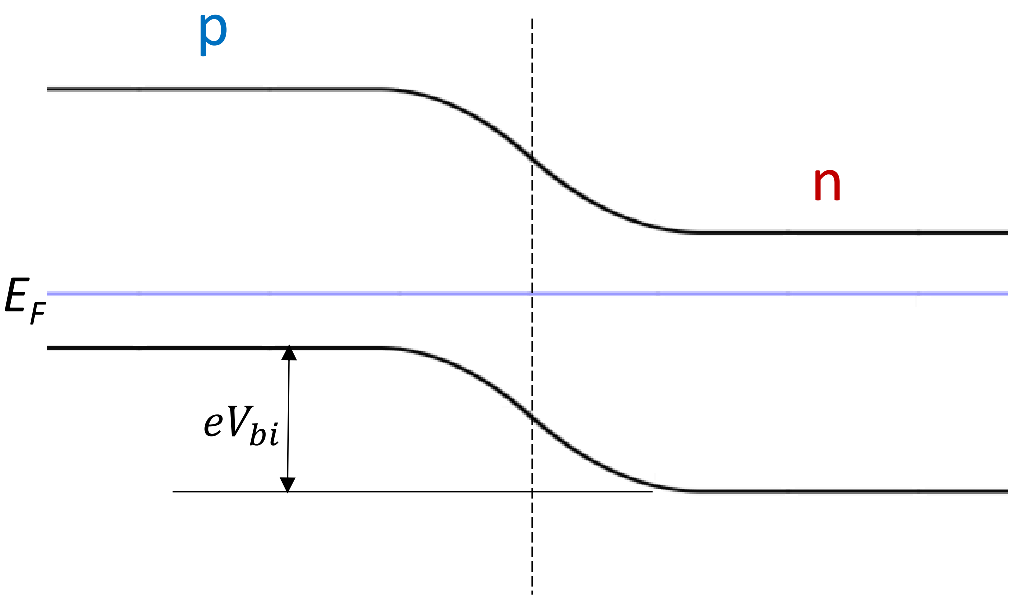
depletion approximation

$$p = N_v \exp\left(\frac{E_v - E_F}{k_B T}\right)$$

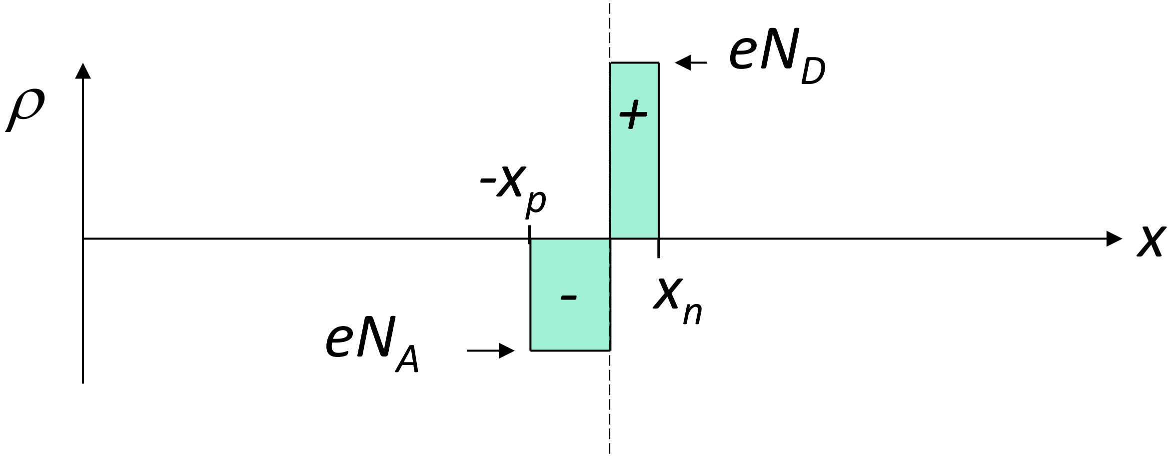


$$n = N_c \exp\left(\frac{E_F - E_c}{k_B T}\right)$$

space charge



exposed ionized dopants



$$N_A x_p = N_D x_n$$

