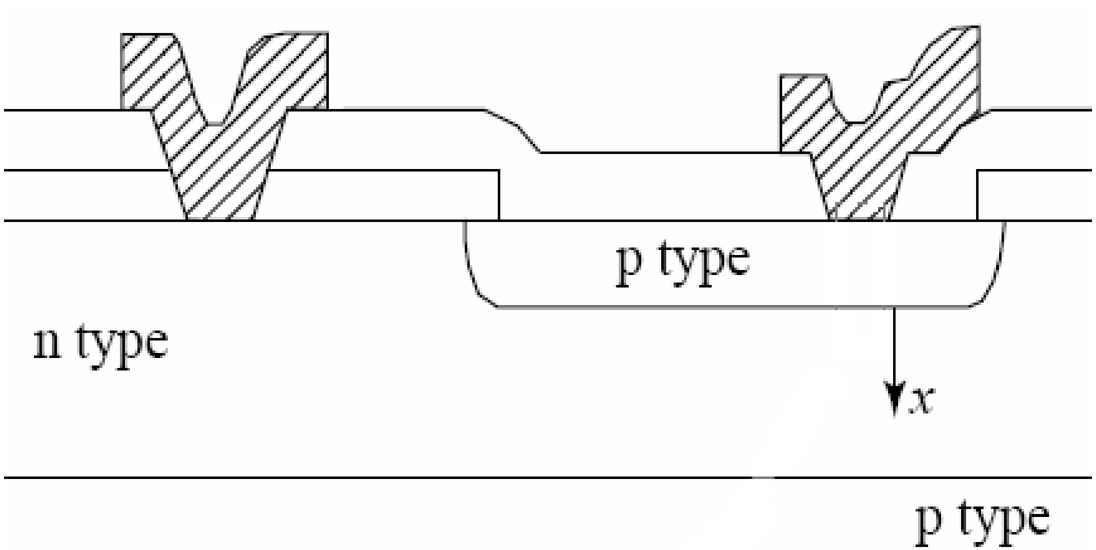
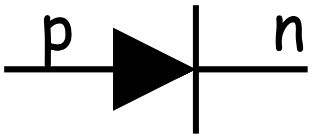
pn junctions

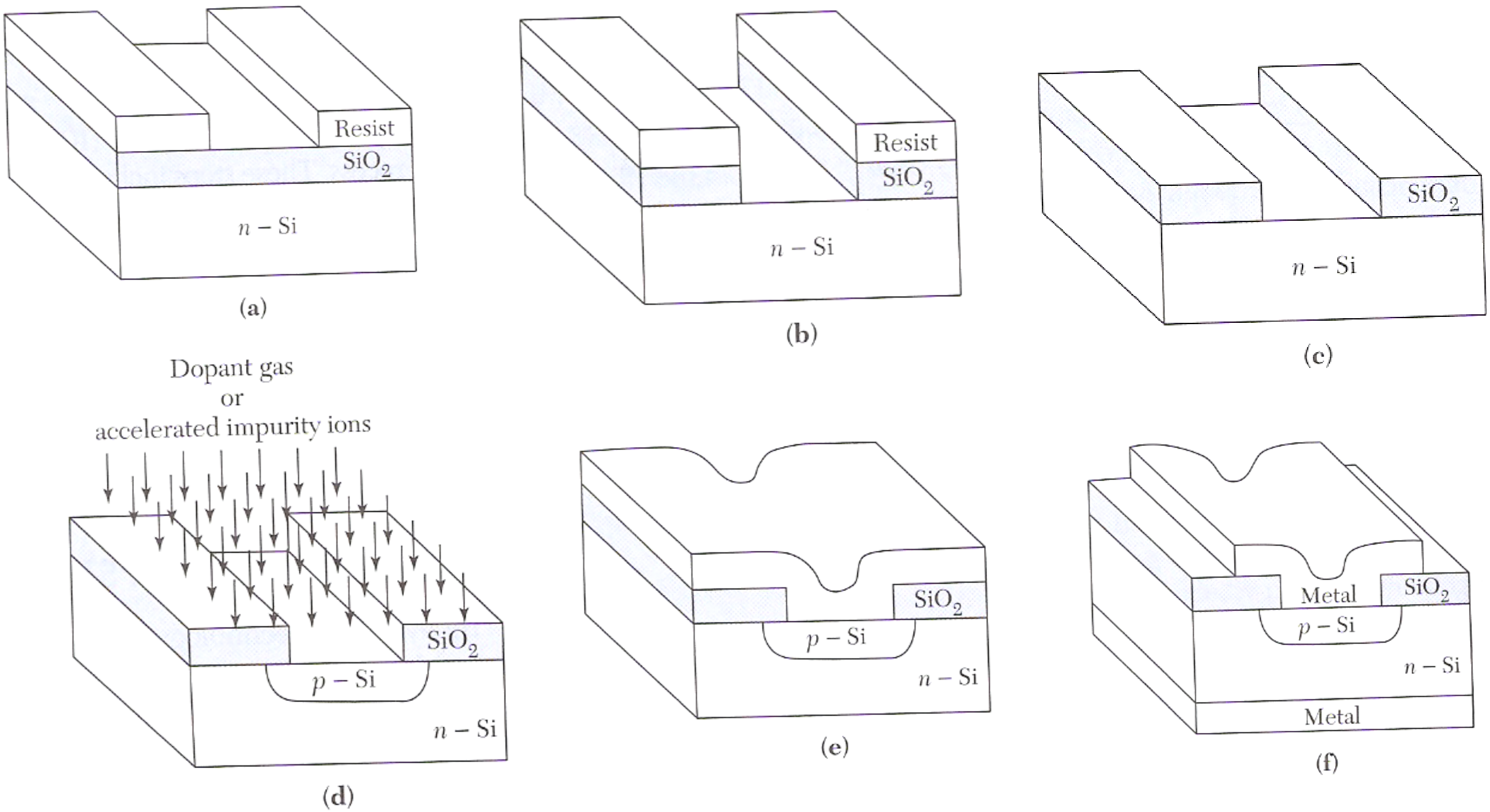
pn junctions are found in:

- diodes
- solar cells
- LEDs
- isolation
- JFETs
- bipolar transistors
- MOSFETs
- solid state lasers

