7. pn - Junctions

Nov. 14, 2018

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

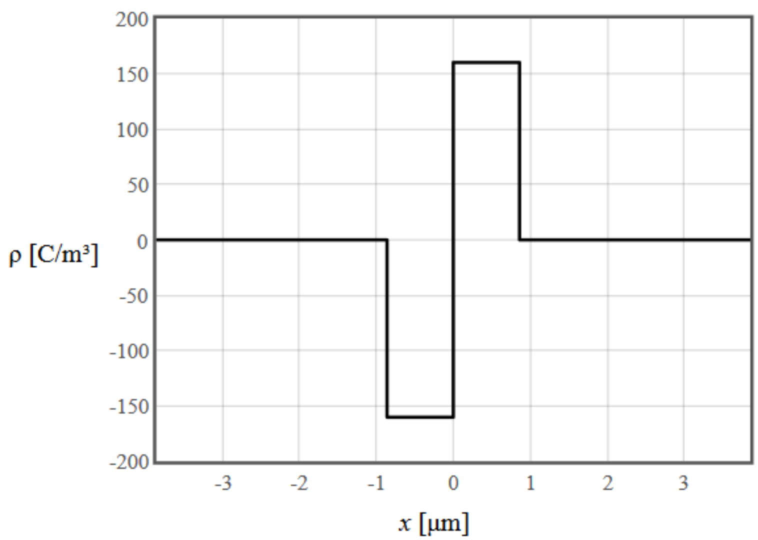
V = -0.5 V Submit

V

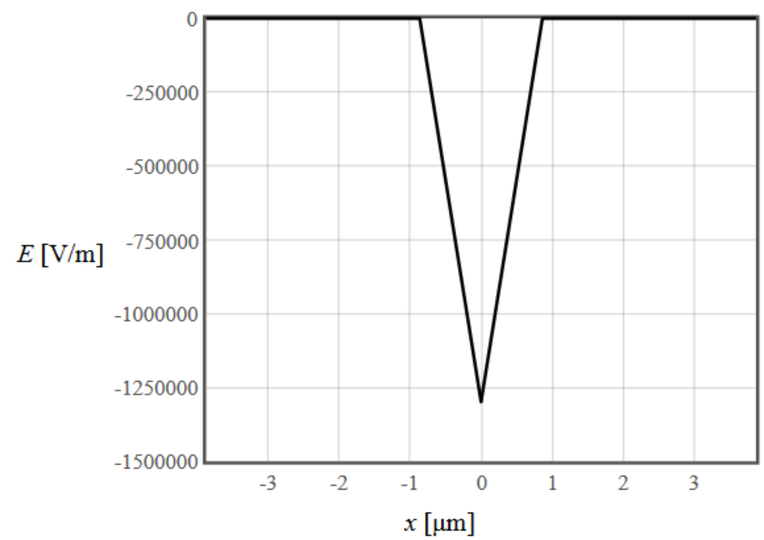
$E_g = 1.12$ eV $W = 1.72$ µm $x_p =$ -0.861 µm $x_n = 0.861$ µm $V_{bi} = 0.618$ V $C_j = 6.17$ nF/cm²

