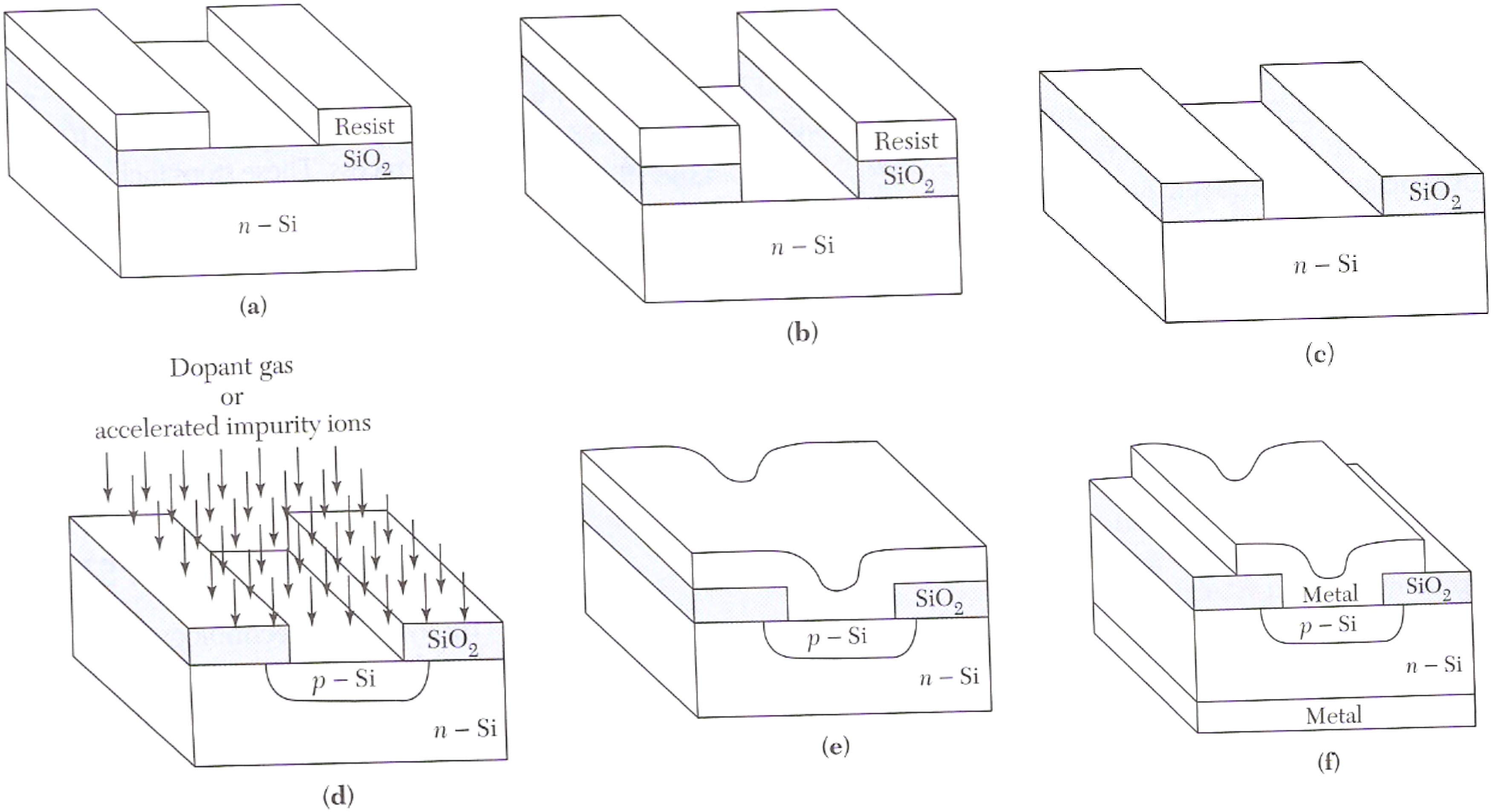
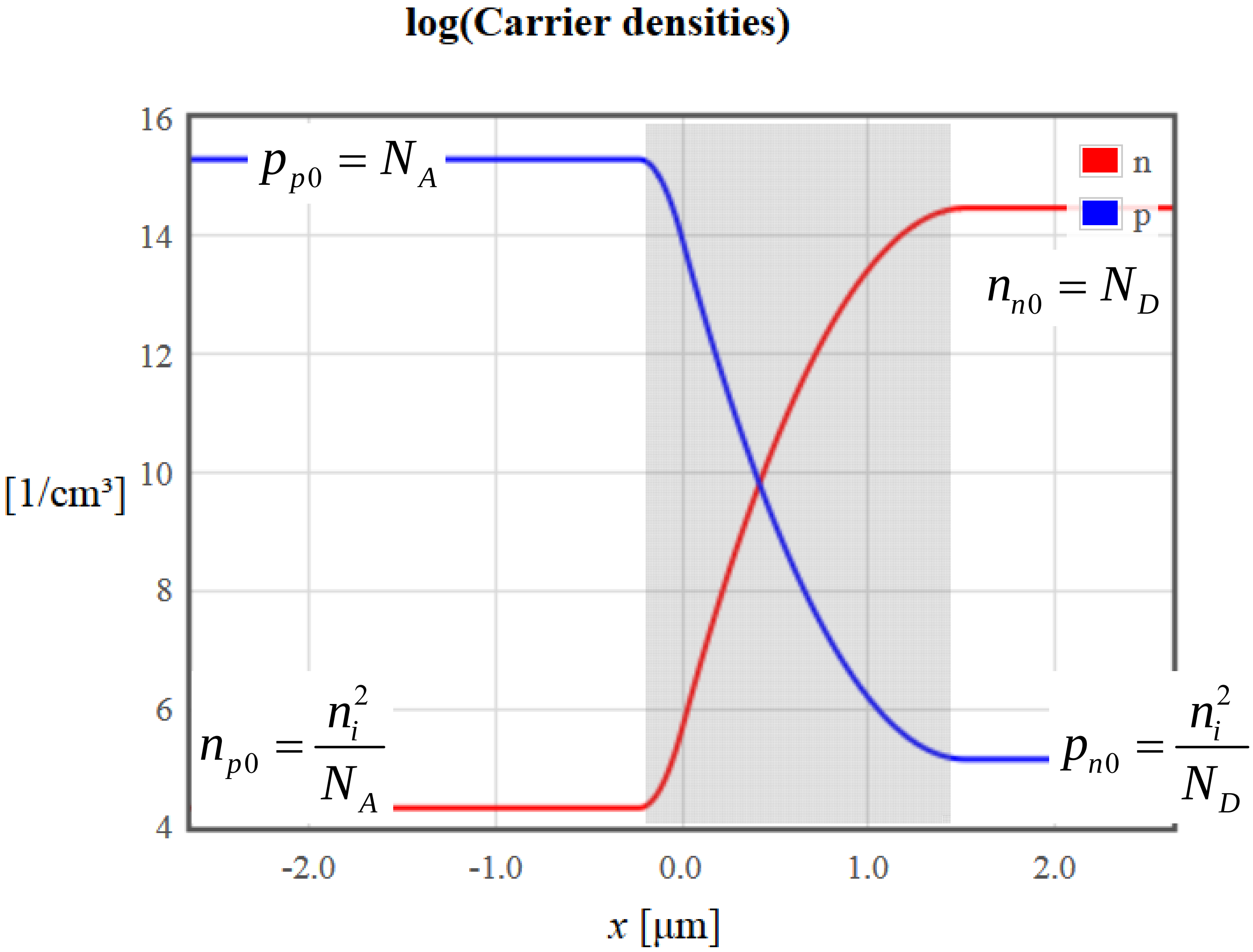
# pn-junctions