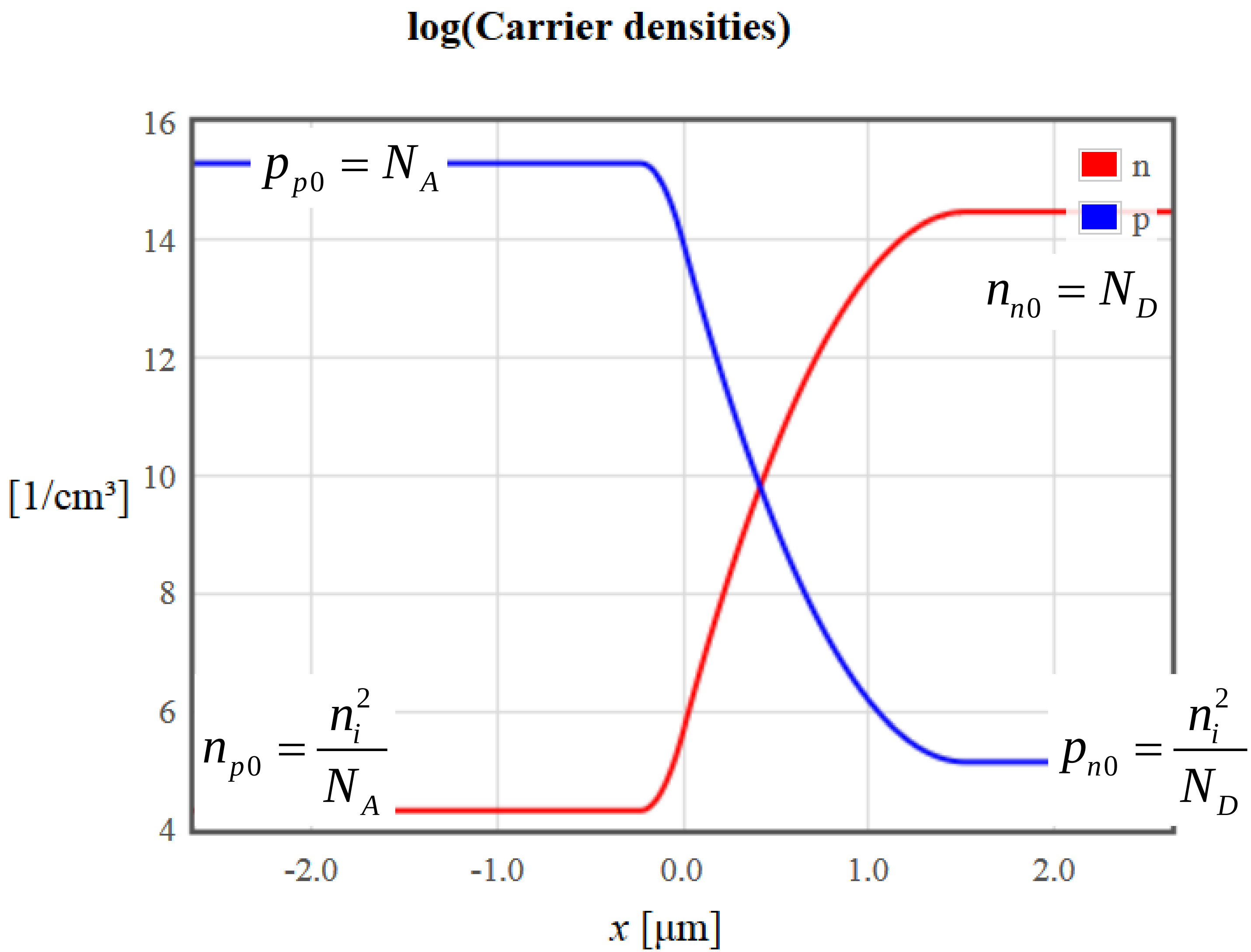




diode fabrication



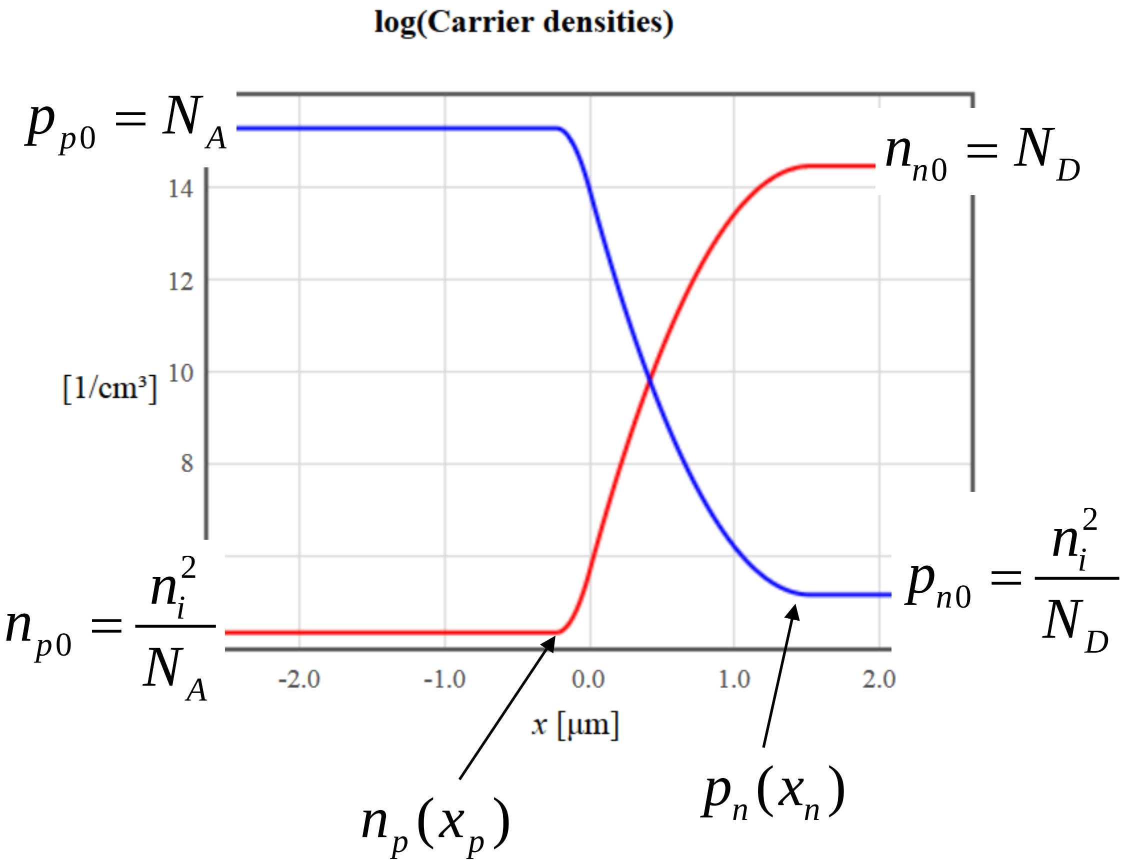
Equilibrium concentrations, V = 0



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

Bias voltage, $V = 0$

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



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

$V = 0$

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

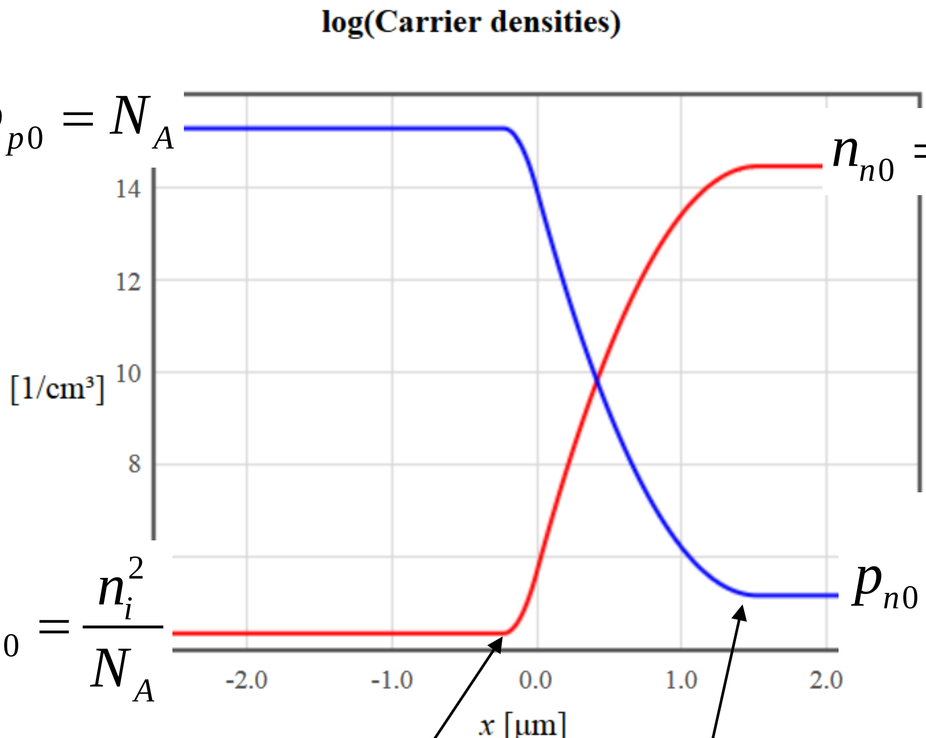
$$p_{n0} = N_A \exp\left(\frac{-eV_{bi}}{k_B T}\right)$$