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

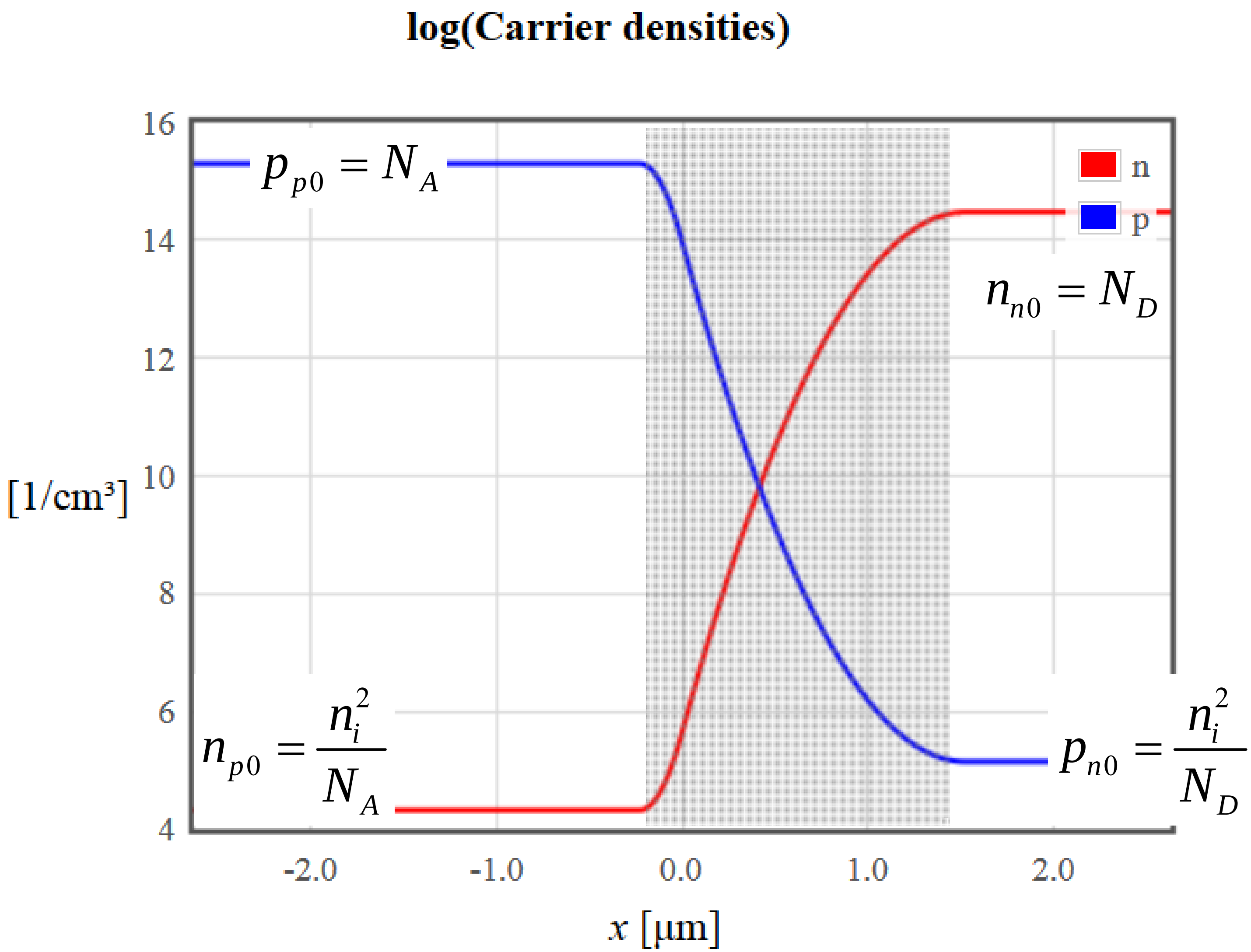
Charge density



Electric field



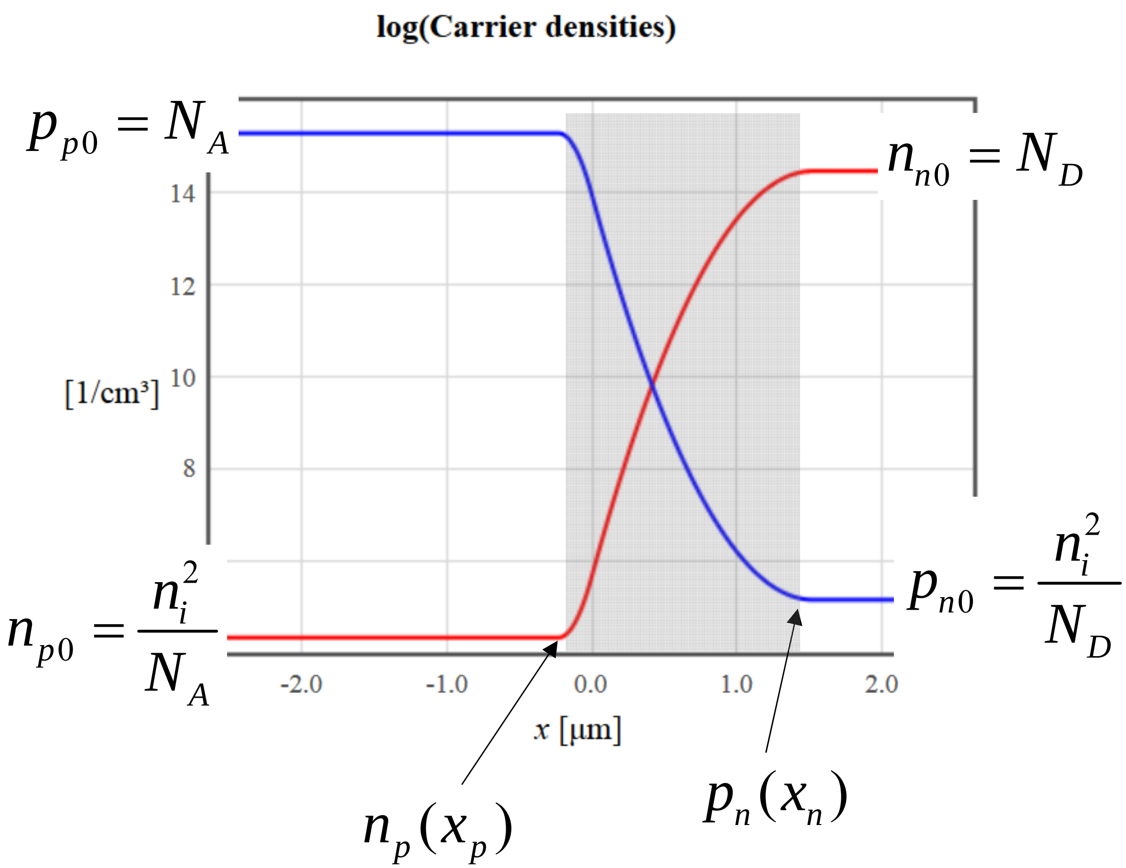
Equilibrium concentrations, V = 0



$$n_{p0} p_{p0} = n_{n0} p_{n0} = n_i^2$$

Bias voltage, V = 0

$$eV_{bi} = k_B T \ln\left(\frac{N_D N_A}{n_i^2}\right) = k_B T \ln\left(\frac{N_D}{n_{p0}}\right) = k_B T \ln\left(\frac{N_A}{p_{n0}}\right)$$



$$n_{p0} p_{p0} = n_{n0} p_{n0} = n_i^2$$

V = 0

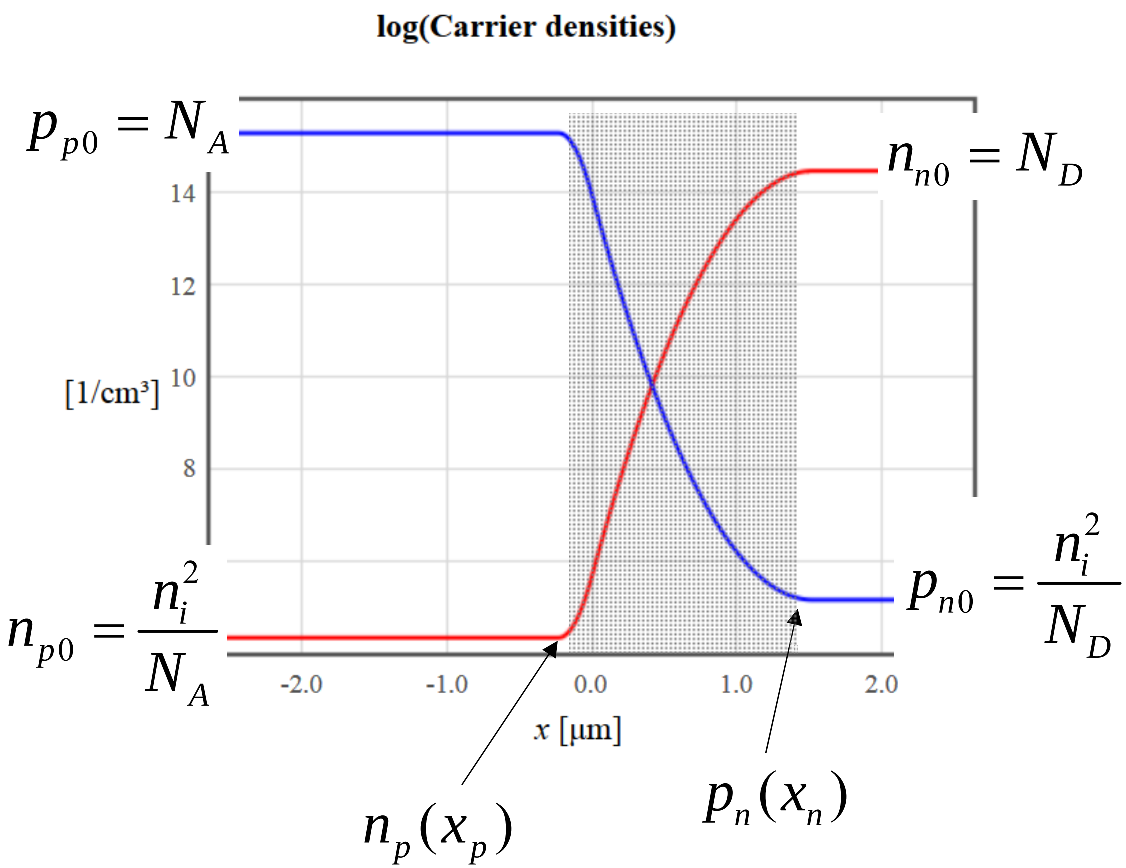
$$n_{p0} = N_D \exp\left(\frac{-eV_{bi}}{k_B T}\right)$$

$$p_{n0} = N_A \exp\left(\frac{-eV_{bi}}{k_B T}\right)$$

Bias voltage, $V \neq 0$

$$eV_{bi} = k_B T \ln\left(\frac{N_D N_A}{n_i^2}\right) = k_B T \ln\left(\frac{N_D}{n_{p0}}\right) = k_B T \ln\left(\frac{N_A}{p_{n0}}\right)$$

$$n_{p0} p_{p0} = n_{n0} p_{n0} = n_i^2$$



$V = 0$

$$n_{p0} = N_D \exp\left(\frac{-eV_{bi}}{k_B T}\right)$$

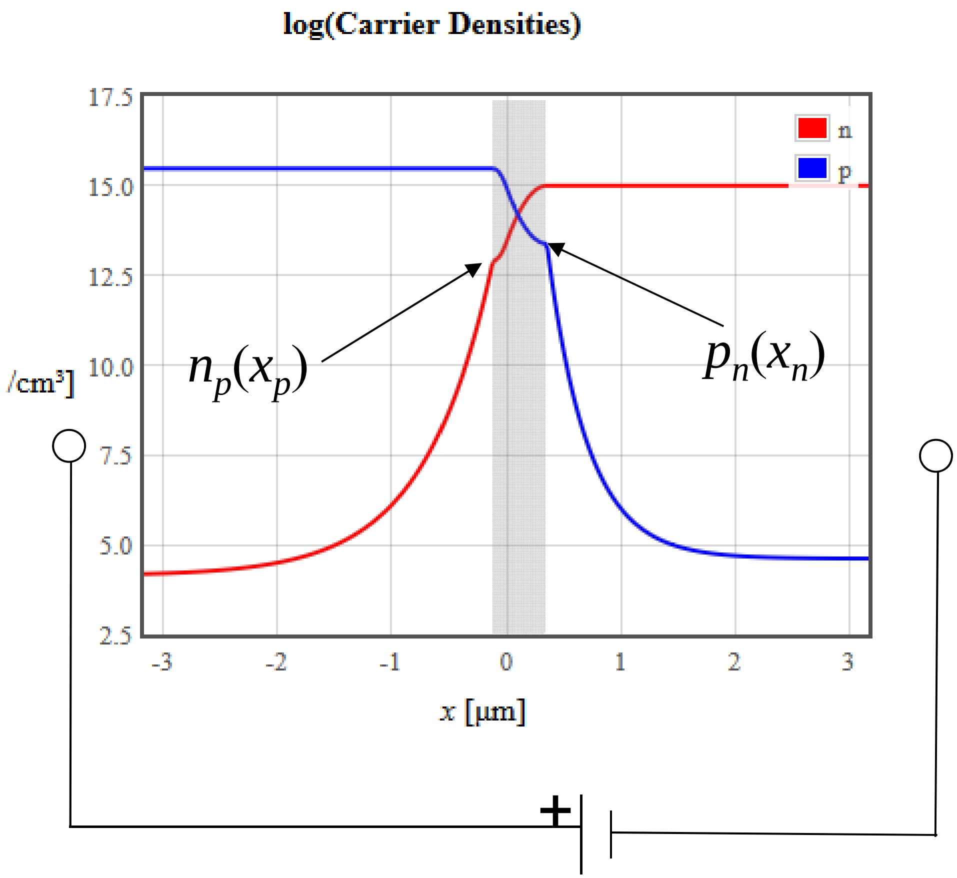
$$p_{n0} = N_A \exp\left(\frac{-eV_{bi}}{k_B T}\right)$$