# diode fabrication



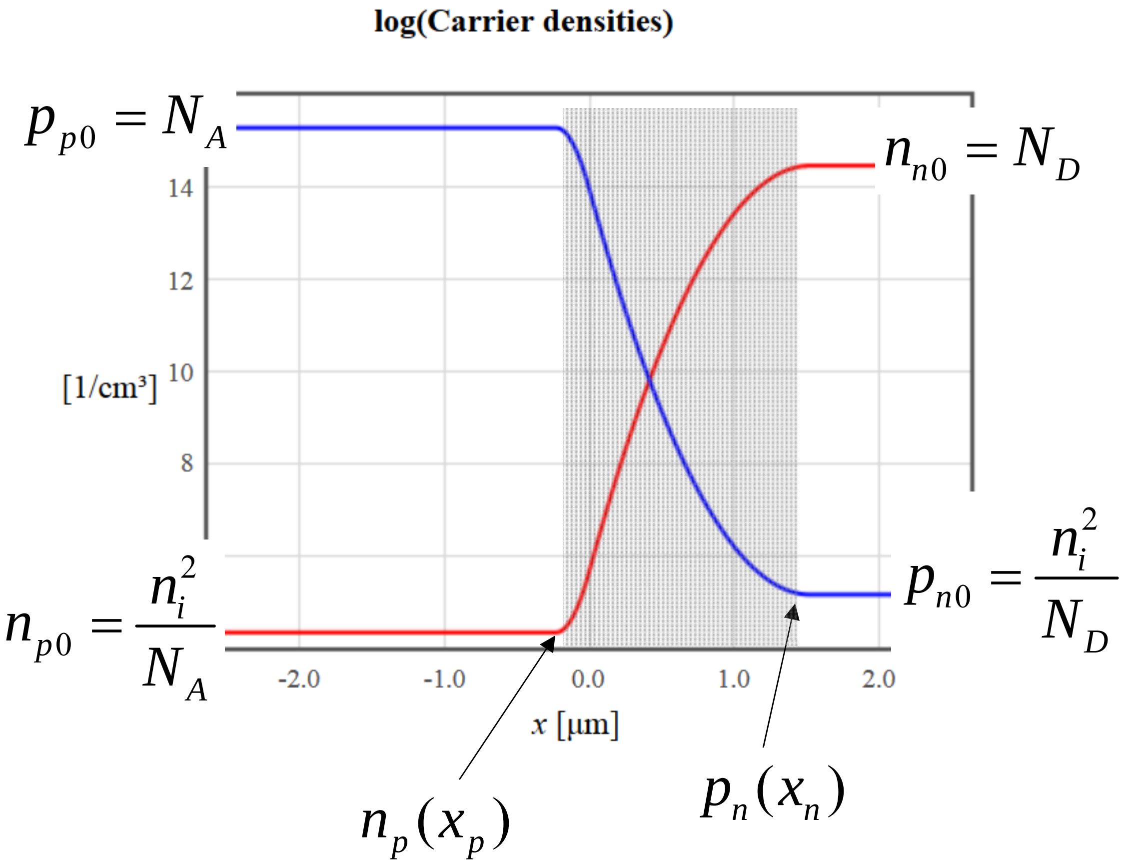
# Equilibrium concentrations, $V$ = 0



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

# Bias voltage, $V = 0$

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



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

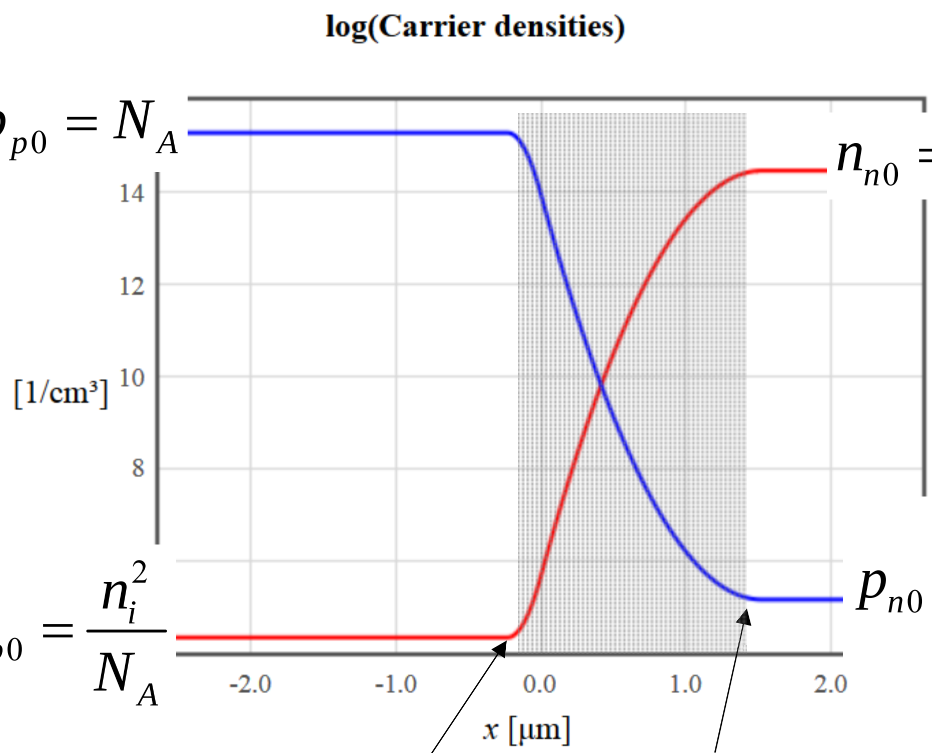
$V = 0$

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

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

# Bias voltage, $V \neq 0$

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



$p_{p0} = N_A$

$n_{n0} = N_D$

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

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

$n_p(x_p)$

$p_n(x_n)$

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

## $V = 0$

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

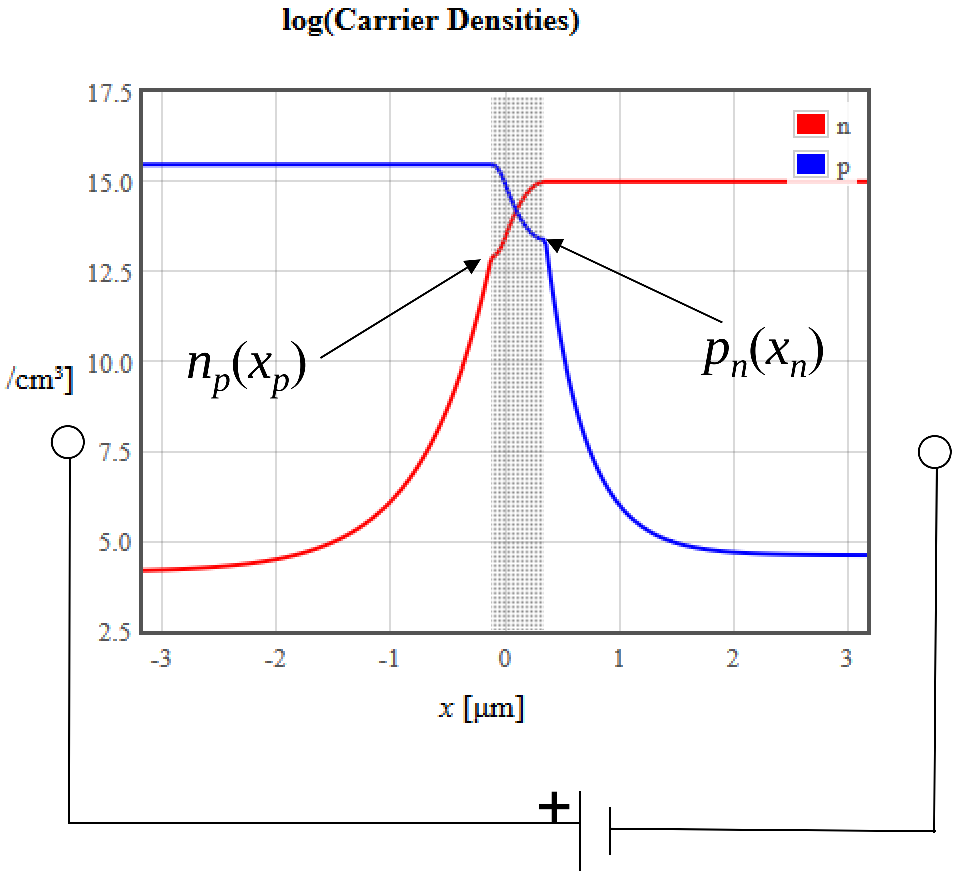
$$p_{n0} = N_A \exp\left(\frac{-eV_{bi}}{k_B T}\right)$$