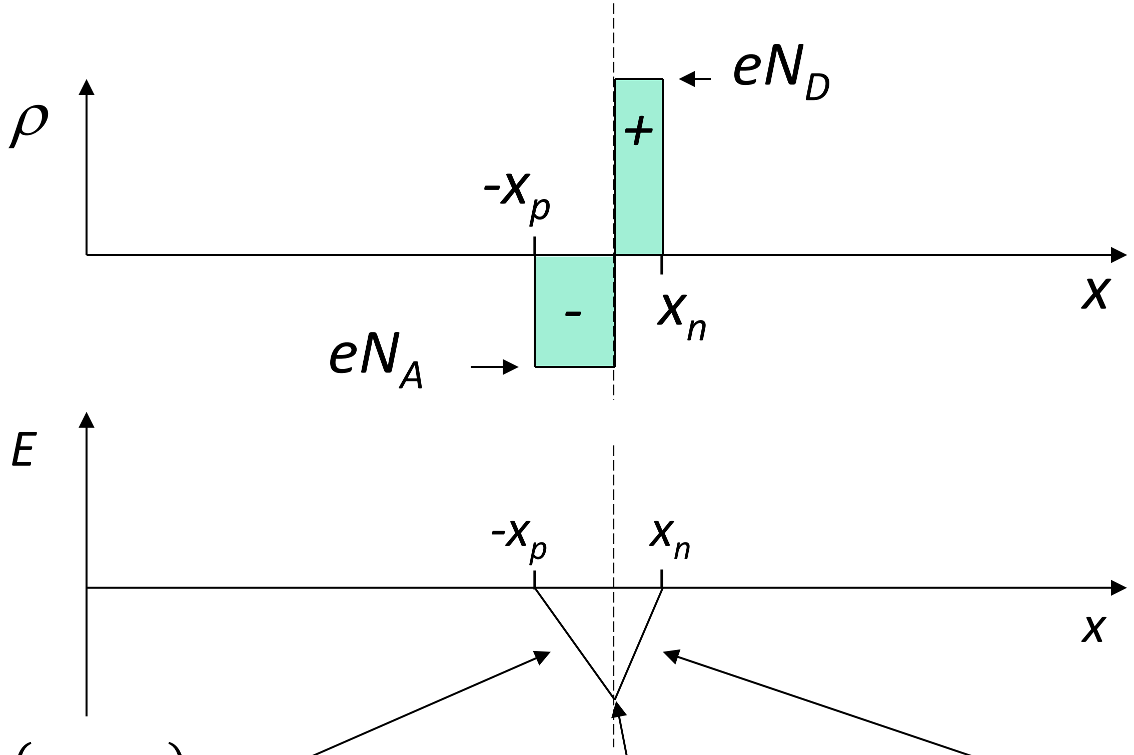
electric field

Gauss's law

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon}$$

in 1-D is

$$\frac{dE}{dx} = \frac{\rho}{\varepsilon}$$



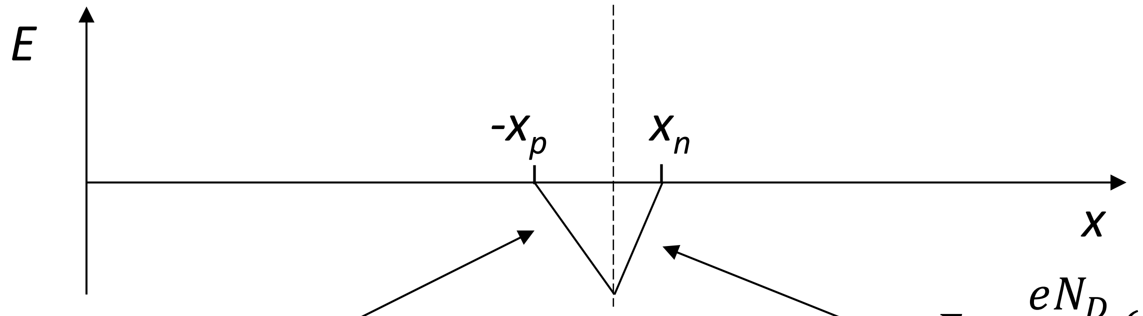
$$E = -\frac{eN_A}{\varepsilon}(x + x_p)$$