$V \neq 0$

$$n_p(x_p) = N_D \exp\left(\frac{-e(V_{bi} - V)}{k_B T}\right)$$

$$p_n(x_n) = N_A \exp\left(\frac{-e(V_{bi} - V)}{k_B T}\right)$$

Forward bias, V > 0



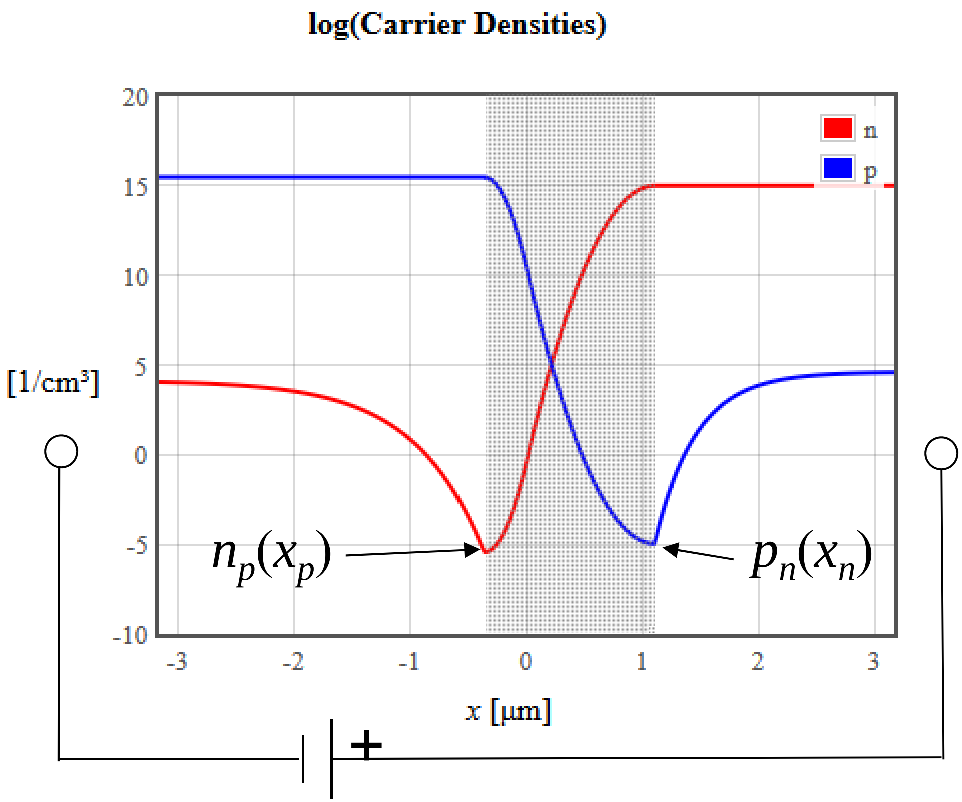
Electrons and holes are driven towards the junction.
The depletion region becomes narrower

$$n_p(x_p) = N_D \exp\left(\frac{-e(V_{bi} - V)}{k_B T}\right)$$

$$p_n(x_n) = N_A \exp\left(\frac{-e(V_{bi} - V)}{k_B T}\right)$$

Minority electrons are injected into the p-region
Minority holes are injected into the n-region

Reverse bias, V < 0



Electrons and holes are driven away from the junction.
The depletion region becomes wider

$$n_p(x_p) = N_D \exp\left(\frac{-e(V_{bi} - V)}{k_B T}\right)$$

$$p_n(x_n) = N_A \exp\left(\frac{-e(V_{bi} - V)}{k_B T}\right)$$

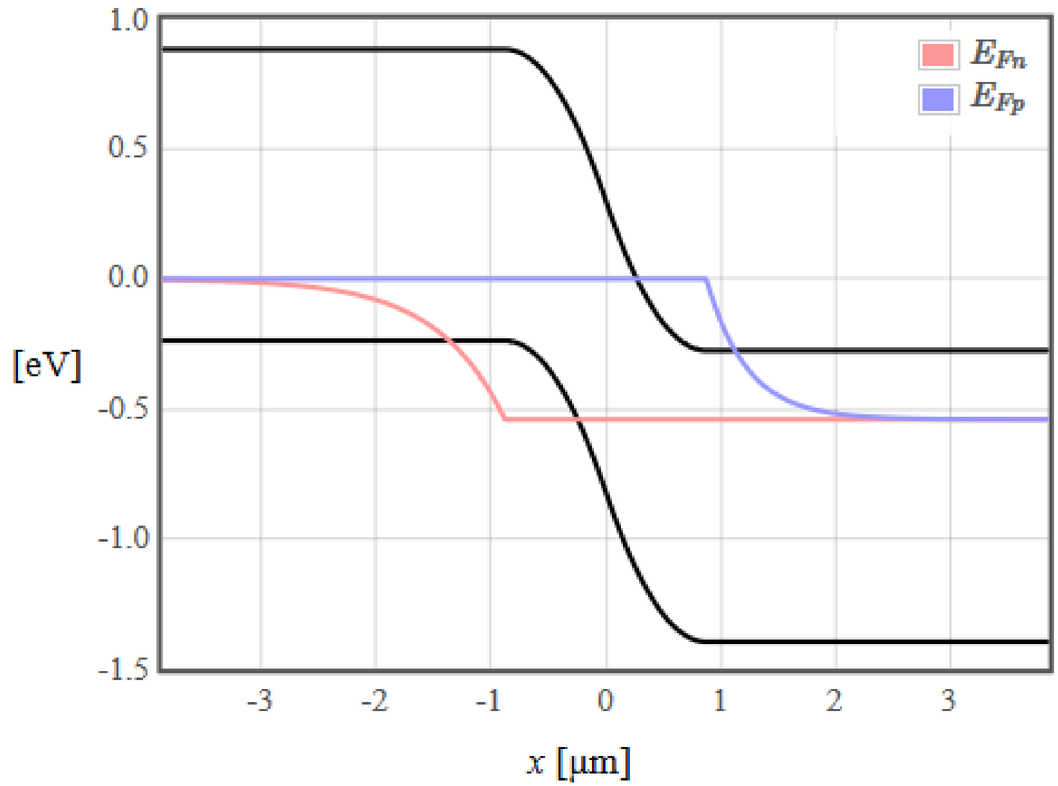
Minority electrons are extracted from the p-region by the electric field
Minority holes are extracted from the n-region by the electric field

Quasi Fermi level

When the charge carriers are not in equilibrium the Fermi energy can be different for electrons and holes.

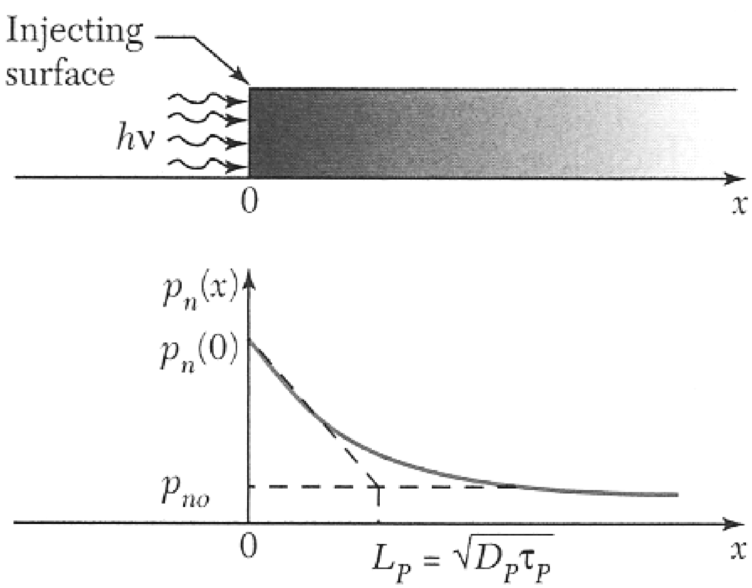
$$n = N_c \exp\left(\frac{E_{Fn} - E_c}{k_B T}\right)$$