## $V \neq 0$

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

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

# Forward bias, V > 0



Electrons and holes are driven towards the junction.

The depletion region becomes narrower

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

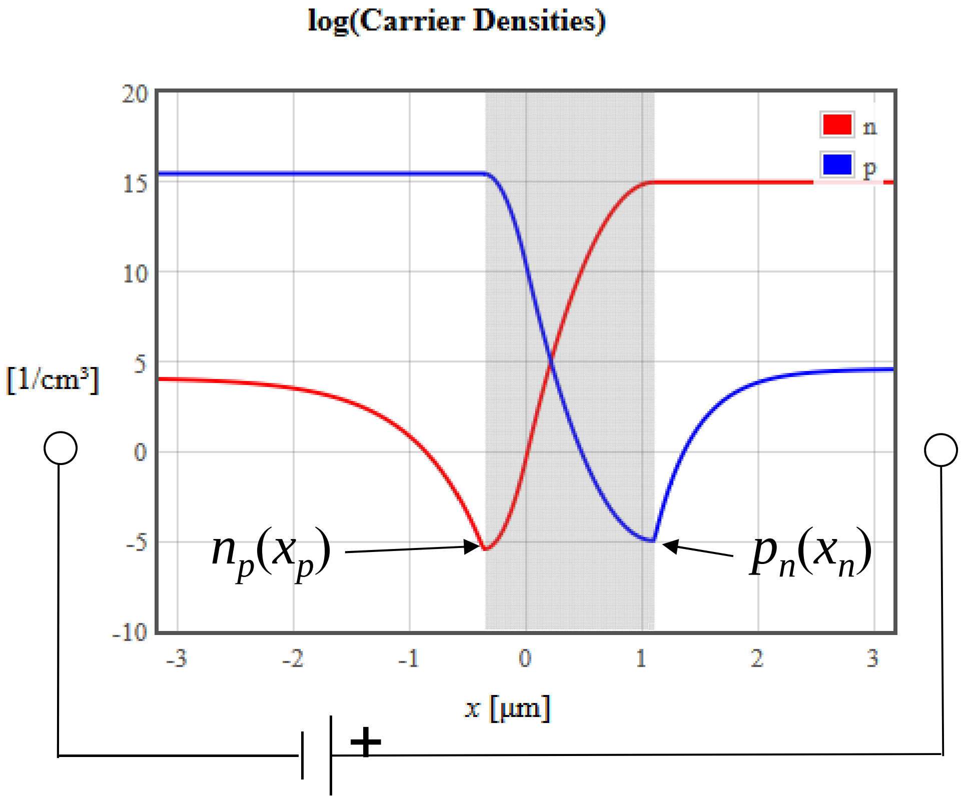
$$p_n(x_n) = N_A \exp\left(\frac{-e\left(V_{bi} - V\right)}{k_B T}\right)$$

Minority electrons are 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



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

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

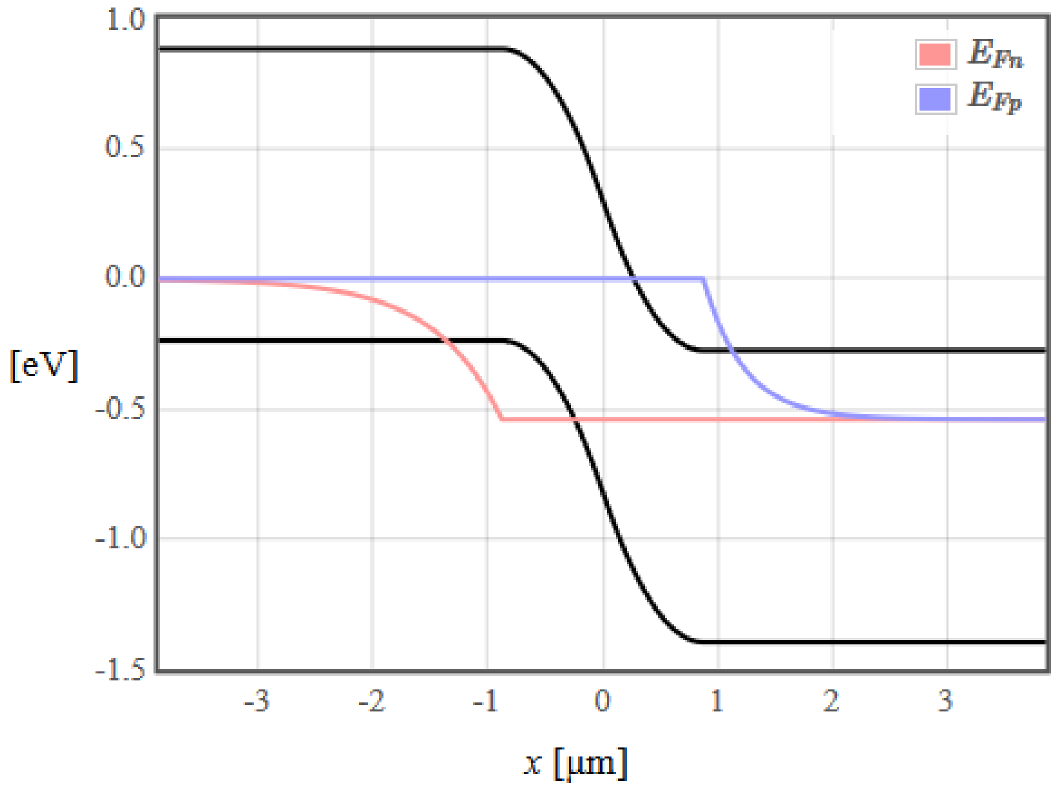
Minority electrons are extracted from the p-region by the electric field
Minority holes are extracted from the n-region by the electric field

# Quasi Fermi level

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

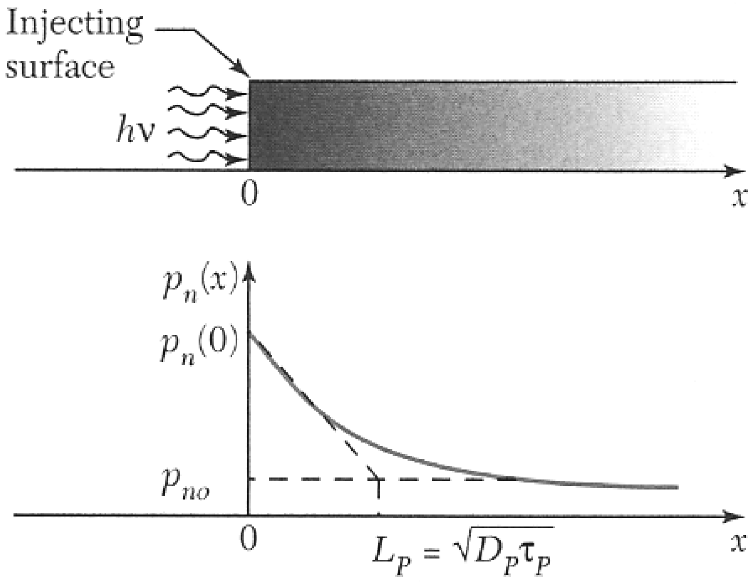
$$n = N_c \exp\left(\frac{E_{Fn} - E_c}{k_B T}\right)$$