Bias voltage, $V \neq 0$

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

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

$p_{p0} = N_A$



$n_{n0} = N_D$

$p_{n0} = \dfrac{n_i^2}{N_D}$

$n_{p0} = \dfrac{n_i^2}{N_A}$

$n_p(x_p)$ $\qquad$ $p_n(x_n)$

$V = 0$

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

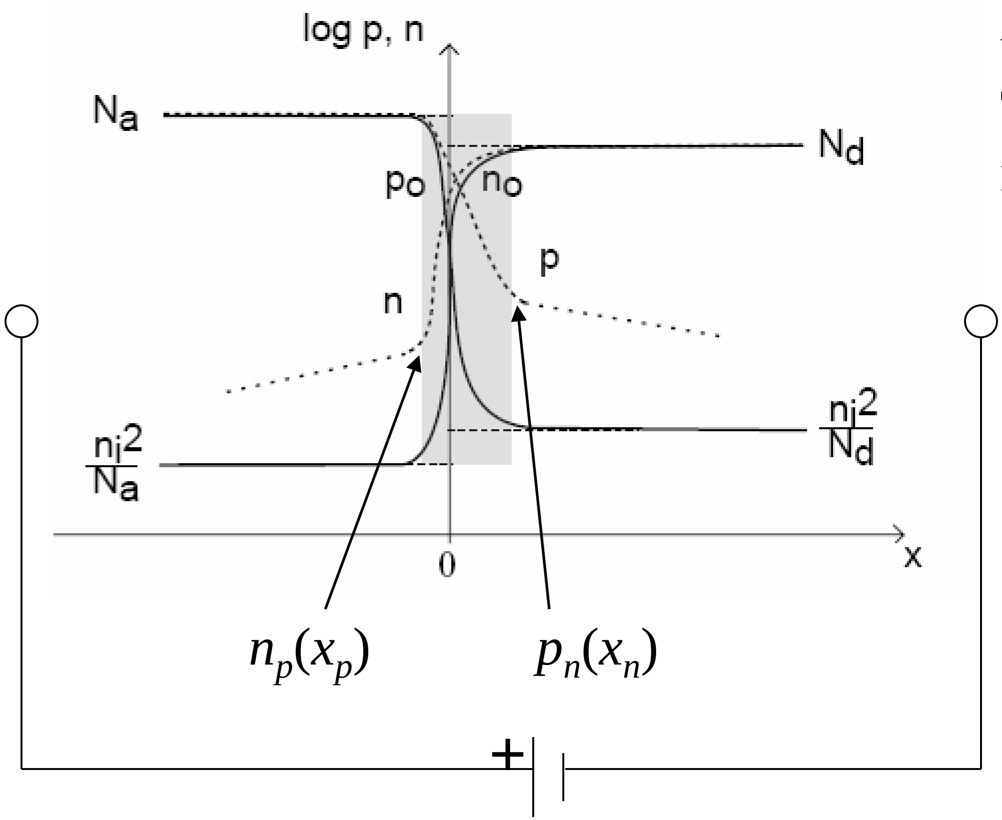
$$p_{n0} = N_A \exp\left(\frac{-eV_{bi}}{k_B T}\right)$$

$V \neq 0$

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

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

Forward bias, V > 0



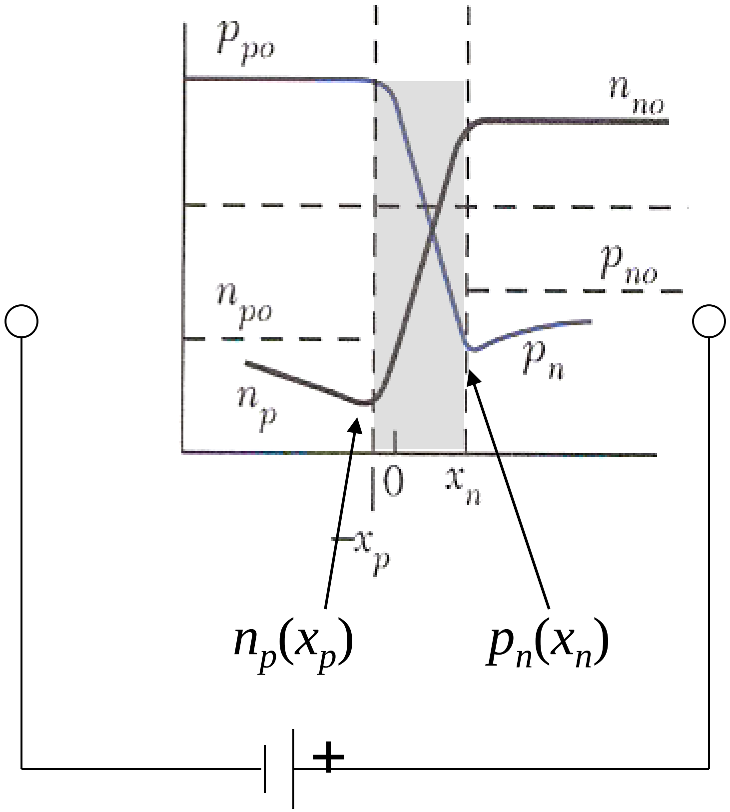
Electrons and holes are driven towards the junction.
The depletion region becomes narrower

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

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

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

Reverse bias, V < 0

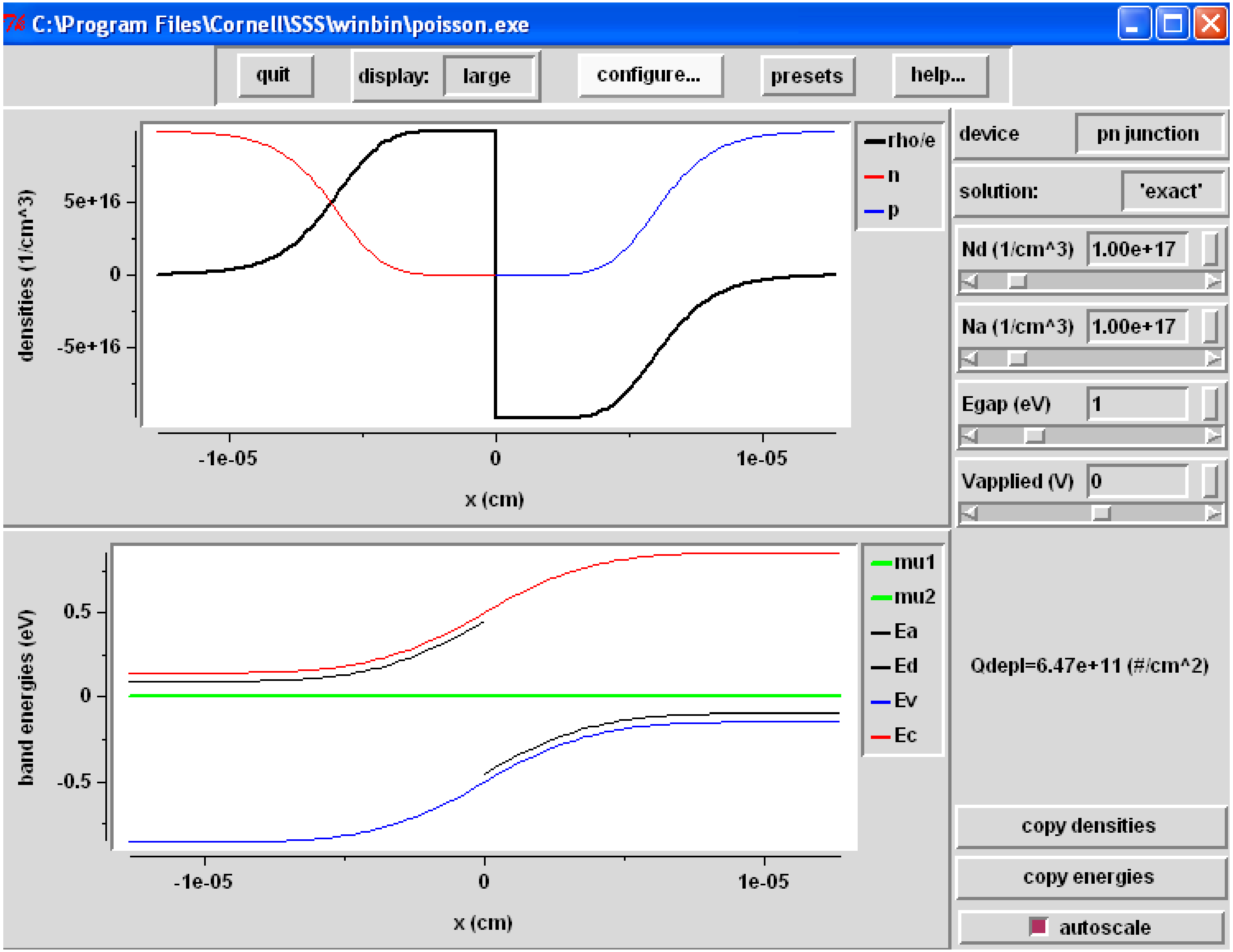


Electrons and holes are driven away from the junction.
The depletion region becomes wider

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

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

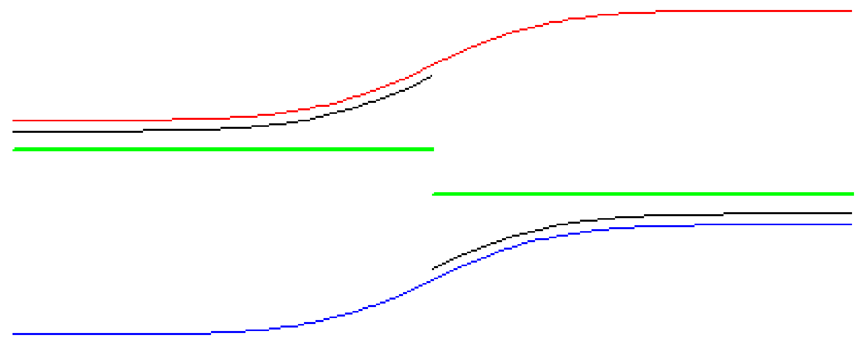
Minority electrons are extracted from the p-region by the electric field
Minority holes are extracted from the n-region by the electric field