$$E = \frac{eN_D}{\varepsilon}(x - x_n)$$

$$|E_{\max}| = \frac{eN_D x_n}{\varepsilon} = \frac{eN_A x_p}{\varepsilon}$$

E pushes the holes towards *p* and the electrons towards *n*

electrostatic potential



$$E = -\frac{eN_A}{\varepsilon}(x + x_p)$$

$$E = \frac{eN_D}{\varepsilon}(x - x_n)$$

$$\frac{dV}{dx} = -E$$

$$-x_p > x > 0 \qquad 0 > x > x_n$$

$$V = \frac{eN_A}{\varepsilon}\left(\frac{x^2}{2} + x x_p\right) \qquad V = \frac{-eN_D}{\varepsilon}\left(\frac{x^2}{2} - x x_n\right)$$

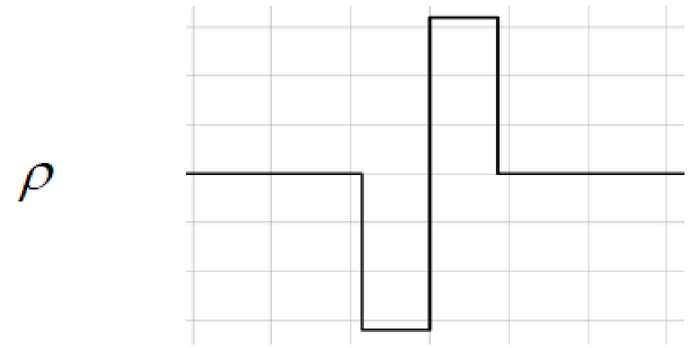
$$V(-x_p) = \frac{-eN_A}{2\varepsilon}x_p^2 \qquad V(0) = 0 \qquad V(x_n) = \frac{eN_D}{2\varepsilon}x_n^2$$

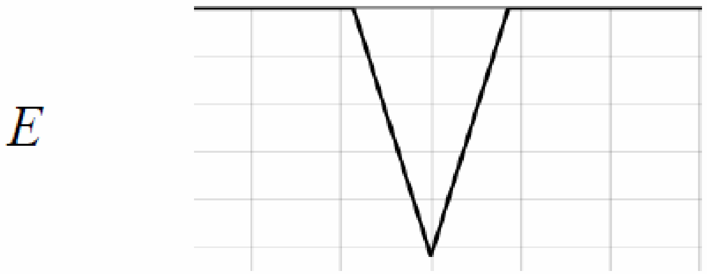
abrupt pn junction

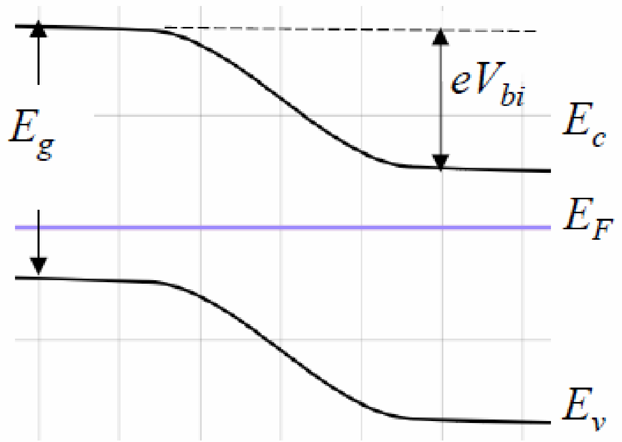
$$V_{bi} = \frac{k_B T}{e} \ln\left(\frac{N_D N_A}{n_i^2}\right)$$