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



# Review of Diffusion

n-type



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

recombination time

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

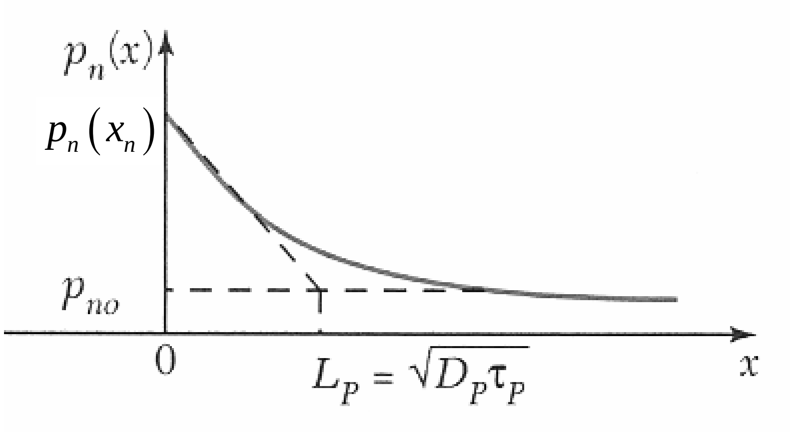
$$L_p = \sqrt{D_p \tau_p}$$

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

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

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

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

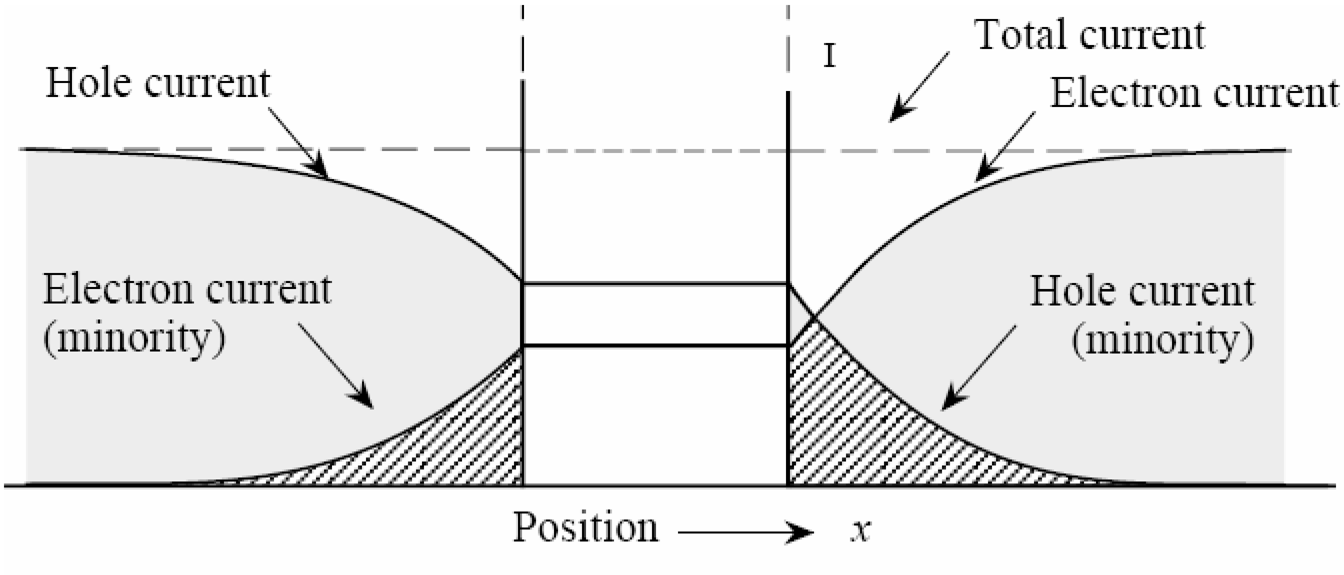
$$p_{p0} = p_{n0}\exp\left(\frac{eV_{bi}}{k_B T}\right)$$

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

# Diffusion current

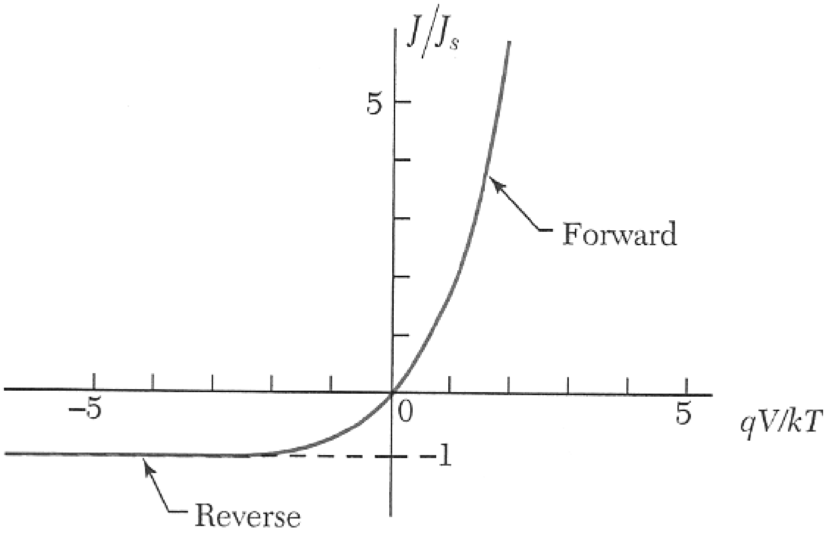
$$J_{diff,p} = \frac{p_{n0} e D_p}{L_p}\left(\exp\left(\frac{eV}{k_B T}\right) - 1\right)$$

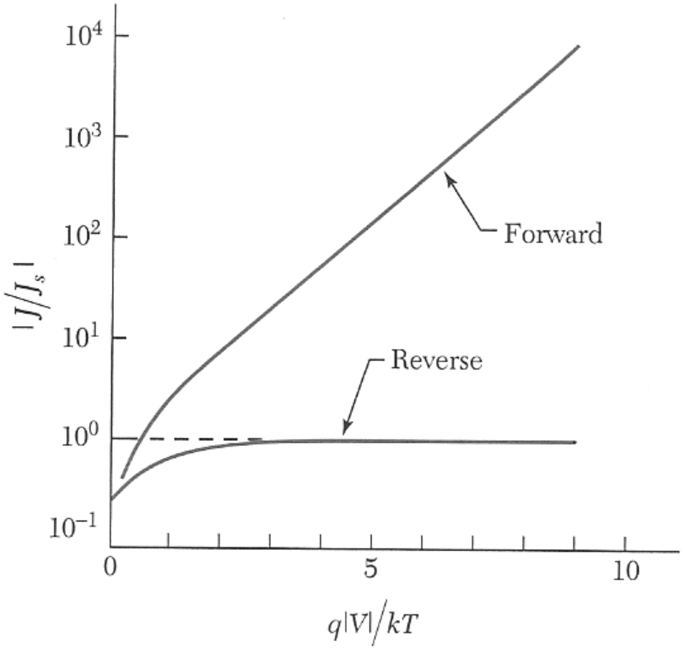
$$J_{diff,n} = \frac{n_{p0} e D_n}{L_n}\left(\exp\left(\frac{eV}{k_B T}\right) - 1\right)$$