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



Review of Diffusion

n-type



$$D_p \frac{\partial^2 p_n}{\partial x^2} = \frac{p_n - p_{n0}}{\tau_p}$$

recombination time

$$p_n(x) = p_{n0} + \left(p_n(0) - p_{n0}\right)\exp\left(\frac{-x}{L_p}\right)$$

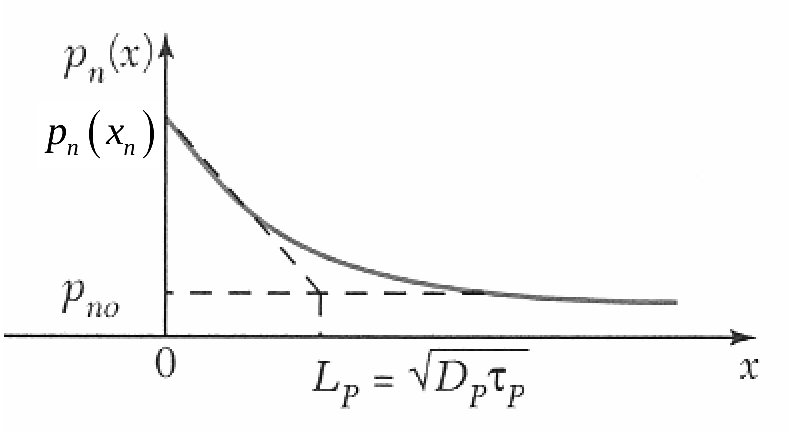
$$L_p = \sqrt{D_p \tau_p}$$

diffusion length

Injection only occurs at the surface. There the minority carrier density is $p_n(0)$.

Diffusion current

n-type



$$p_n(x) = p_{n0} + \left(p_n(x_n) - p_{n0}\right)\exp\left(\frac{-x}{L_p}\right)$$

$$J_{diff,p} = -eD_p \frac{dp}{dx}$$

$$J_{diff,p} = -eD_p \frac{dp}{dx} = \left(p_n(x_n) - p_{n0}\right)\frac{eD_p}{L_p}\exp\left(\frac{-x}{L_p}\right)$$

At the edge of the depletion region:

$$J_{diff,p} = -eD_p \frac{dp}{dx} = \left(p_n(x_n) - p_{n0}\right)\frac{eD_p}{L_p}$$

Diffusion current

$$J_{diff,p} = \left(p_n(x_n) - p_{n0} \right) \frac{eD_p}{L_p}$$

$$p_n(x_n) = p_{p0} \exp\left(-\frac{e(V_{bi} - V)}{k_B T} \right)$$

$$J_{diff,p} = \left(p_{p0} \exp\left(-\frac{e(V_{bi} - V)}{k_B T} \right) - p_{n0} \right) \frac{eD_p}{L_p}$$

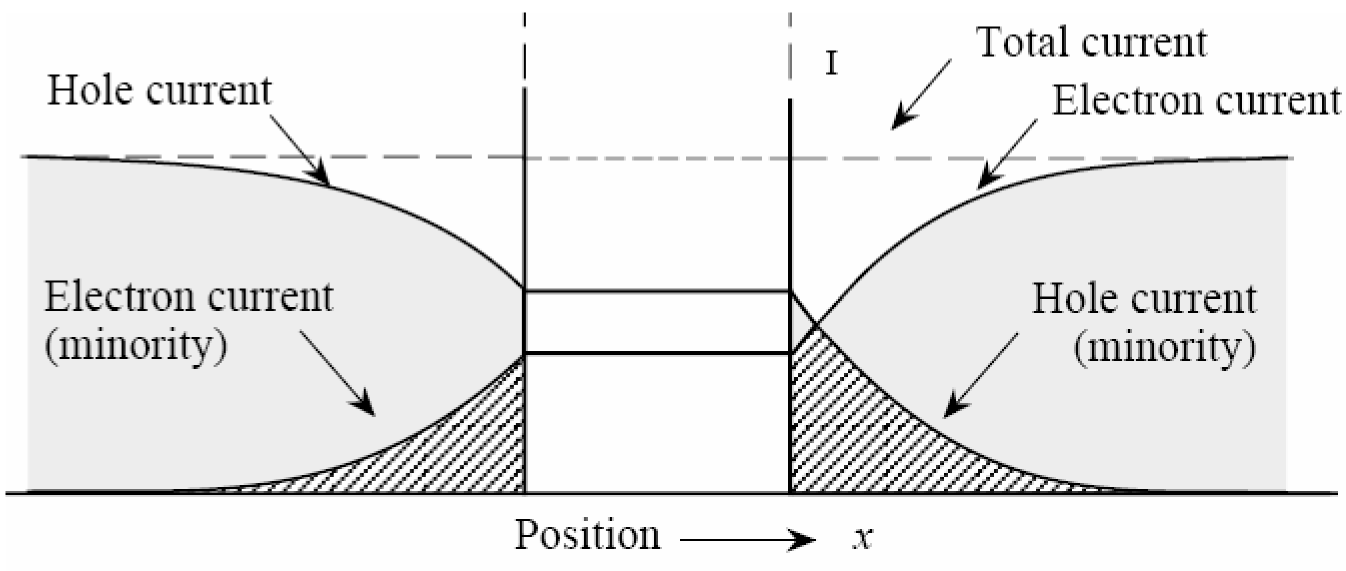
$$p_{p0} = p_{n0} \exp\left(\frac{eV_{bi}}{k_B T} \right)$$

$$J_{diff,p} = p_{n0} \frac{eD_p}{L_p} \left(\exp\left(\frac{eV}{k_B T} \right) - 1 \right)$$

Diffusion current

$$J_{diff,p} = \frac{p_{n0} e D_p}{L_p}\left(\exp\left(\frac{eV}{k_B T}\right) - 1\right)$$

$$J_{diff,n} = \frac{n_{p0} e D_n}{L_n}\left(\exp\left(\frac{eV}{k_B T}\right) - 1\right)$$

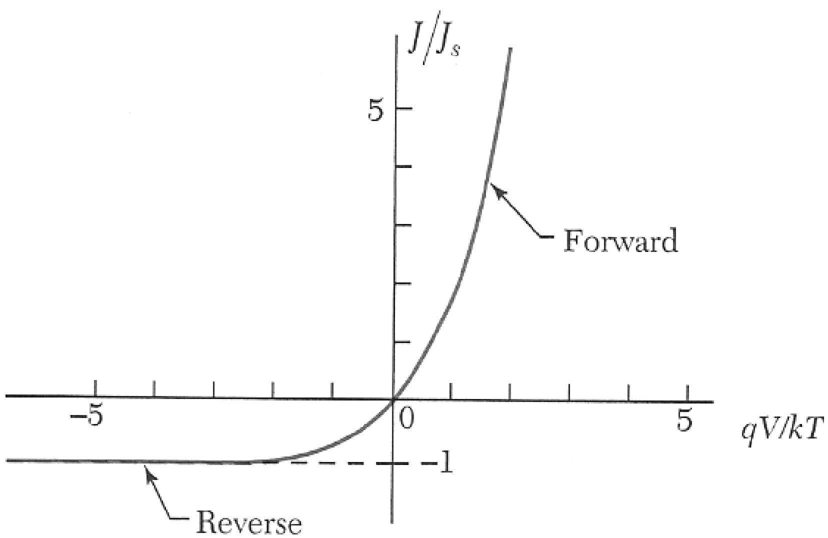


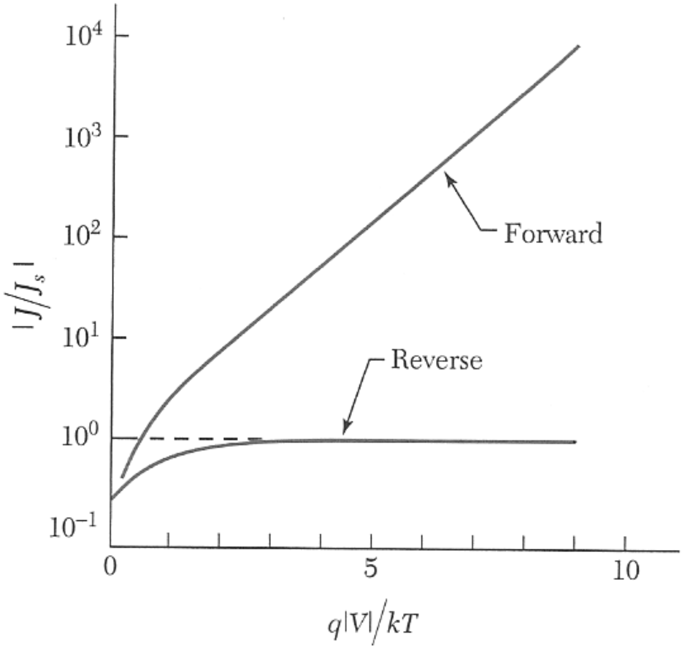
Diode current

$$I = eA\left(\frac{p_{n0}D_p}{L_p}+\frac{n_{p0}D_n}{L_n}\right)\left(\exp\left(\frac{eV}{k_BT}\right)-1\right) = I_s\left(\exp\left(\frac{eV}{k_BT}\right)-1\right)$$