$$= \frac{e N_A x_p^2}{2\varepsilon} + \frac{e N_D x_n^2}{2\varepsilon}$$

https://lampz.tugraz.at/~hadley/psd/L6/abrupt.html

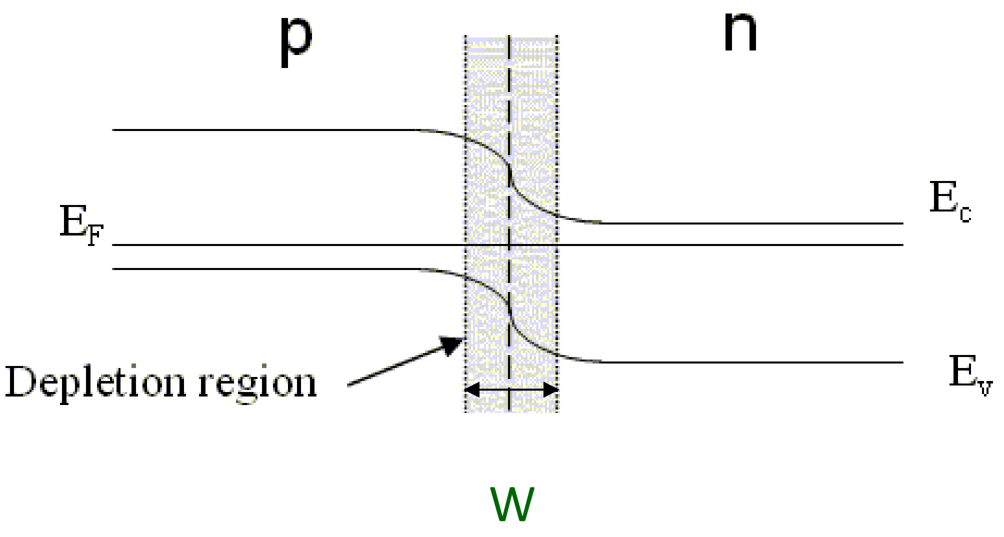






Depletion width

$$V_{bi} = \frac{k_B T}{e} \ln\left(\frac{N_D N_A}{n_i^2}\right) = \frac{e N_A x_p^2}{2\varepsilon} + \frac{e N_D x_n^2}{2\varepsilon}$$



$$N_A x_p = N_D x_n = N_D(W - x_p) = N_A(W - x_n)$$

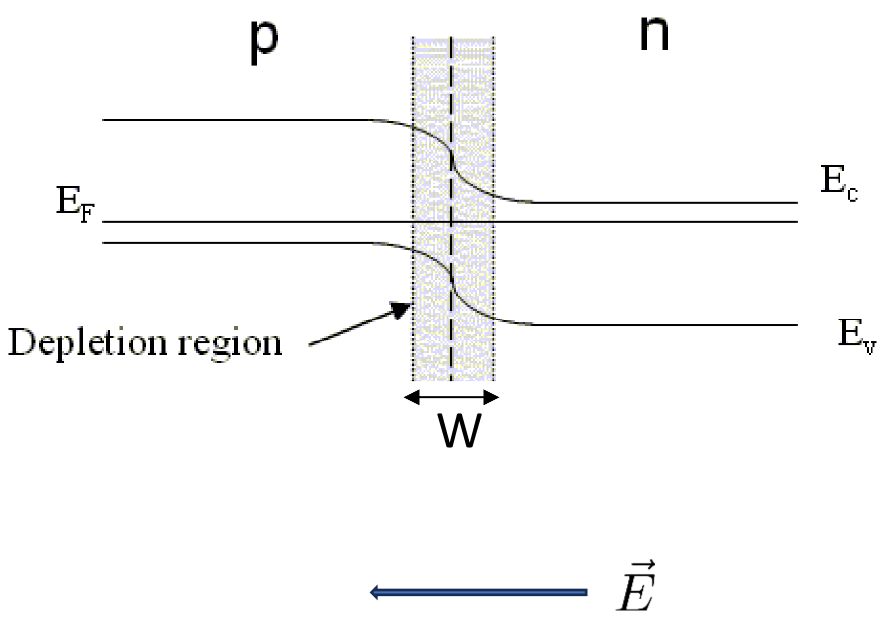
$$x_p = \frac{N_D W}{N_A + N_D} \qquad x_n = \frac{N_A W}{N_A + N_D}$$

$$V_{bi} = \frac{e}{2\varepsilon} \frac{N_D N_A}{N_D + N_A} W^2$$

$$W = \sqrt{\frac{2\varepsilon(N_D + N_A)V_{bi}}{e N_D N_A}}$$

light doping: wide depletion width

Depletion width



V_{bi} ~ 1V

W ~ 10 nm - 10 μm

E_{max} ~ 10^4 V/cm

The electric field pushes the electrons towards the n-region and the holes towards the p-region.

Diffusion sends electrons towards the p-region and holes towards the n-region.