C:\Program Files\Cornell\SSS\winbin\poisson.exe
quit
display: large
configure...
presets
help...
densities (1/cm^3)
5e+16
0
-5e+16
-1e-05
0
1e-05
x (cm)
rho/e
n
p
device
pn junction
solution:
'exact'
Nd (1/cm^3) 1.00e+17
Na (1/cm^3) 1.00e+17
Egap (eV) 1
Vapplied (V) 0
band energies (eV)
0.5
0
-0.5
-1e-05
0
1e-05
x (cm)
mu1
mu2
Ea
Ed
Ev
Ec
Qdepl=6.47e+11 (#/cm^2)
copy densities
copy energies
autoscale

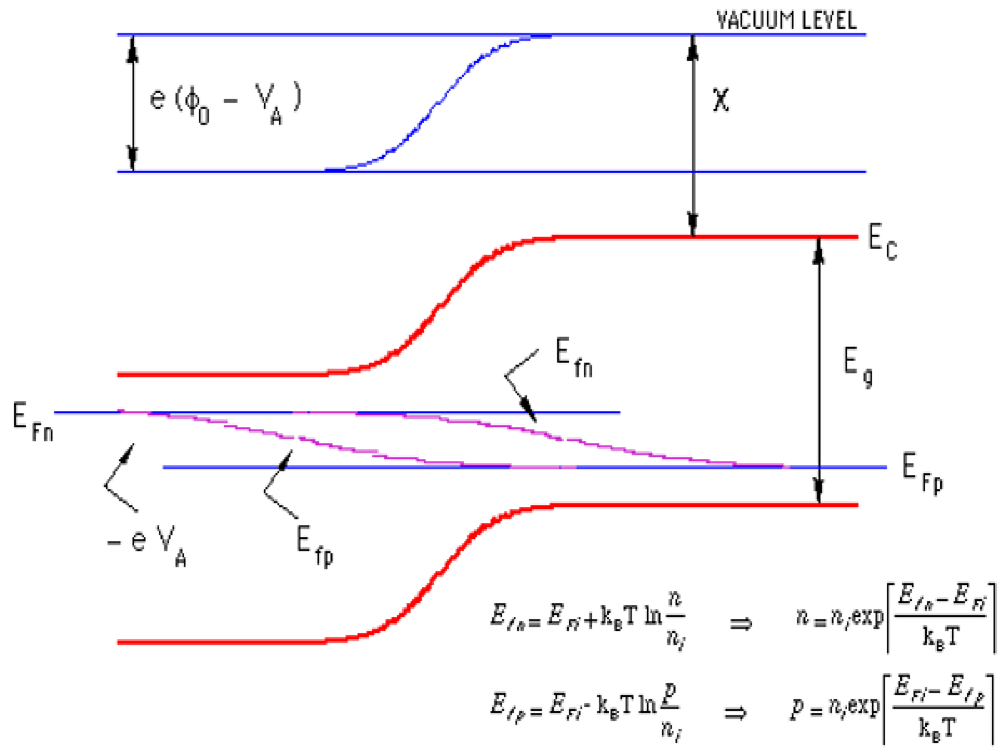
Quasi Fermi level

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



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

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



http://people.seas.harvard.edu/~jones/ap216/lectures/ls_2/ls2_u7/ls2_unit_7.html

Student Projects

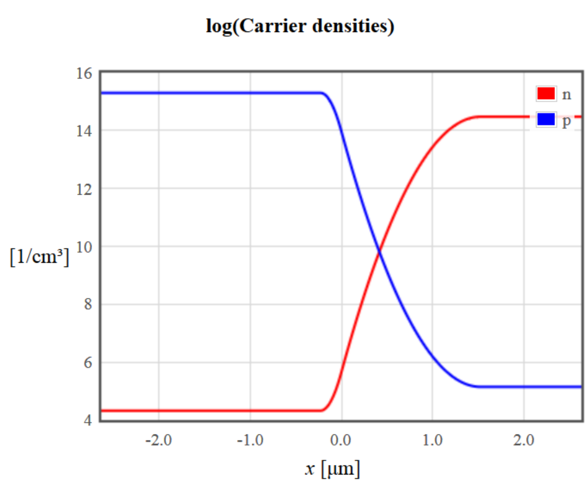
Write derivation of V_{bi} , $n_p(x_p)$, and $p_n(x_n)$ in mathjax

The electric field can be calculated by integrating Gauss's law for the positive and the negative charged regions,

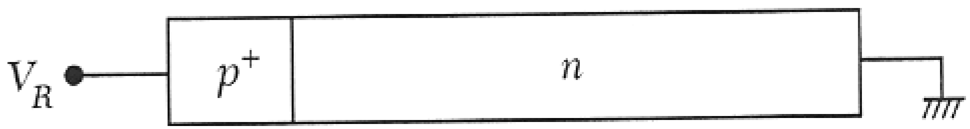
$$\frac{dE}{dx} = \frac{\rho}{\epsilon_r \epsilon_0}$$

$$E_p = \frac{-eN_A}{\epsilon_r \epsilon_0} \int dx = \frac{-eN_A}{\epsilon_r \epsilon_0} x + c_1 \qquad E_n = \frac{eN_D}{\epsilon_r \epsilon_0} \int dx = \frac{eN_D}{\epsilon_r \epsilon_0} x + c_2$$

Write program to plot n and p with a bias

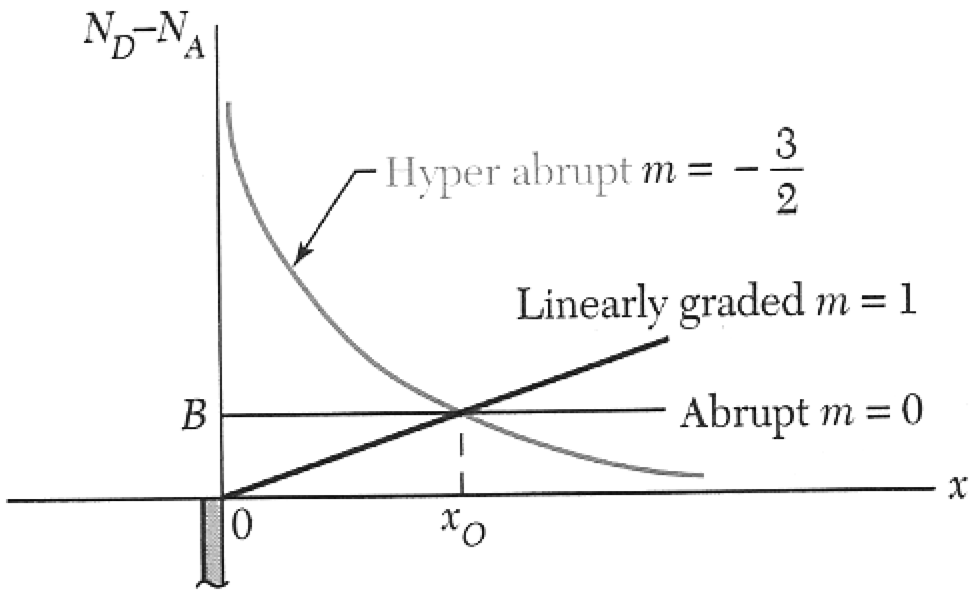


Varactor



$$C_j \propto \left(V_{bi} + V_R\right)^{-n}$$

abrupt: n = 1/2
linearly graded: n = 1/3



$$N_D - N_A \propto \left(x + x_o\right)^m$$

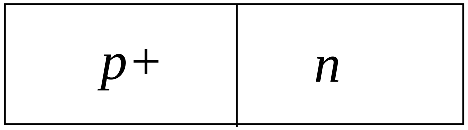
$n = 1/(m+2)$

Capacitance-voltage characteristics

specific capacitance $$C_j = \frac{\varepsilon}{W} \quad \text{F m}^{-2}$$

abrupt junction: $$W = \frac{\varepsilon}{C_j} = \sqrt{\frac{2\varepsilon\left(N_D + N_A\right)\left(V_{bi} - V\right)}{eN_D N_A}}$$

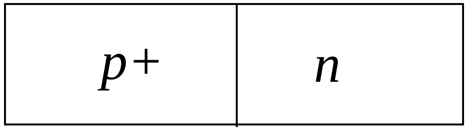
a one sided abrupt junction in reverse bias:



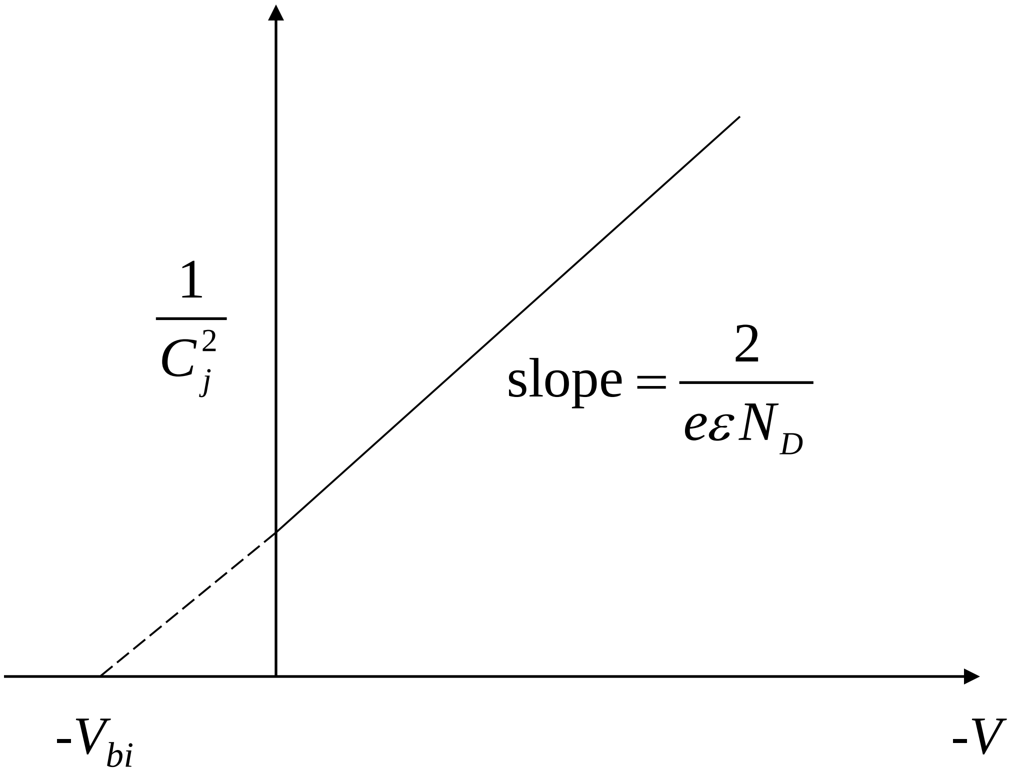
$$\frac{1}{C_j^2} = \frac{2\left(V_{bi} - V\right)}{e\varepsilon N_D}$$

Capacitance-voltage characteristics

a one sided abrupt junction in reverse bias:



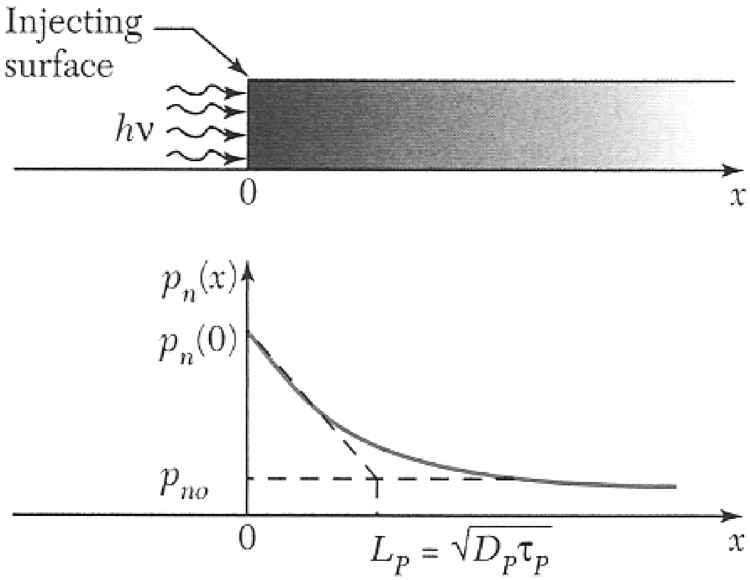
$$\frac{1}{C_j^2} = \frac{2\left(V_{bi} - V\right)}{e\varepsilon N_D}$$



slope gives impurity concentration and the intercept gives V_{bi}

Review of Diffusion

n-type



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

recombination time

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

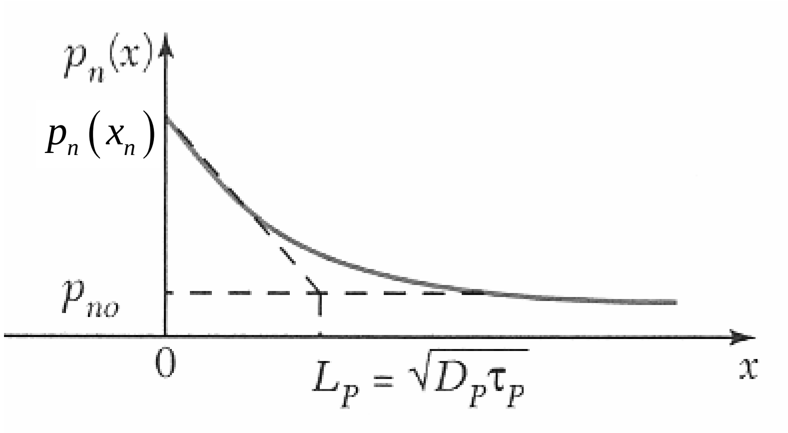
$$L_p = \sqrt{D_p \tau_p}$$

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

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

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

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

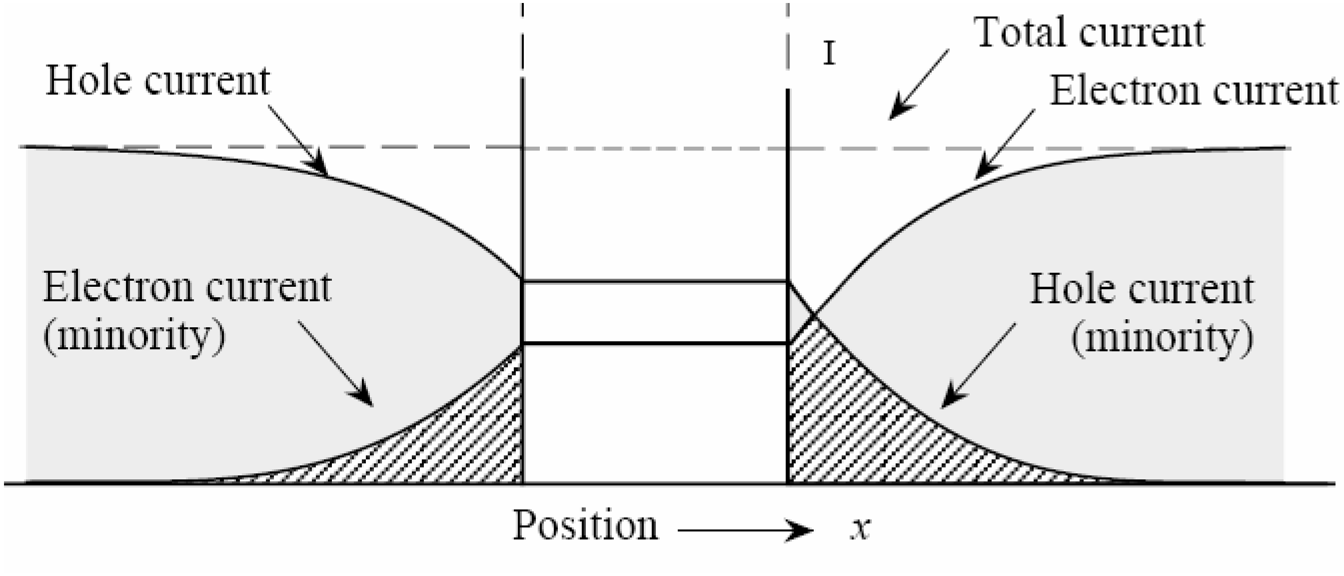
$$p_{p0} = p_{n0} \exp\left(\frac{eV_{bi}}{k_B T} \right)$$