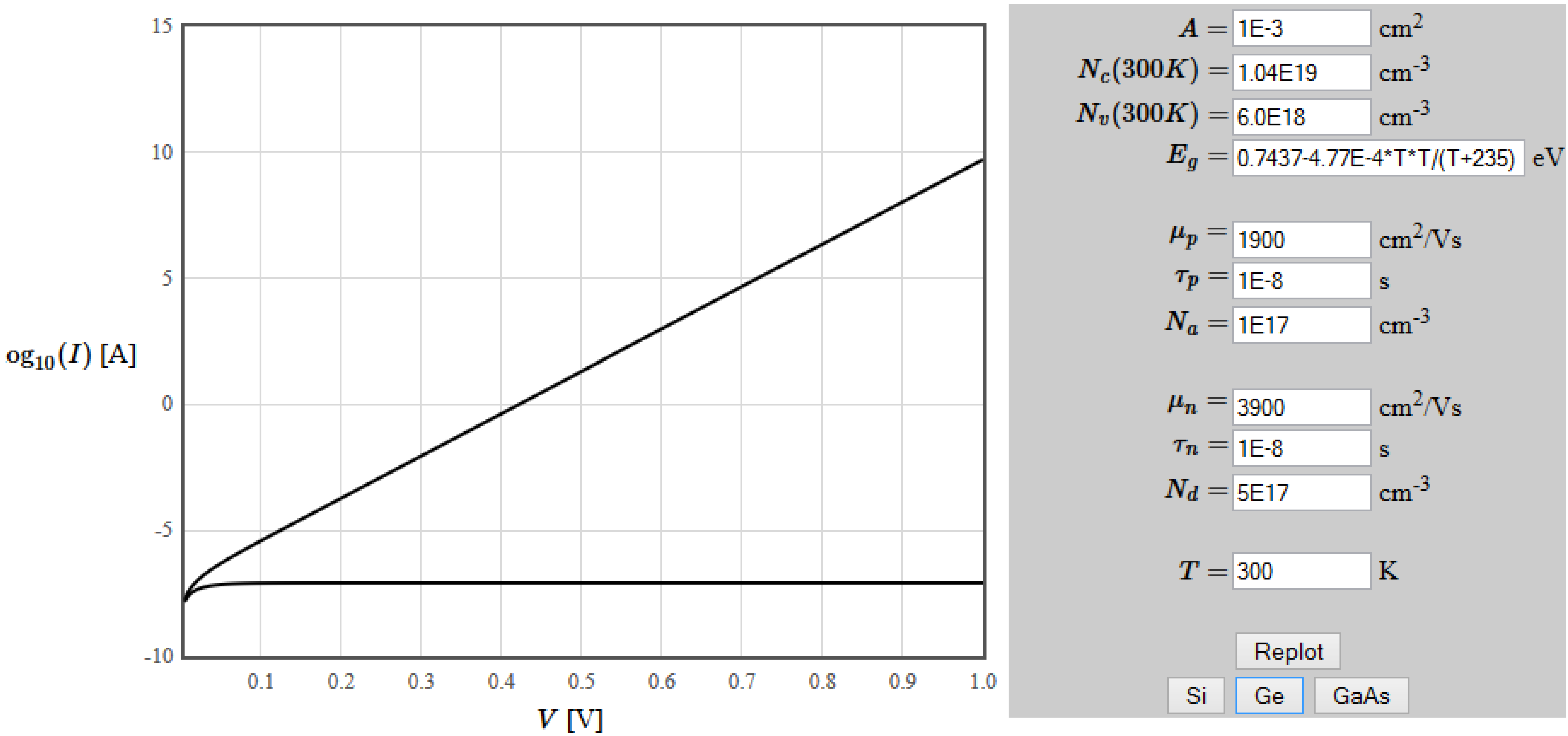
Area

Saturation current





Diode I-V charateristics



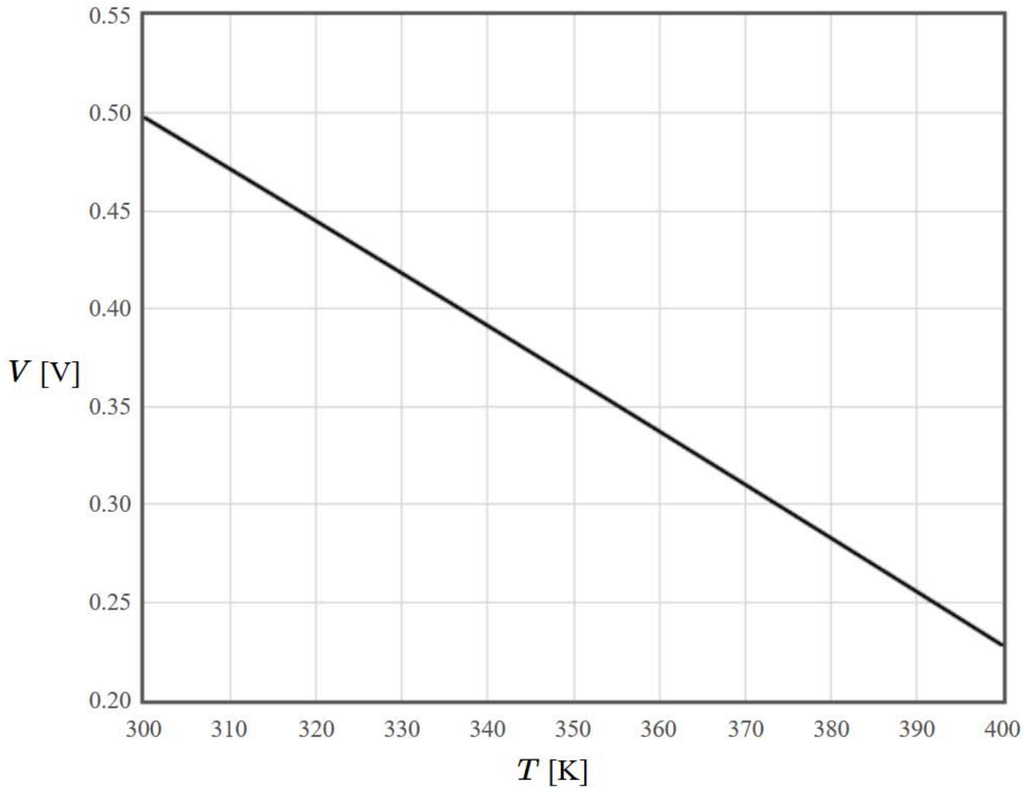
http://lamp.tu-graz.ac.at/~hadley/psd/L6/pnIV.php

Thermometer

$$I_S = Aen_i^2\left(\frac{D_p}{L_pN_d}+\frac{D_n}{L_nN_a}\right)$$

$$n_i = \sqrt{N_c\left(\frac{T}{300}\right)^{3/2}N_v\left(\frac{T}{300}\right)^{3/2}}\exp\left(\frac{-E_g}{2k_BT}\right)$$

$$D_n = \frac{\mu_n k_B T}{e}$$



$A =$ 1E-3 cm^2
$N_c(300K) =$ 2.78E19 cm^{-3}
$N_v(300K) =$ 9.84E18 cm^{-3}
$E_g =$ 1.166-4.73E-4*T*T/(T+636) eV