Abrupt pn junctions in the depletion approximation

In an abrupt pn junction, the doping changes abruptly from p to n. It is common to solve for the band bending, the local electric field, the carrier concentration profiles, and the local conductivity in the depletion approximation. In this approximation it is assumed that there is a depletion width W around the transition from p to n where the charge carrier densities are negligible. Outside the depletion width the charge carrier densities are equal to the doping densities so that the semiconductor is electrically neutral outside the depletion width. Using this approximation it is possible to calculate the important properties of the pn junction.

N_A = 1E15 1/cm³ N_D = 1E15 1/cm³ E_g = 1.166-4.73E-4*T*T/(T+636) eV

$N_v(300)$ = 9.84E18 1/cm³ $N_c(300)$ = 2.78E19 1/cm³ ϵ_r = 12 T = 300 K

μ_p = 480 cm²/V s μ_n = 1350 cm²/V s τ_p = 1E-10 s τ_n = 1E-10 s

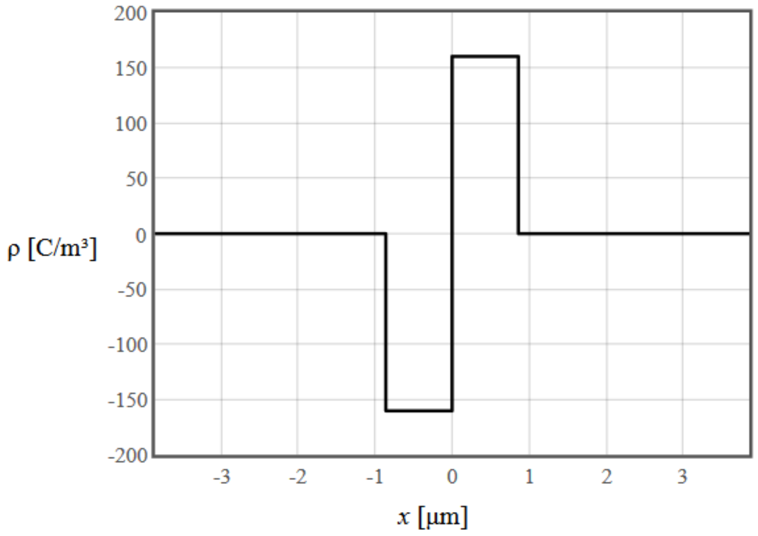
V = -0.5 V

V Submit

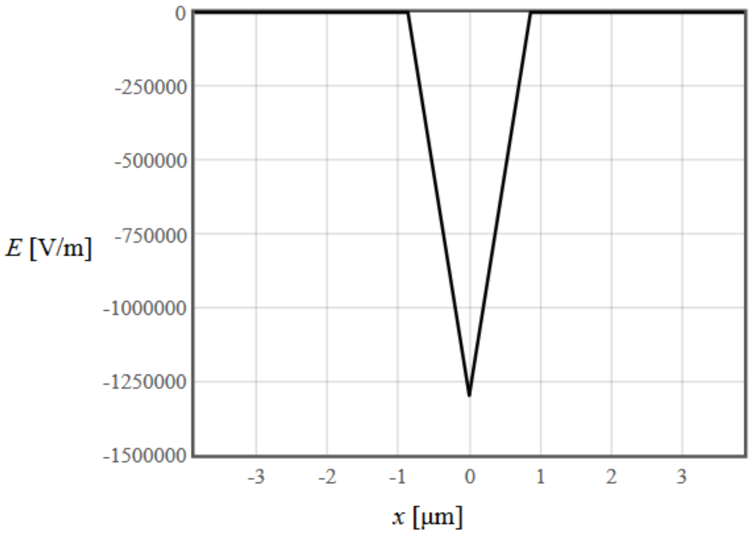
$E_g = 1.12$ eV $W = 1.72$ µm $x_p =$ -0.861 µm $x_n = 0.861$ µm $V_{bi} = 0.618$ V $C_j = 6.17$ nF/cm²