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

Diffusion current

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

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

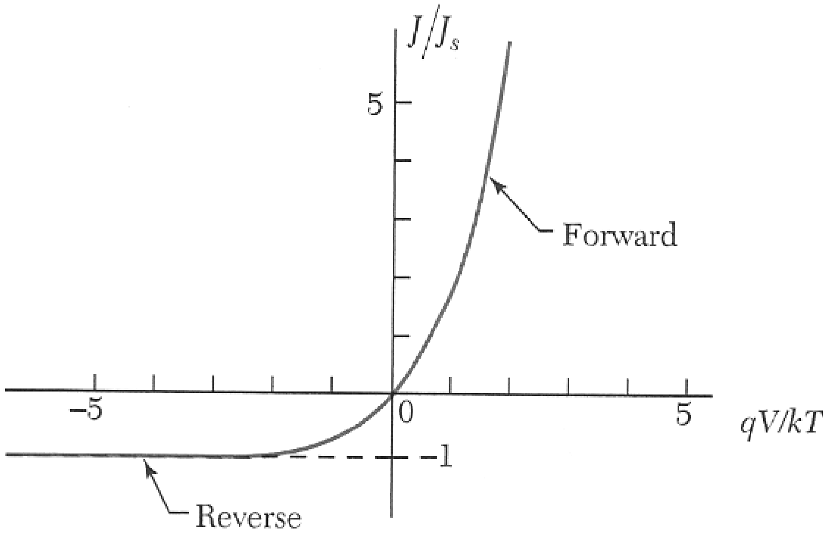


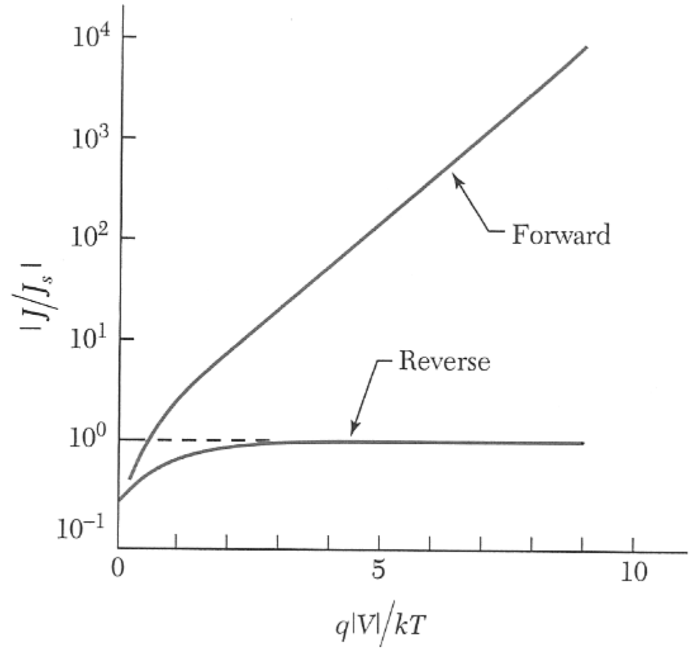
Diode current

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

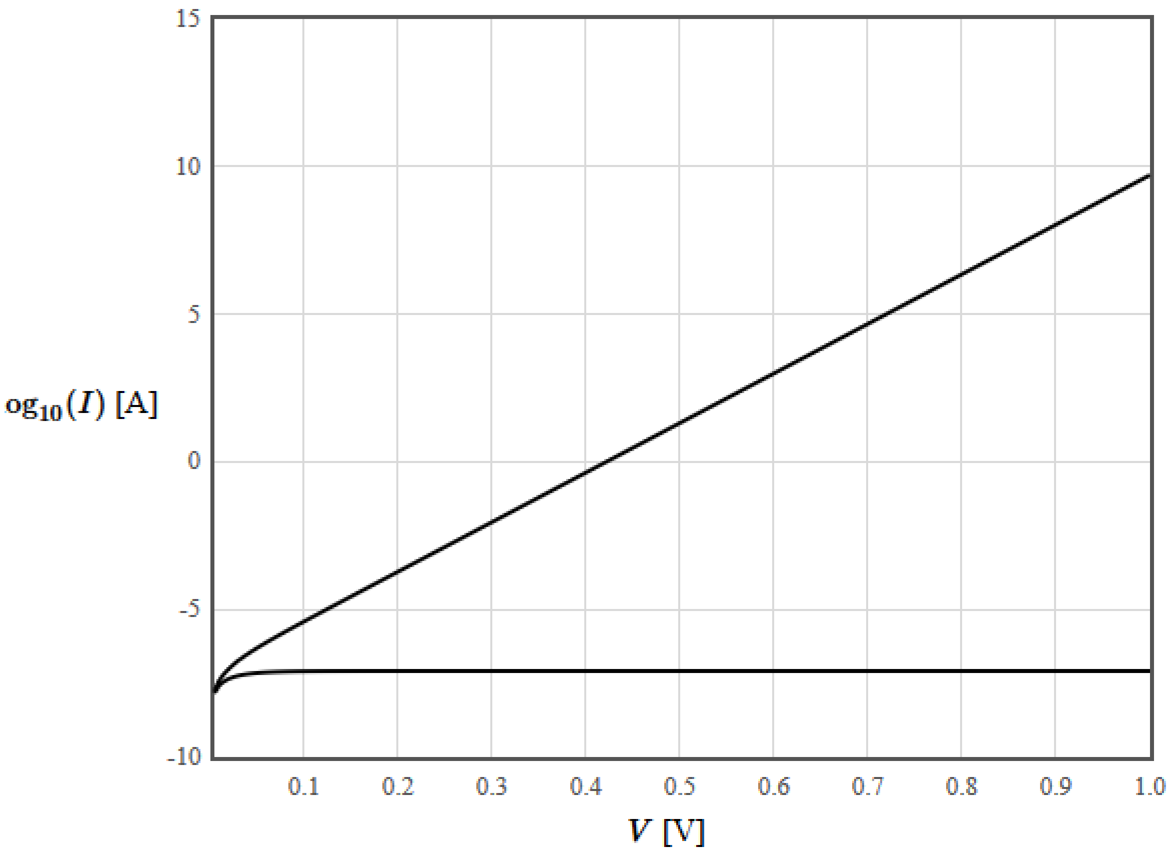
Area

Saturation current





Diode I-V charateristics



$A =$ 1E-3 cm^2

$N_c(300K) =$ 1.04E19 cm^{-3}

$N_v(300K) =$ 6.0E18 cm^{-3}

$E_g =$ 0.7437-4.77E-4*T*T/(T+235) eV

$\mu_p =$ 1900 cm^2/Vs

$\tau_p =$ 1E-8 s

$N_a =$ 1E17 cm^{-3}

$\mu_n =$ 3900 cm^2/Vs

$\tau_n =$ 1E-8 s

$N_d =$ 5E17 cm^{-3}

$T =$ 300 K

Replot

Si Ge GaAs

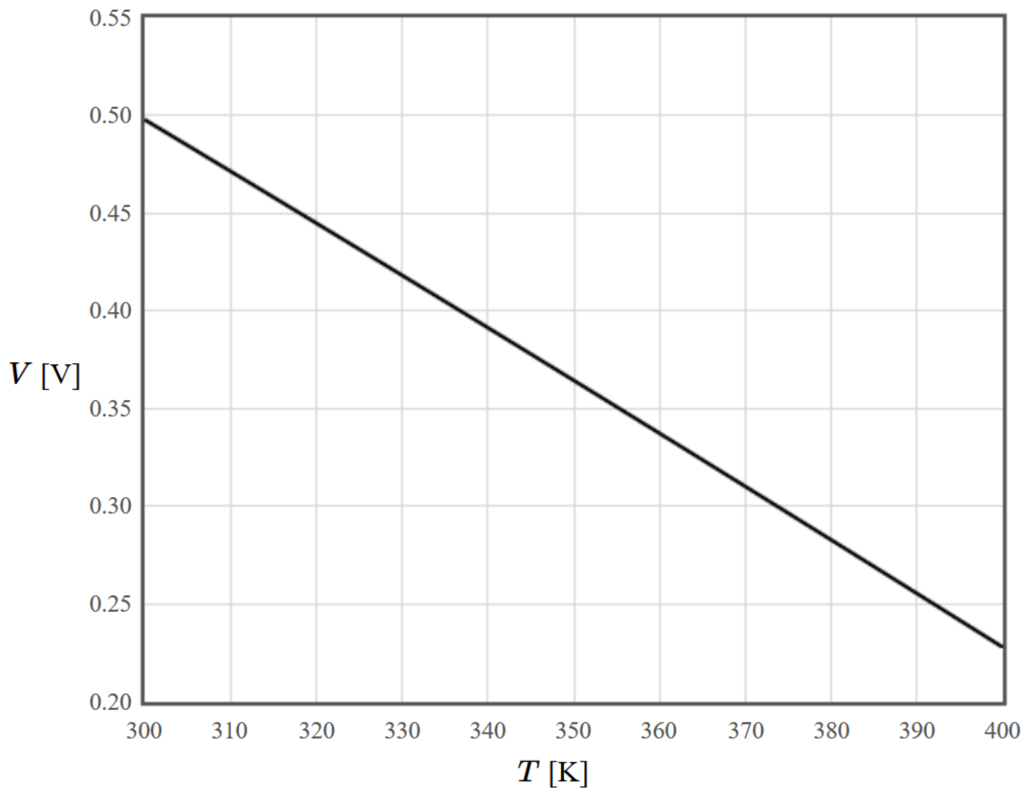
http://lamp.tu-graz.ac.at/~hadley/psd/L6/pnIV.php