$\mu_p =$ 480 cm^2/Vs
$\tau_p =$ 1E-8 s
$N_a =$ 1E17 cm^{-3}

$\mu_n =$ 1350 cm^2/Vs
$\tau_n =$ 1E-8 s
$N_d =$ 5E17 cm^{-3}

$T_{start} =$ 300 K
$T_{stop} =$ 400 K
$I =$ 1E-6 A

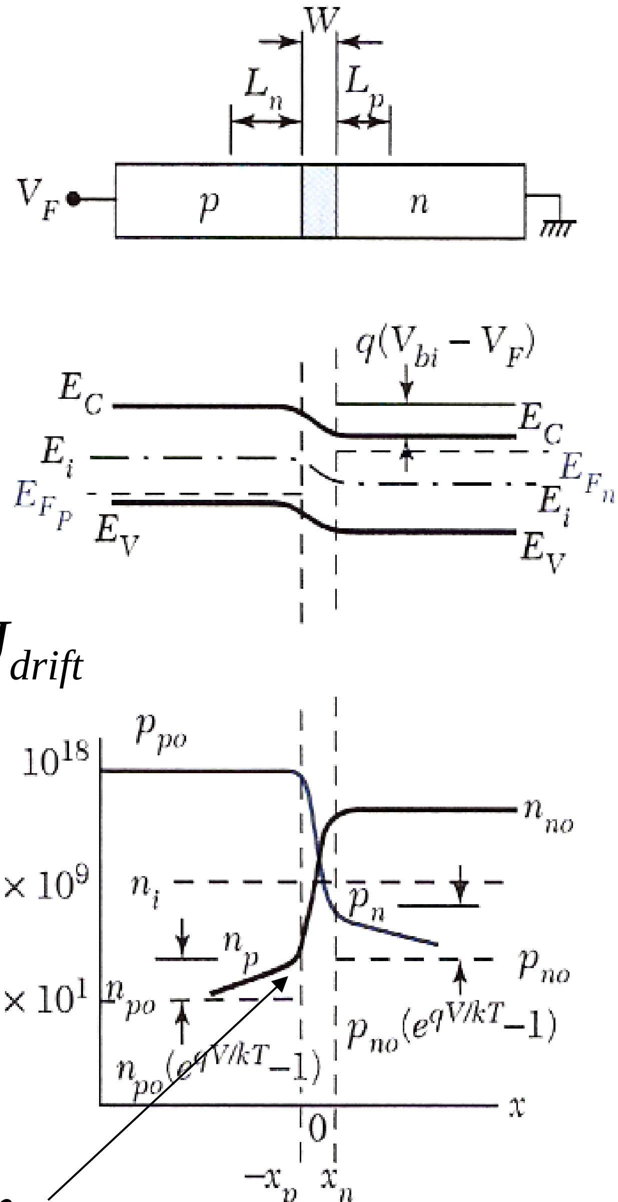
Replot
Si Ge GaAs

Forward

Reverse

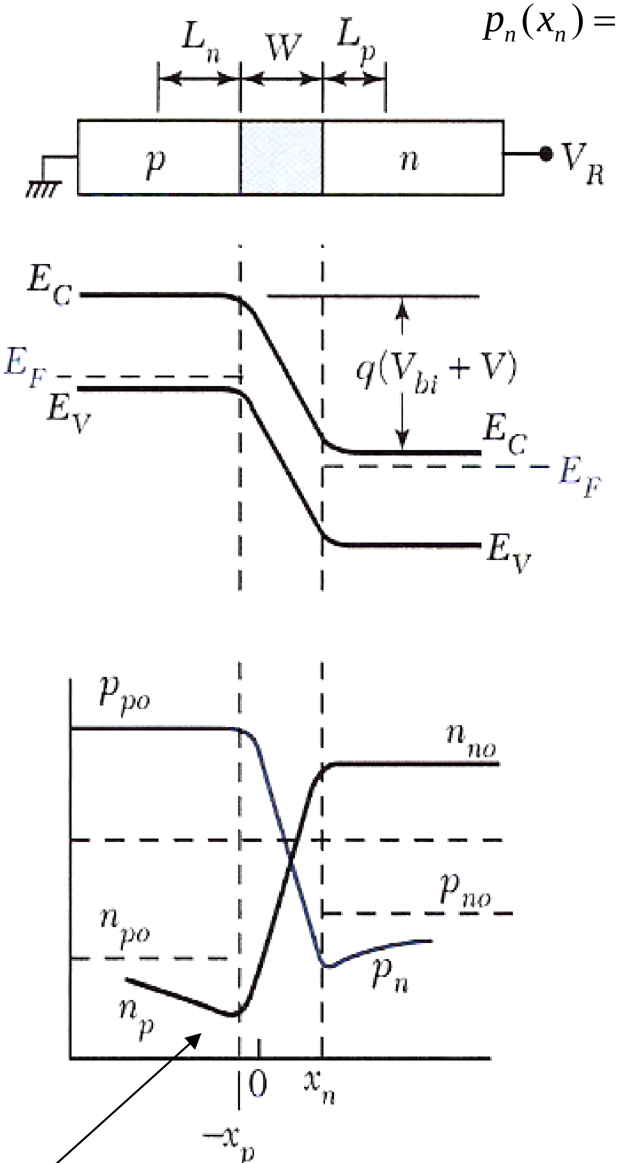
$$n_p(x_p) = N_D \exp\left(\frac{-e(V_{bi} - V)}{k_B T}\right)$$

$$p_n(x_n) = N_A \exp\left(\frac{-e(V_{bi} - V)}{k_B T}\right)$$



$J_{diff} > J_{drift}$

Injection

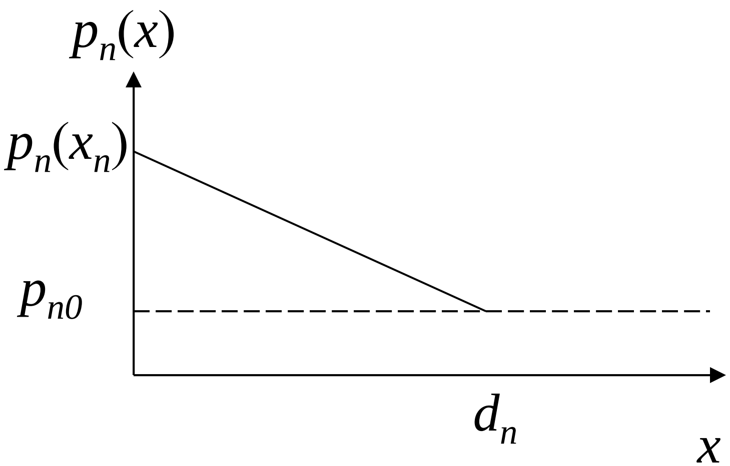


$J_{diff} < J_{drift}$

Extraction

Short diode

n-type



$d_n << L_p$

Metal contact is much closer to the depletion region than the diffusion length

$$J_{diff,p} = -eD_p \frac{dp}{dx}$$

$$J_{diff,p} = -eD_p \frac{dp}{dx} = \frac{eD_p}{d_n}\left(p_n(x_n) - p_{n0}\right)$$

Diffusion current

$$J_{diff,p} = \left(p_n(x_n) - p_{n0} \right) \frac{eD_p}{d_n}$$

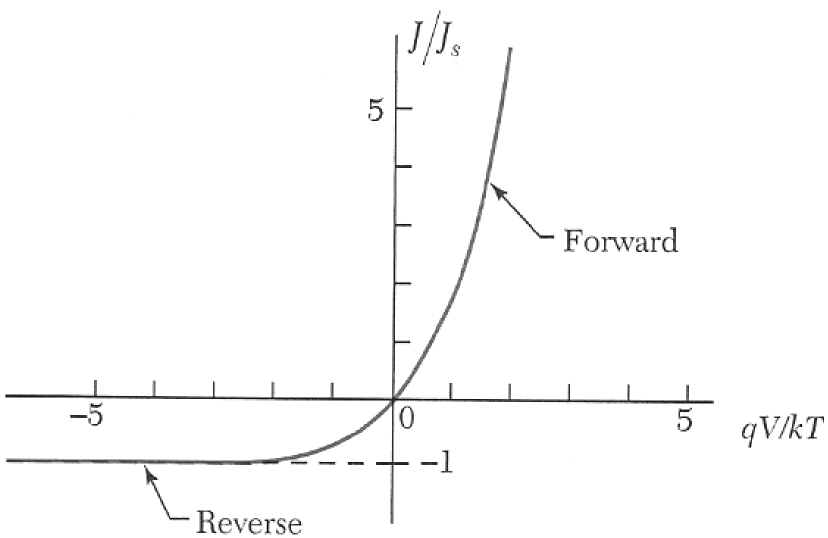
$$J_{diff,p} = \left(p_{n0} \exp\left(\frac{e(V)}{k_B T} \right) - p_{n0} \right) \frac{eD_p}{d_n}$$