$D_p = 12.4$ cm²/s $D_n = 34.9$ cm²/s $L_p = 0.352$ µm $L_n = 0.591$ µm

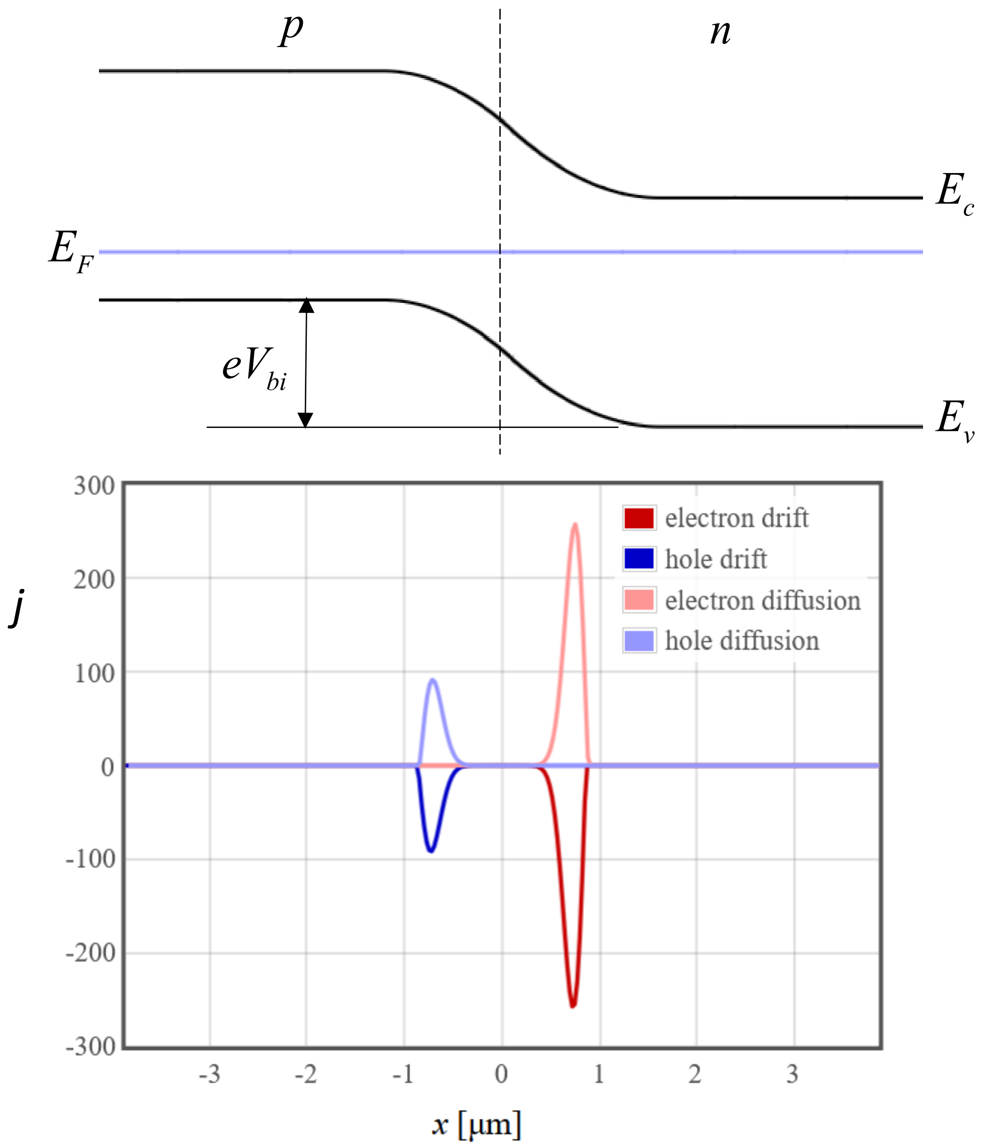
Charge density



Electric field



Drift and diffusion



$$\vec{j}_n = en\mu_n\vec{E} + eD_n\nabla n$$

$$n = N_c \exp\left(\frac{E_F - E_c}{k_B T}\right)$$

$$\nabla n = -\frac{\nabla E_c}{k_B T} N_c \exp\left(\frac{E_F - E_c}{k_B T}\right) = -\frac{\nabla E_c}{k_B T} n$$

$$e\vec{E} = \nabla E_c$$

$$\vec{j}_n = n\nabla E_c\left(\mu_n - \frac{eD_n}{k_B T}\right)$$

Einstein relation

If the E_F is constant, $j = 0$.