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

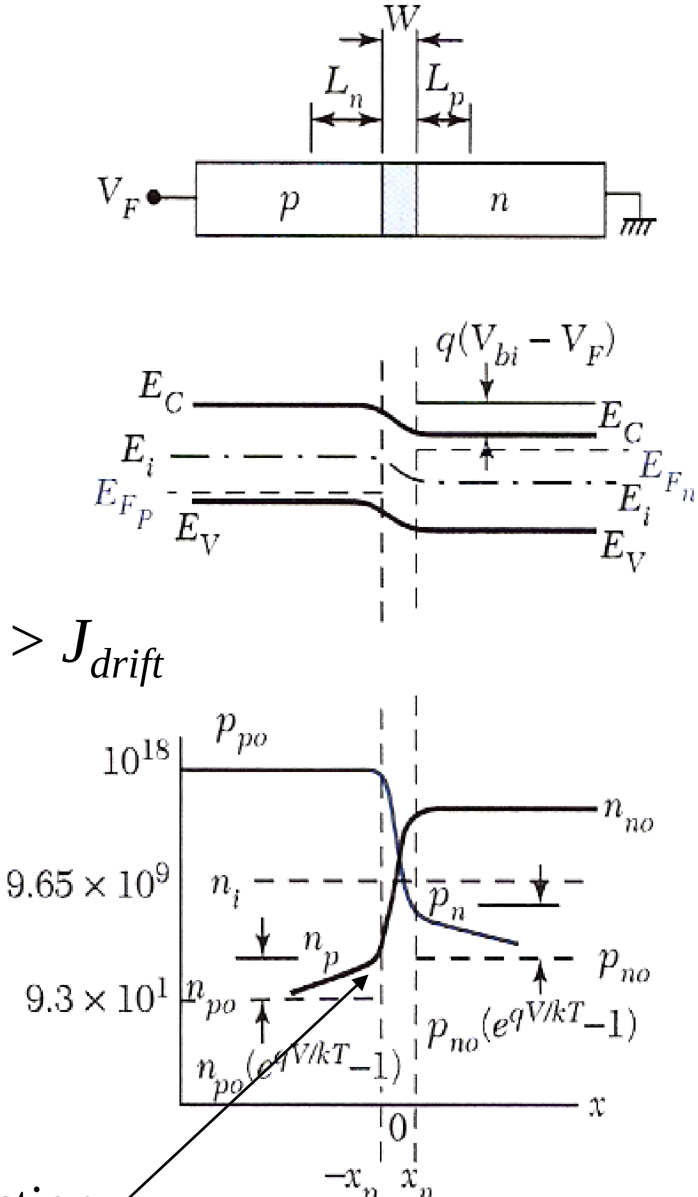
Si Ge GaAs

Forward

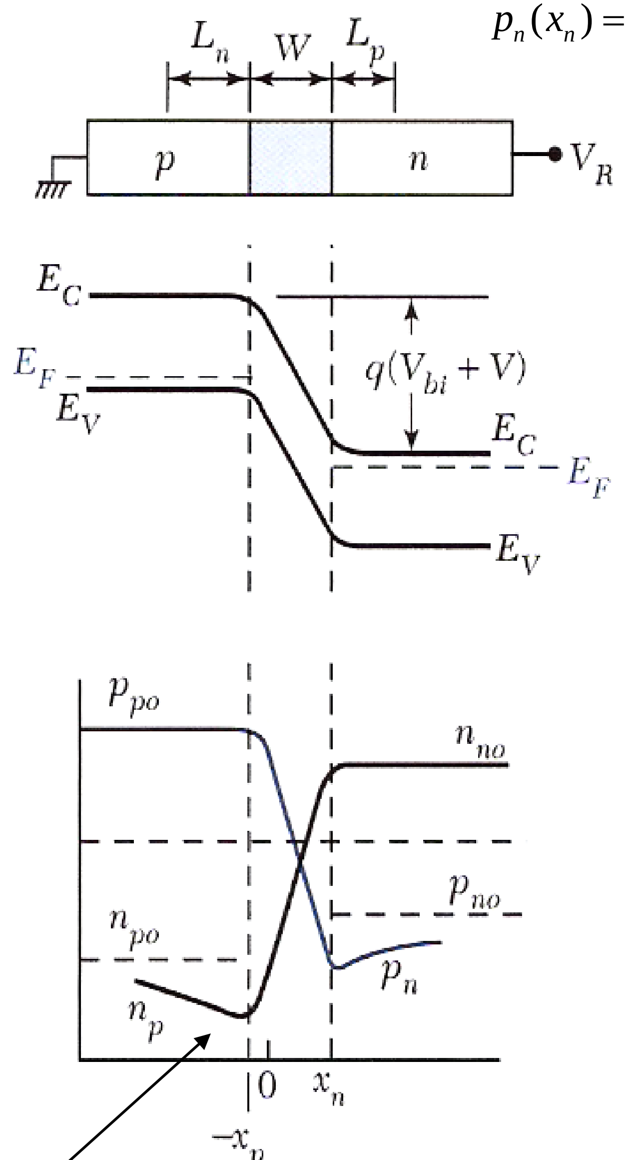
Reverse

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

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



$J_{diff} > J_{drift}$



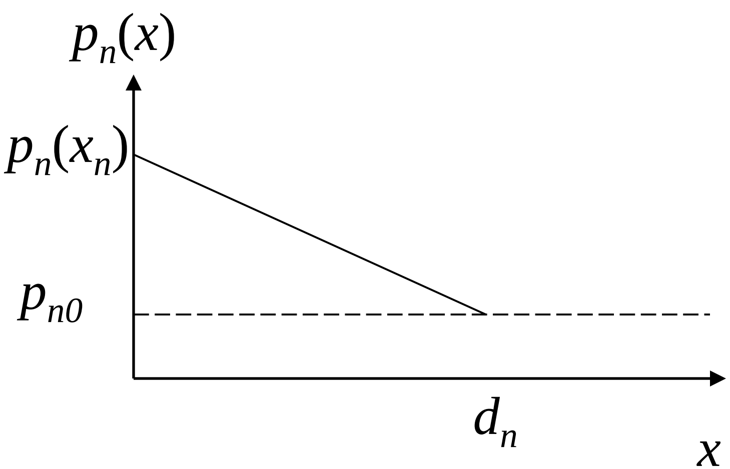
$J_{diff} < J_{drift}$

Injection

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

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

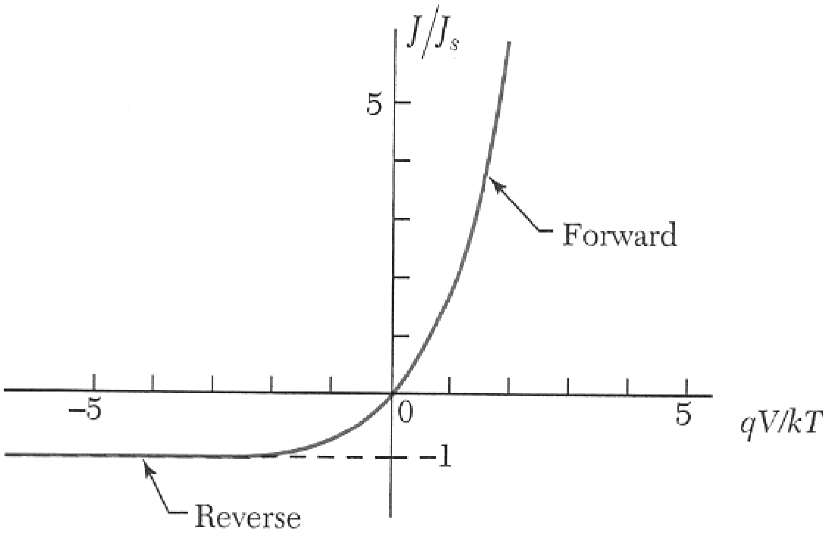
$$J_{diff,p} = \left(p_{n0} \exp\left(\frac{e(V)}{k_B T} \right) - p_{n0} \right) \frac{eD_p}{d_n}$$