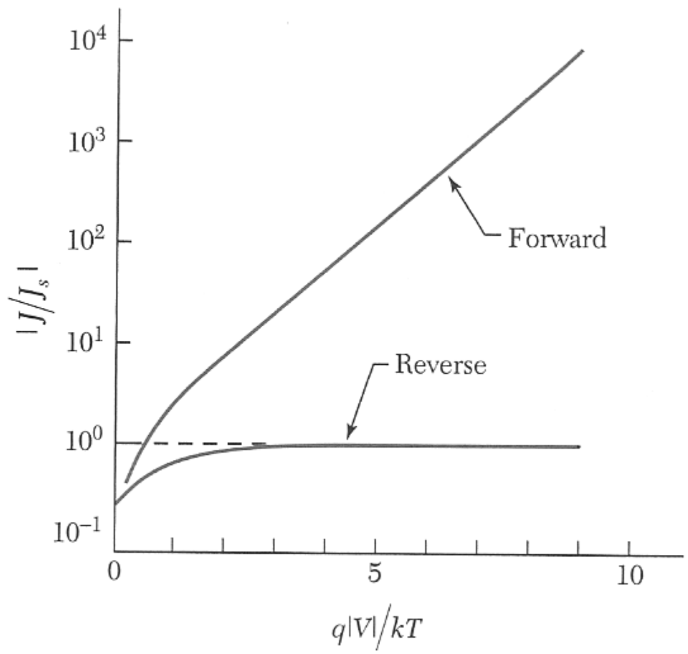
$$J_{diff,p} = \frac{p_{n0} e D_p}{d_n} \left(\exp\left(\frac{eV}{k_B T} \right) - 1 \right)$$

Short diode current

$$I = eA\left(\frac{p_{n0}D_p}{d_n}+\frac{n_{p0}D_n}{d_p}\right)\left(\exp\left(\frac{eV}{k_BT}\right)-1\right) = I_s\left(\exp\left(\frac{eV}{k_BT}\right)-1\right)$$

Area



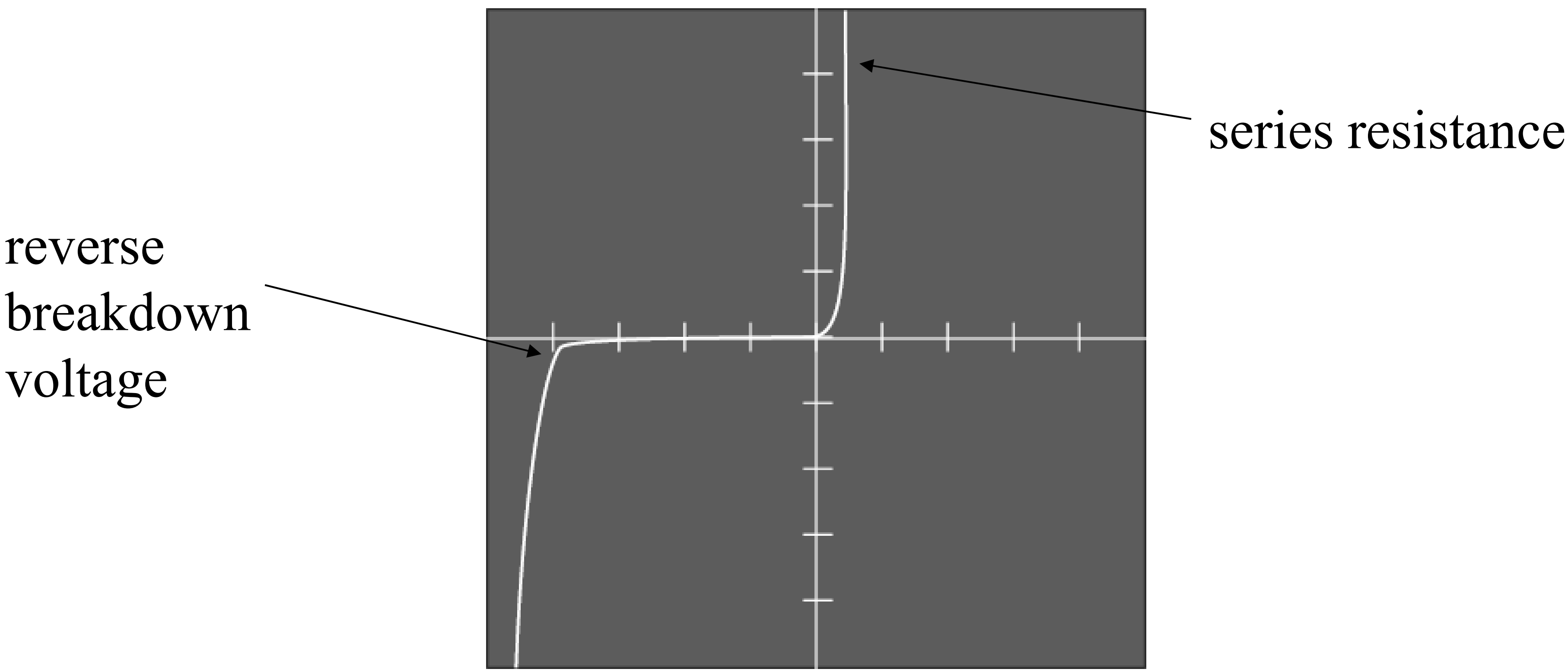


Real diodes

$$I = I_s\left(\exp\left(\frac{eV}{nk_BT}\right) - 1\right)$$

n = nonideality factor

$n = 1$ for an ideal diode



Real diodes

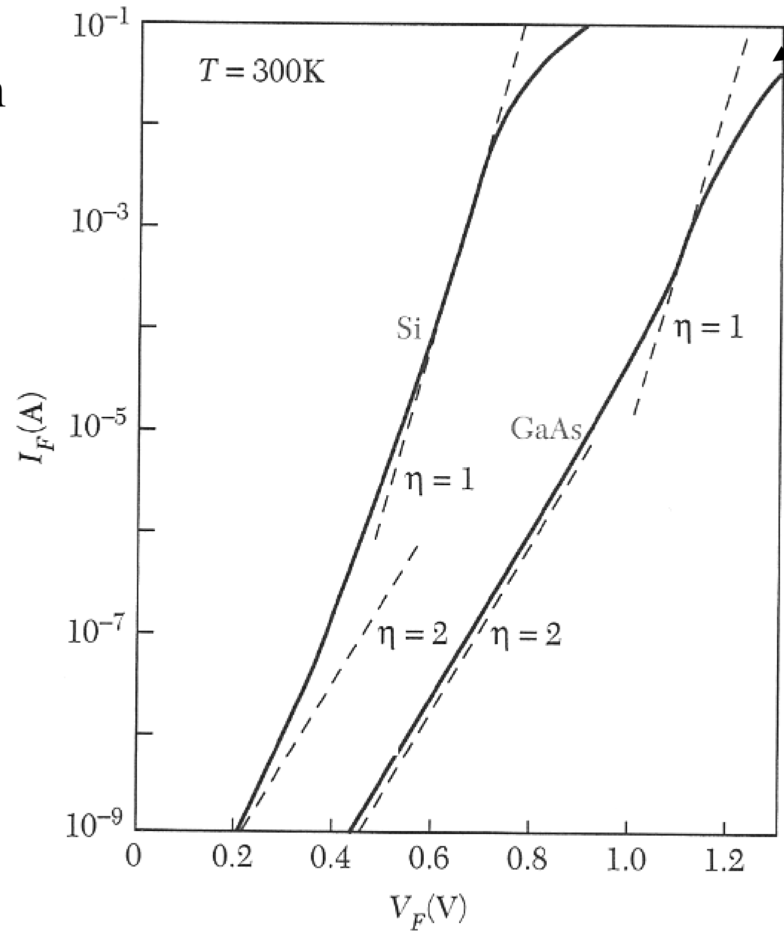
$$I = I_s \left(\exp\left(\frac{eV}{nk_BT} \right) - 1 \right)$$

There is constant generation/recombination of electron hole pairs.

In forward bias there is an extra current from recombination.

In reverse bias there is an extra current from generation.