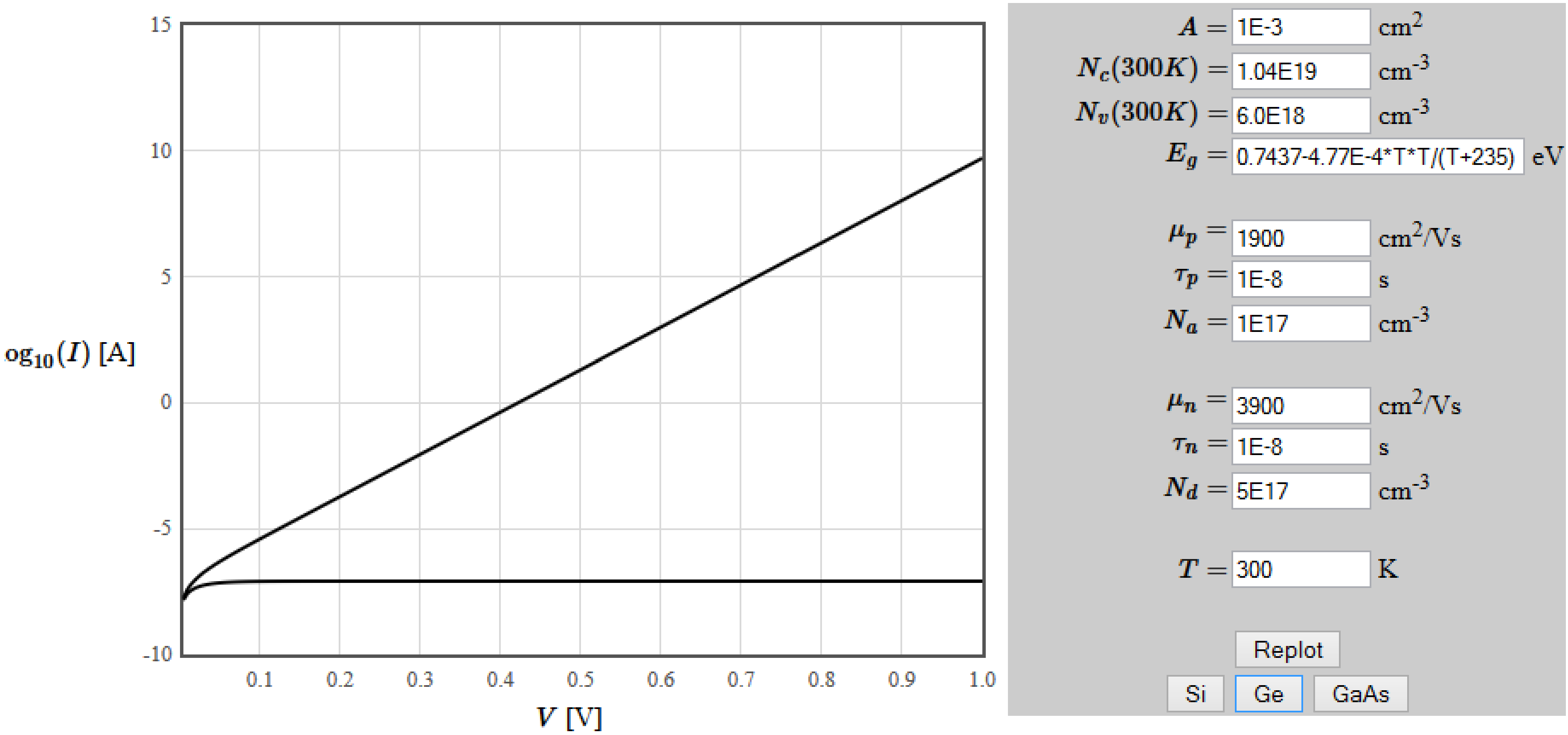
# Diode current

$$I = e\underset{\substack{\uparrow\\ \text{Area}}}{A}\left(\frac{p_{n0}D_p}{L_p}+\frac{n_{p0}D_n}{L_n}\right)\left(\exp\left(\frac{eV}{k_BT}\right)-1\right) = \underset{\substack{\uparrow\\ \text{Saturation current}}}{I_s}\left(\exp\left(\frac{eV}{k_BT}\right)-1\right)$$





# 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

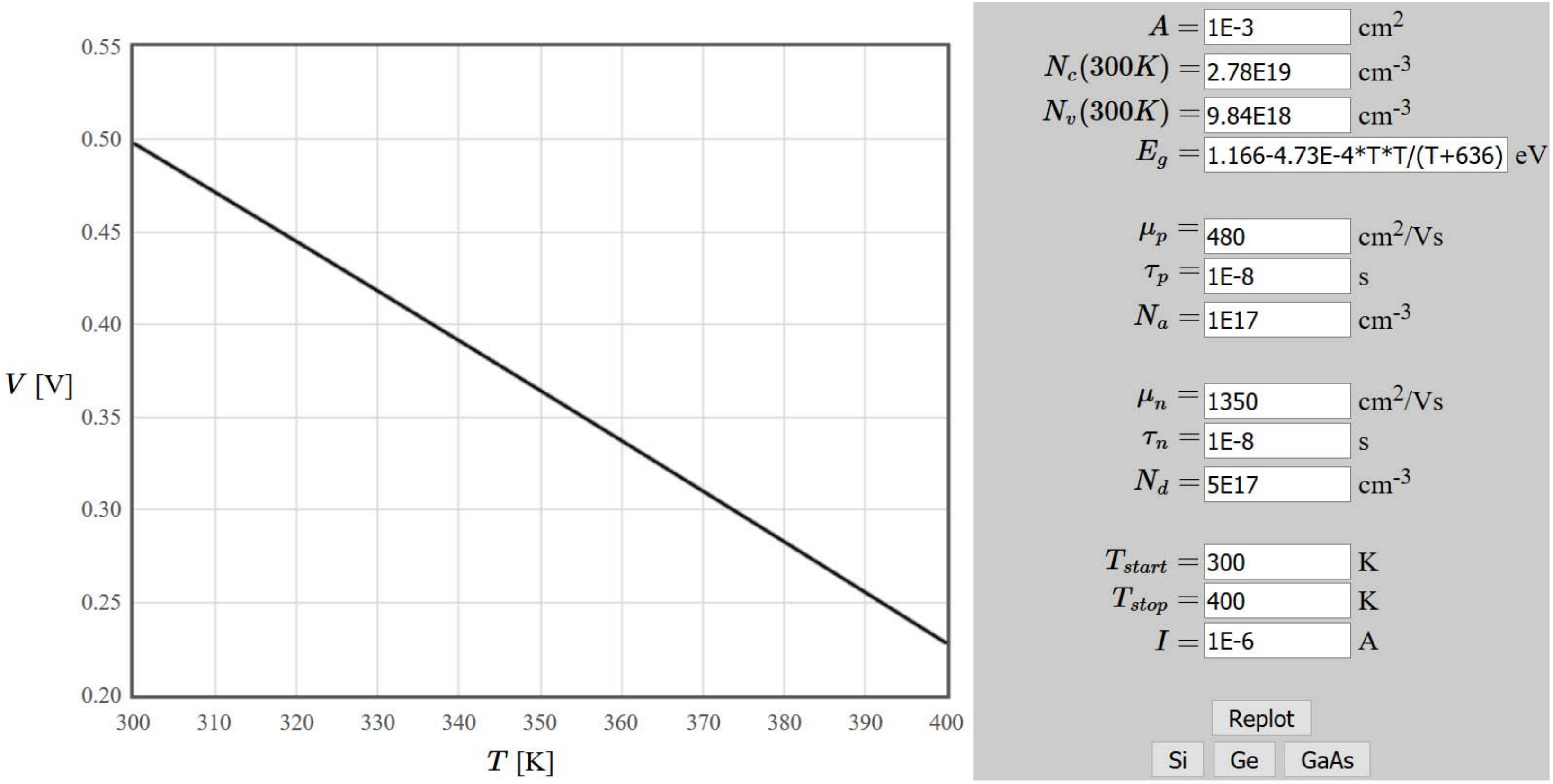
http://lamp.tu-graz.ac.at/~hadley/psd/L6/pnIV.php