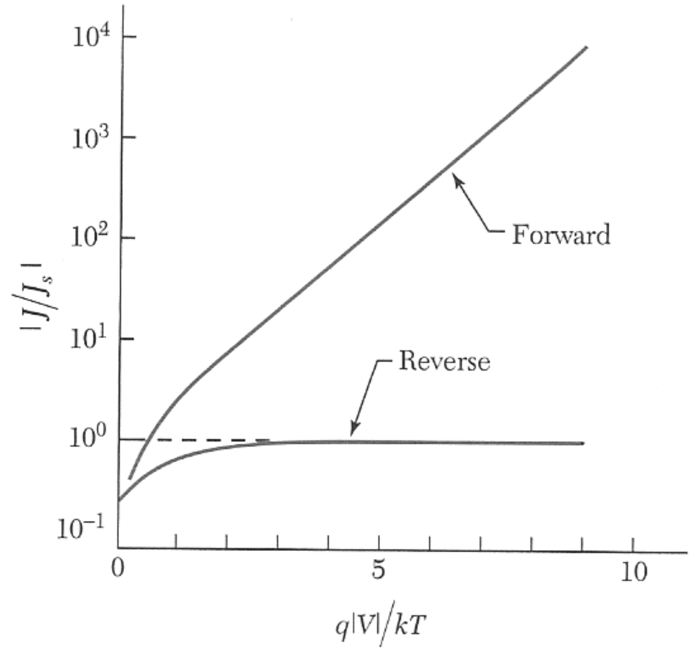
$$J_{diff,p} = \frac{p_{n0} e D_p}{d_n} \left(\exp\left(\frac{eV}{k_B T} \right) - 1 \right)$$

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



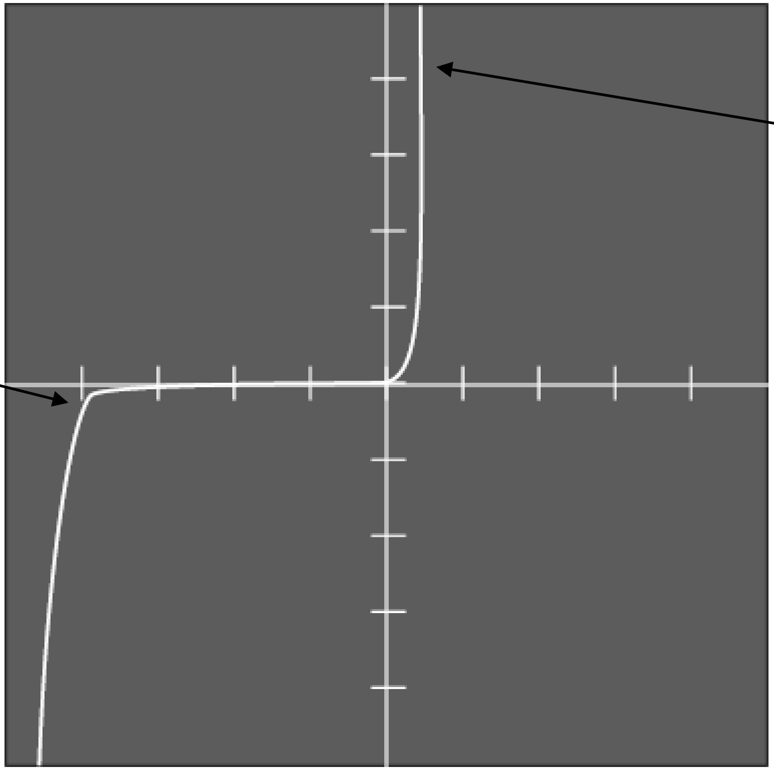


Real diodes

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

n = nonideality factor

n = 1 for an ideal diode



series resistance

reverse breakdown voltage

Real diodes

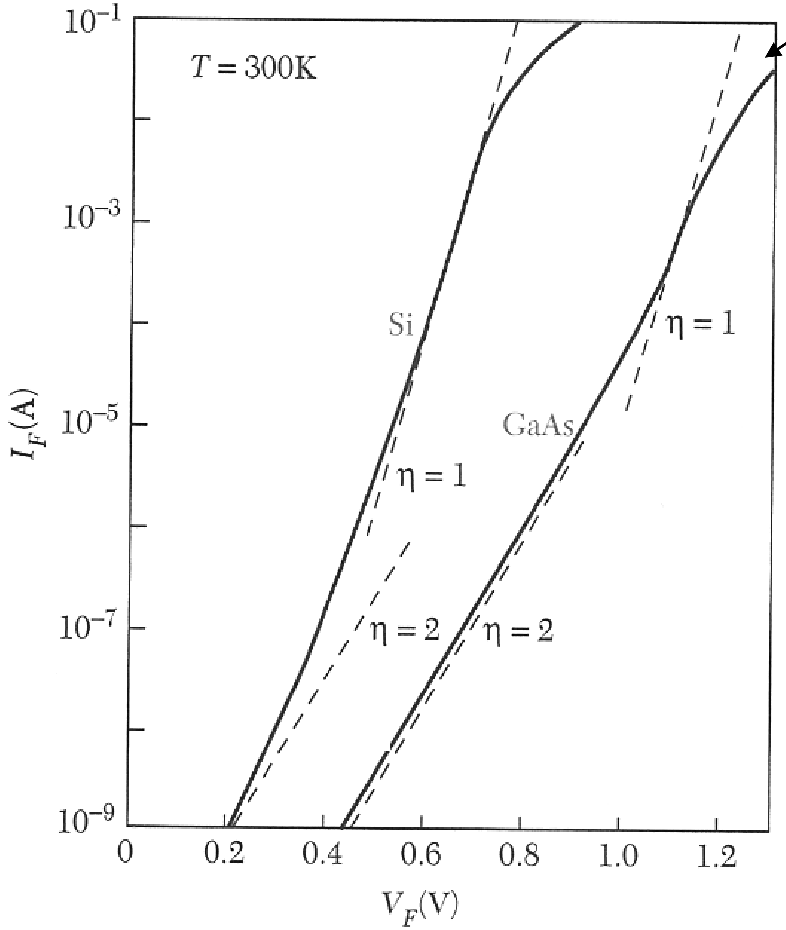
$$I = I_s\left(\exp\left(\frac{eV}{nk_BT}\right) - 1\right)$$

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.

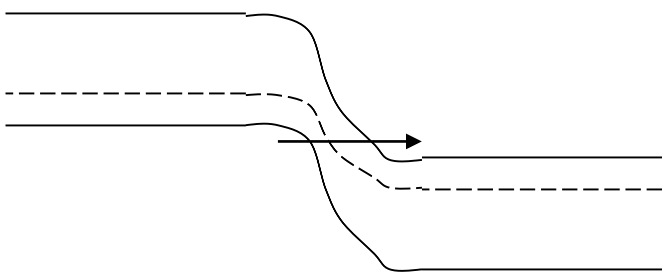
Low bias: recombination dominates, $n = 2$

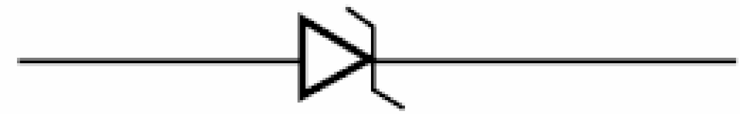


Very high bias: series resistance

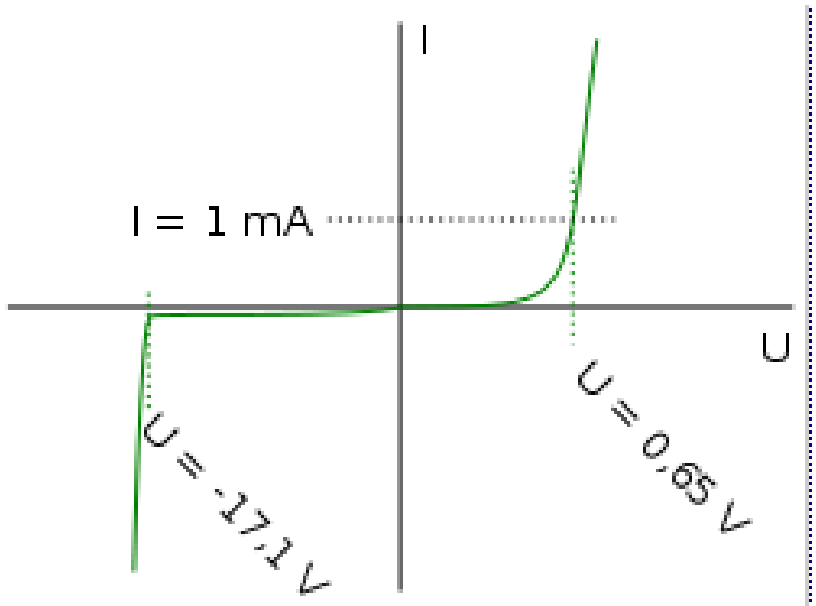
High bias: ideal behavior, $n = 1$

Zener tunneling





(Zener diode)



Electrons tunnel from valence band to conduction band

Occurs at high doping