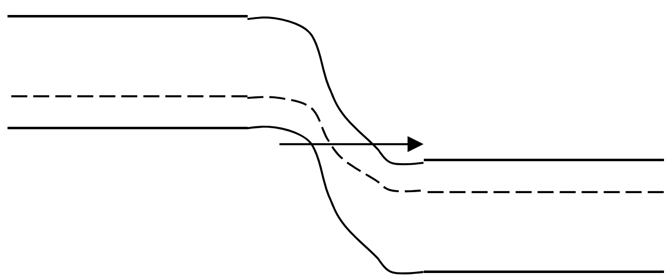
Low bias: recombination dominates, $n = 2$

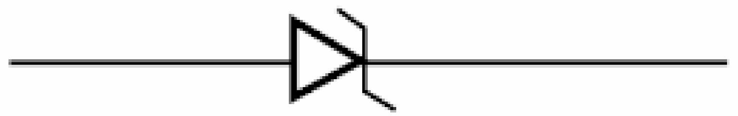


Very high bias: series resistance

High bias: ideal behavior, $n = 1$

Zener tunneling

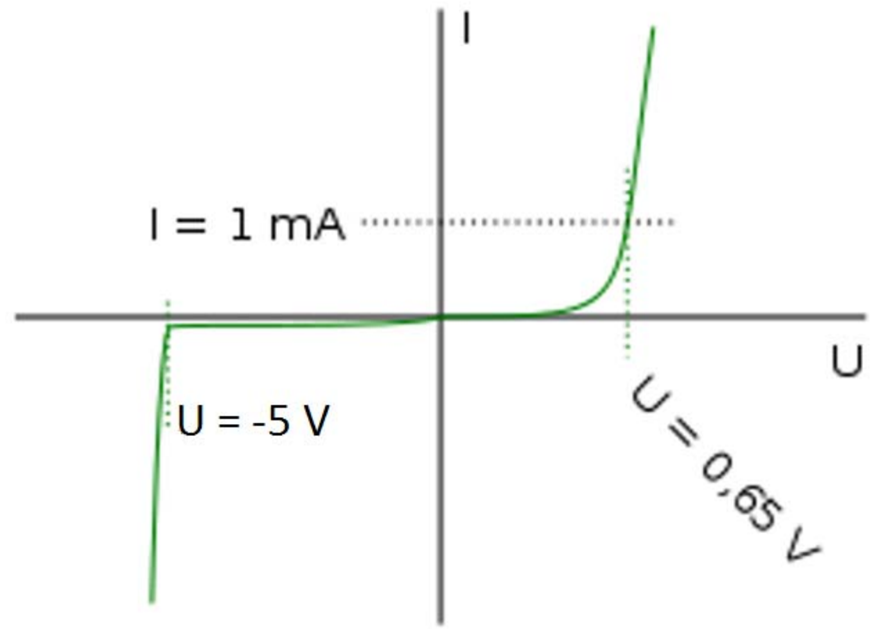




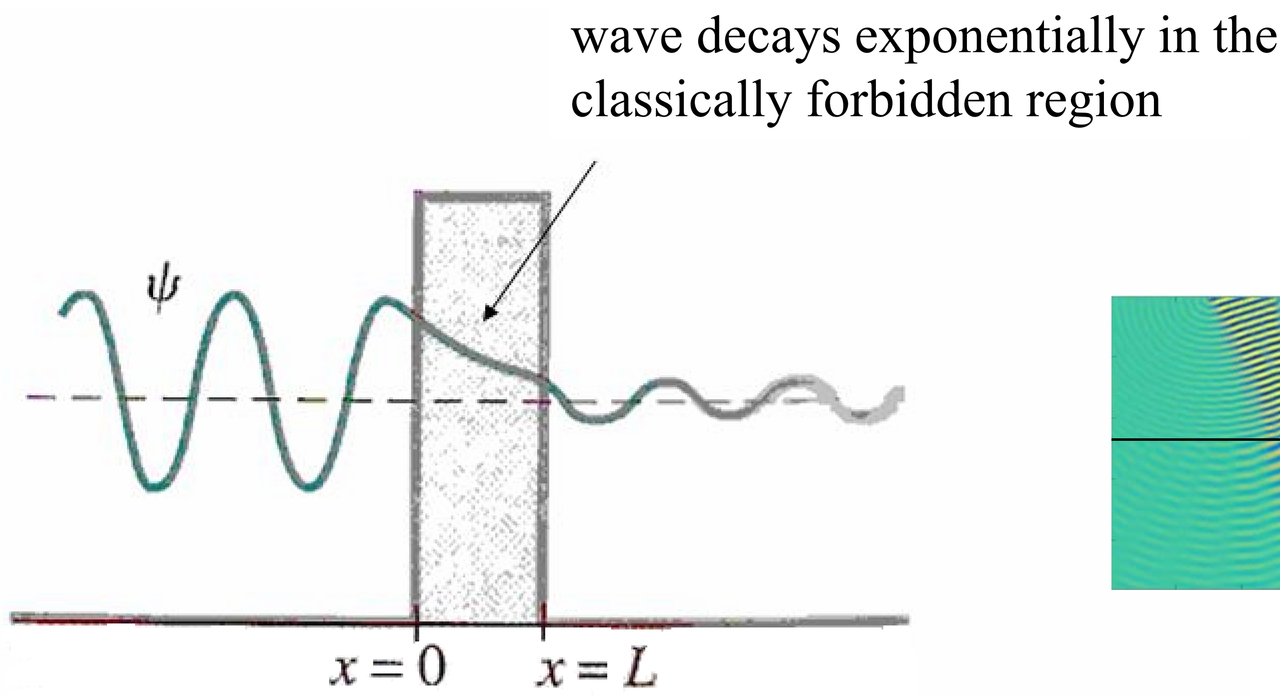
Electrons tunnel from valence band to conduction band

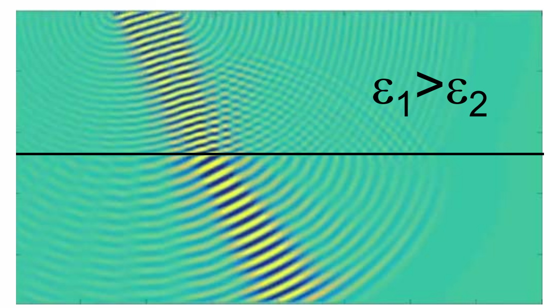
Occurs at high doping

$|V_{zener}| < 5.6$ V



Tunneling





Tunneling is a wave phenomena. Tunneling and total internal reflection are used in a beam splitter.

Zener tunneling

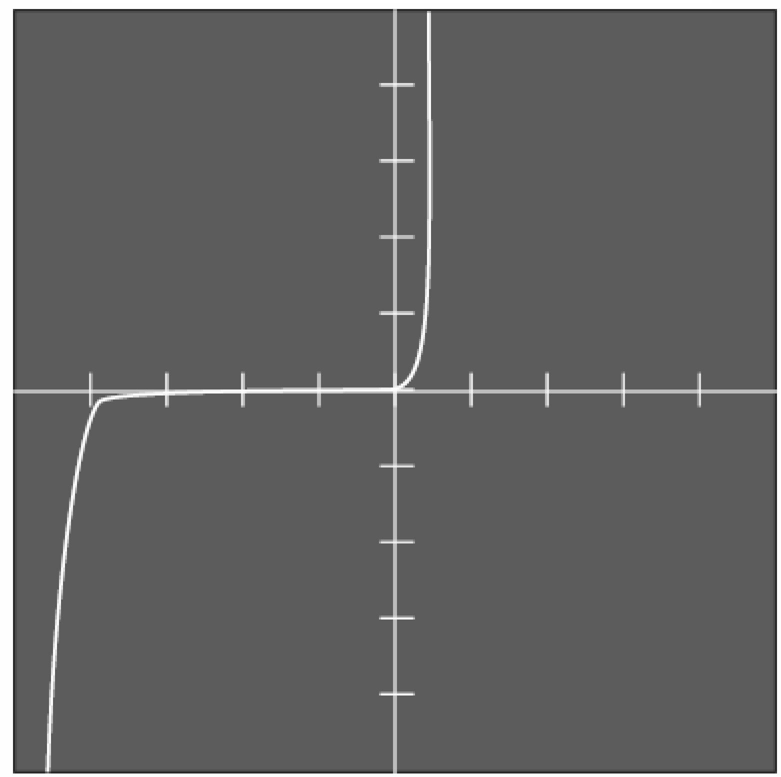
Breakdown voltage is typically much lower than the breakdown voltage of an avalanche diode and can be tuned by adjusting the width of the depletion layer.

Used to provide a reference voltage.

Avalanche breakdown

Impact ionization causes an avalanche of current

Occurs at low doping



Vertical: 5 mA/div
Horizontal: 5 V/div

Avalanche breakdown