# Thermometer

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

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

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



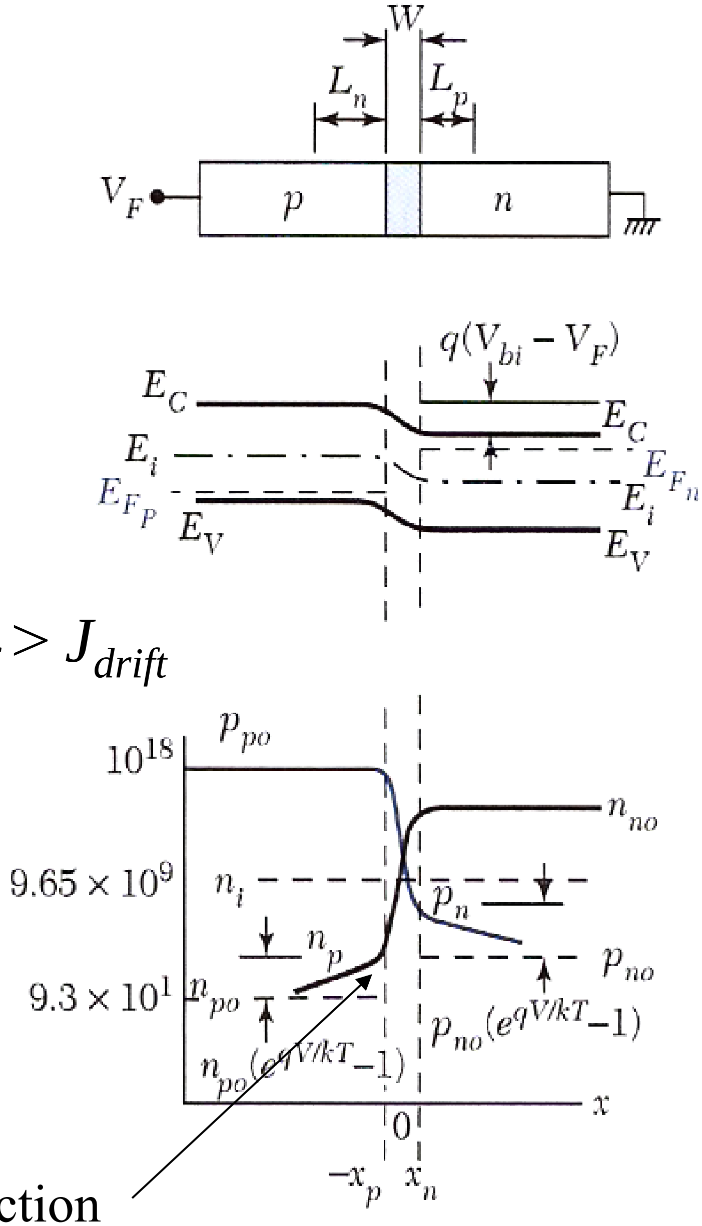
$A =$ 1E-3 cm$^2$
$N_c(300K) =$ 2.78E19 cm$^{-3}$
$N_v(300K) =$ 9.84E18 cm$^{-3}$
$E_g =$ 1.166-4.73E-4*T*T/(T+636) eV

$\mu_p =$ 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

# Forward



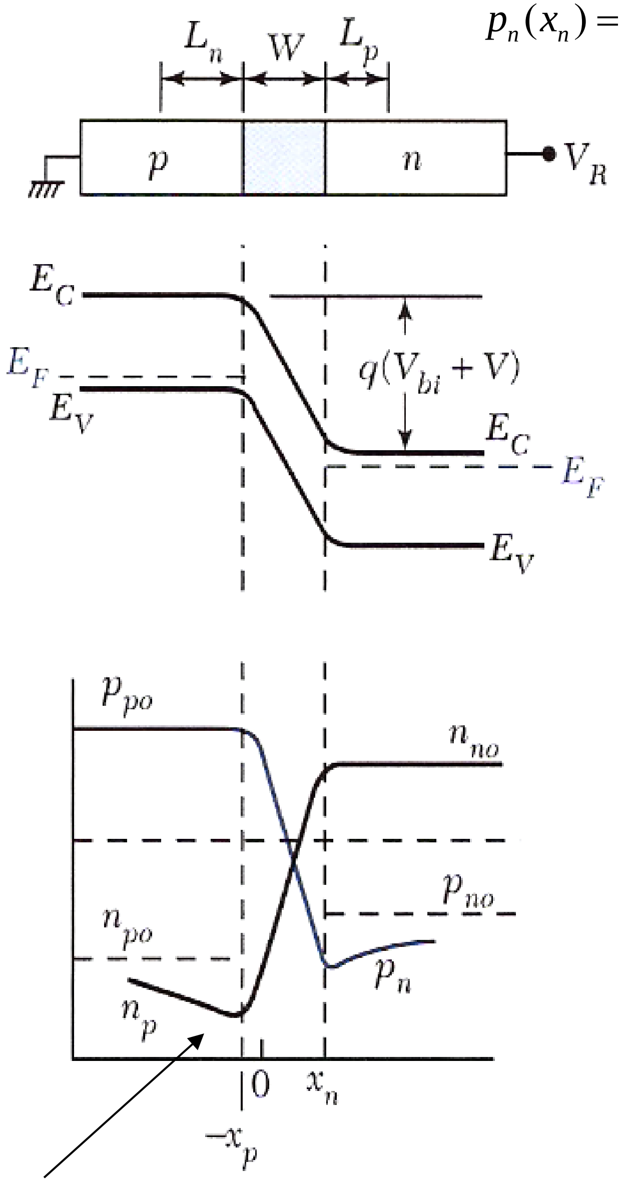
$J_{diff} > J_{drift}$

Injection

# Reverse

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

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

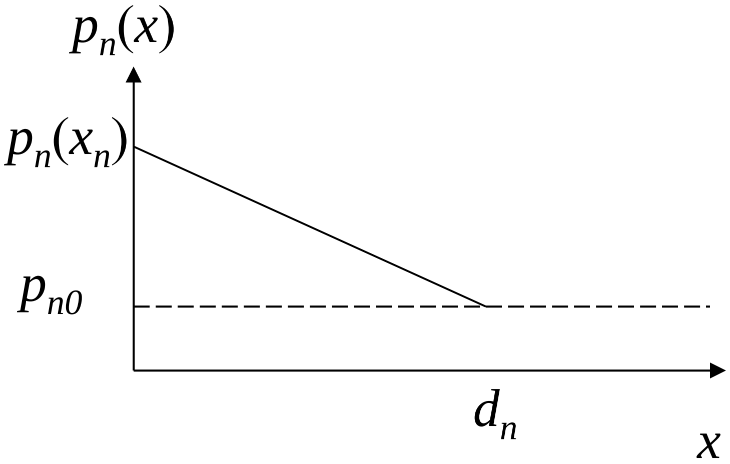


$J_{diff} < J_{drift}$

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

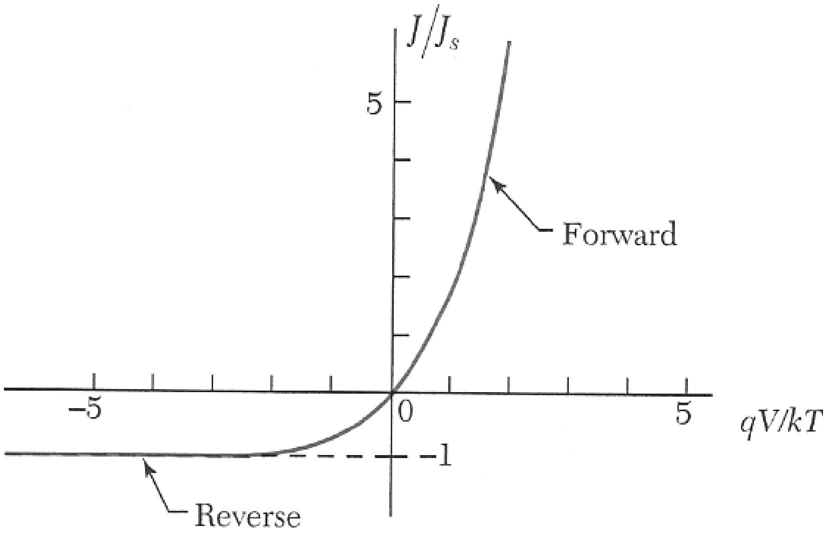
$$J_{diff,p} = \left(p_n(x_n) - p_{n0}\right)\frac{eD_p}{d_n}$$

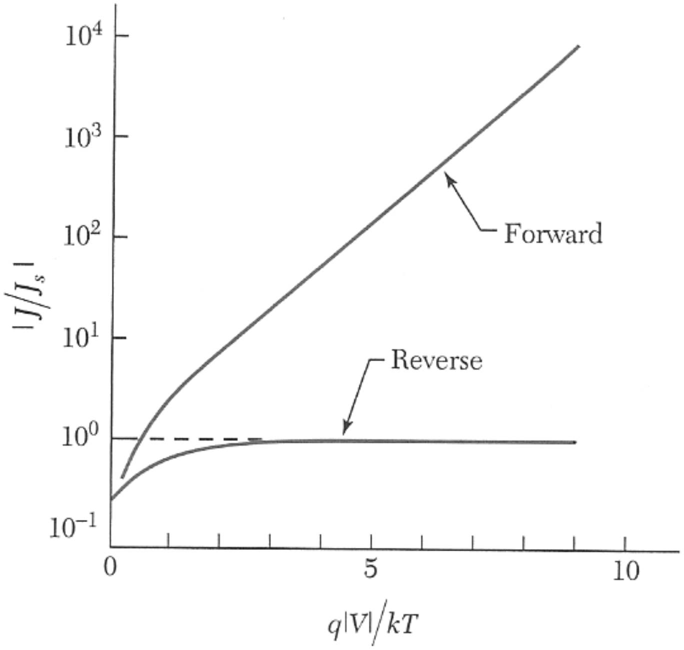
$$J_{diff,p} = \left(p_{n0}\exp\left(\frac{e(V)}{k_B T}\right) - p_{n0}\right)\frac{eD_p}{d_n}$$

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

# Short diode current

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



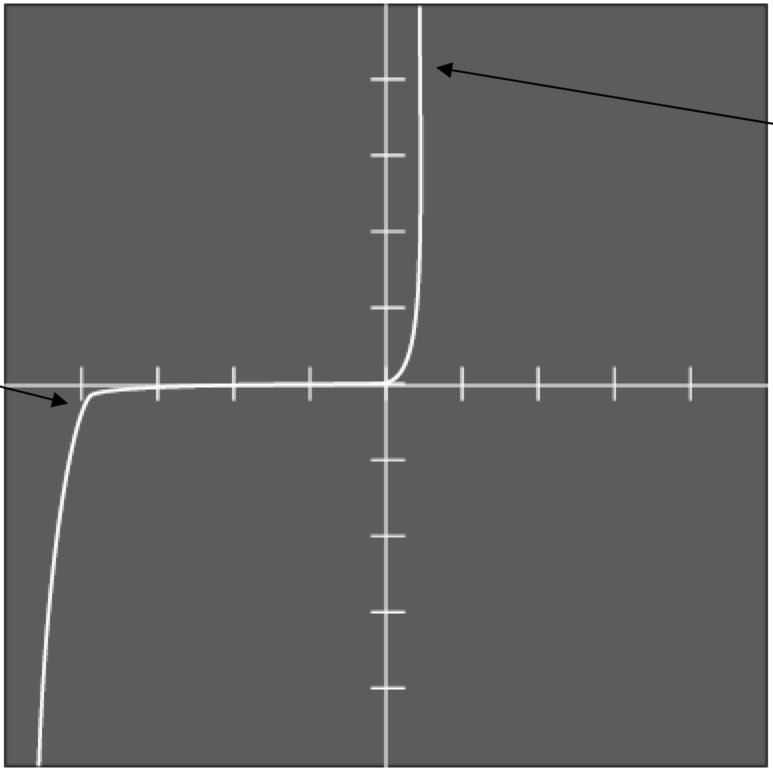


# Real diodes

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

$n$ = nonideality factor

$n = 1$ for an ideal diode



series resistance

reverse breakdown voltage

# Real diodes

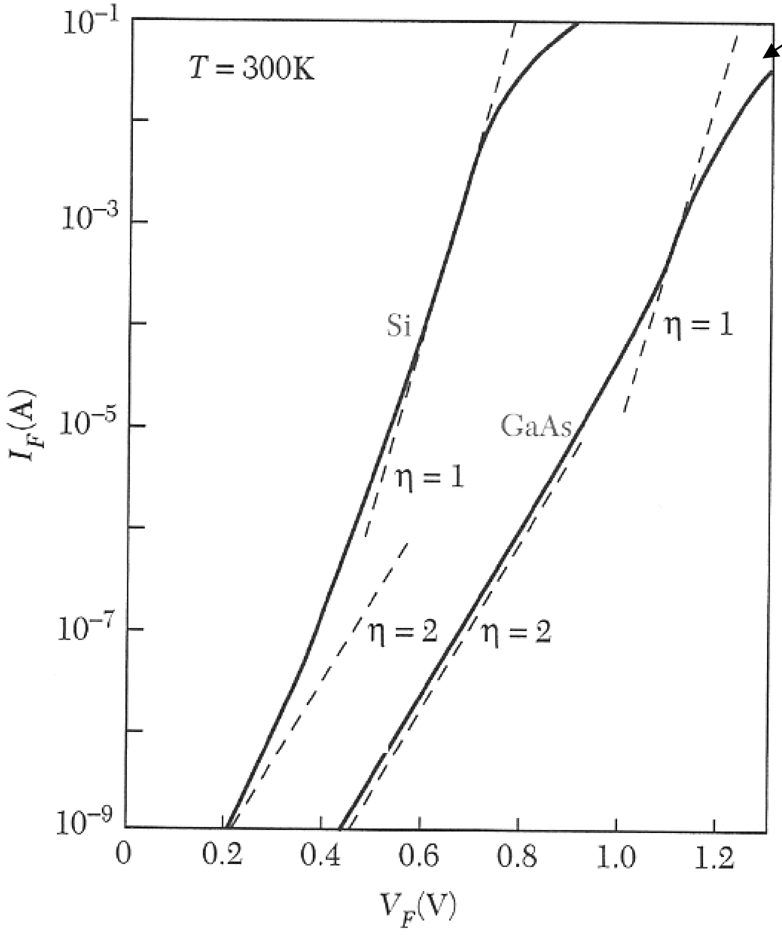
$$I = I_s\left(\exp\left(\frac{eV}{nk_BT}\right)-1\right)$$

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.

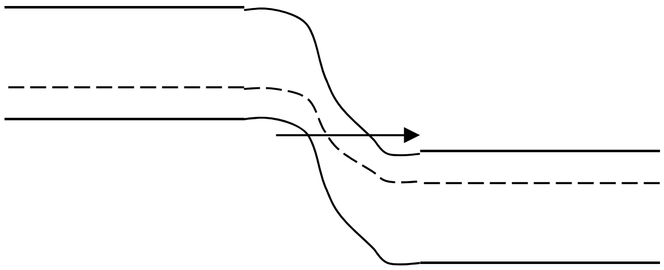
Low bias: recombination dominates, $n = 2$

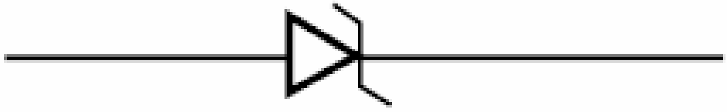


Very high bias: series resistance

High bias: ideal behavior, $n = 1$

# Zener tunneling



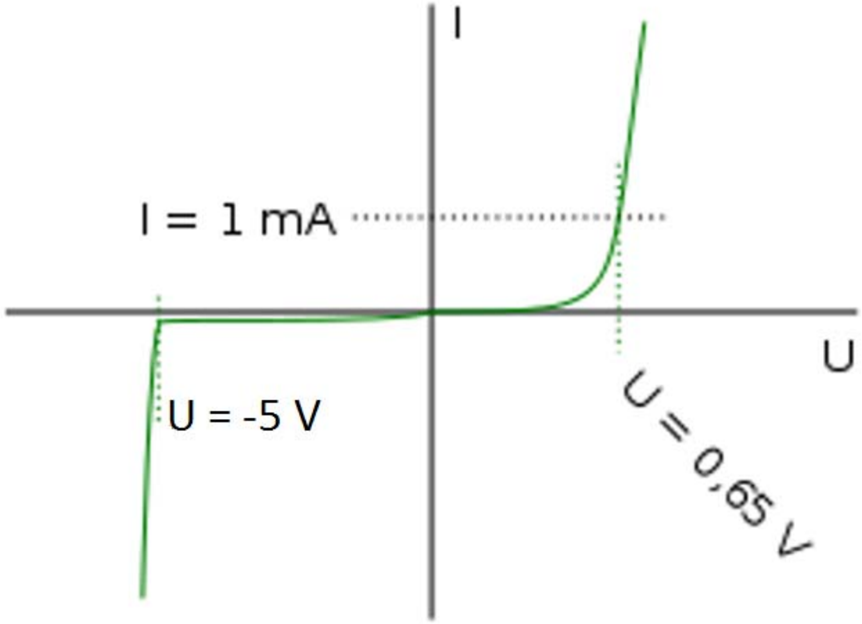


(Zener diode)

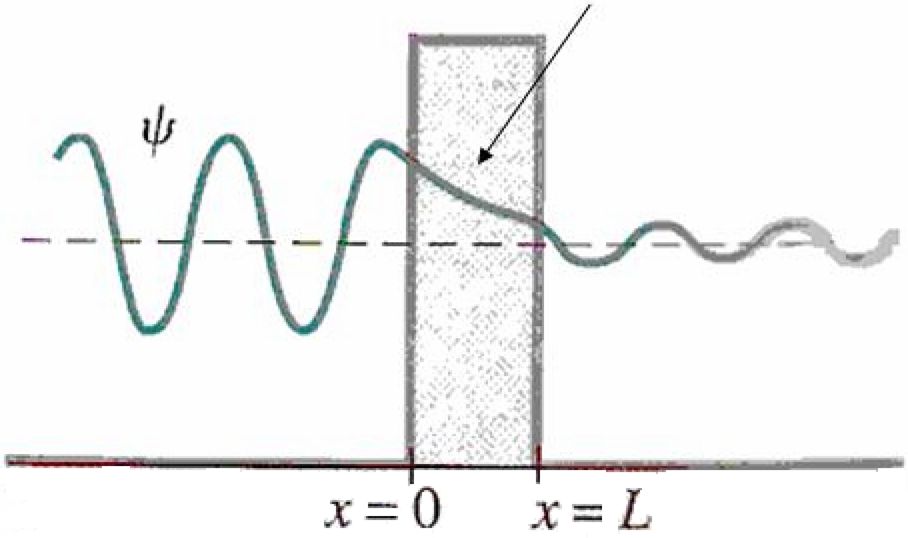
Electrons tunnel from valence band to conduction band

Occurs at high doping

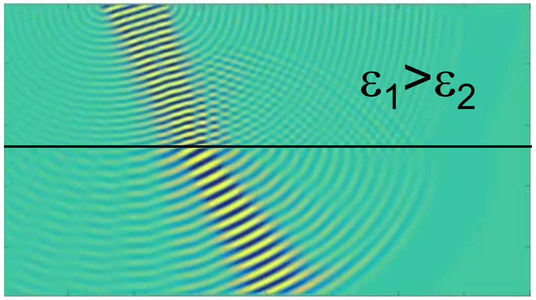
$|V_{zener}| < 5.6$ V



# Tunneling



wave decays exponentially in the classically forbidden region



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

# Zener tunneling

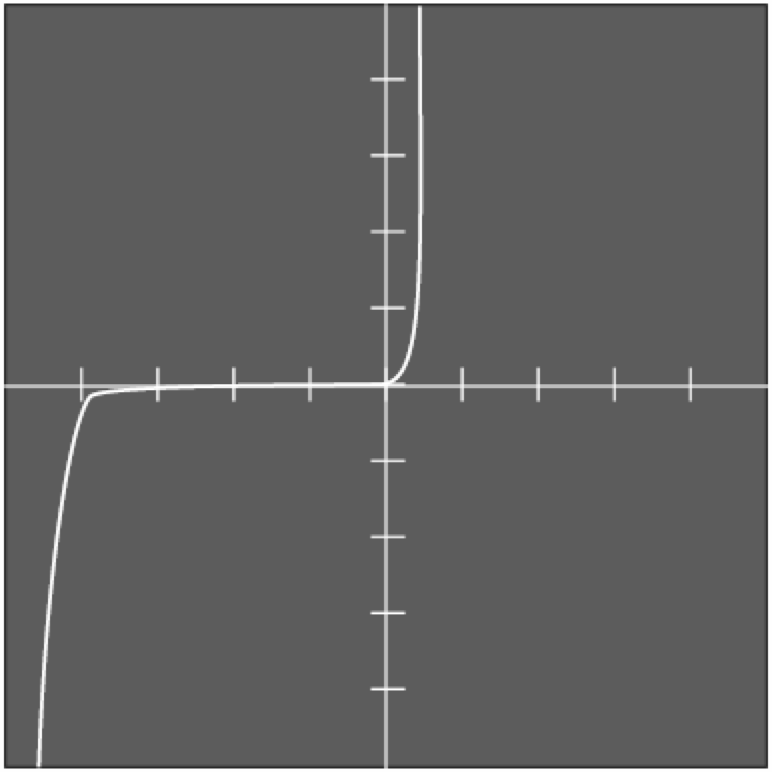
Breakdown voltage is typically much lower than the breakdown voltage of an avalanche diode and can be tuned by adjusting the width of the depletion layer.

Used to provide a reference voltage.

# Avalanche breakdown

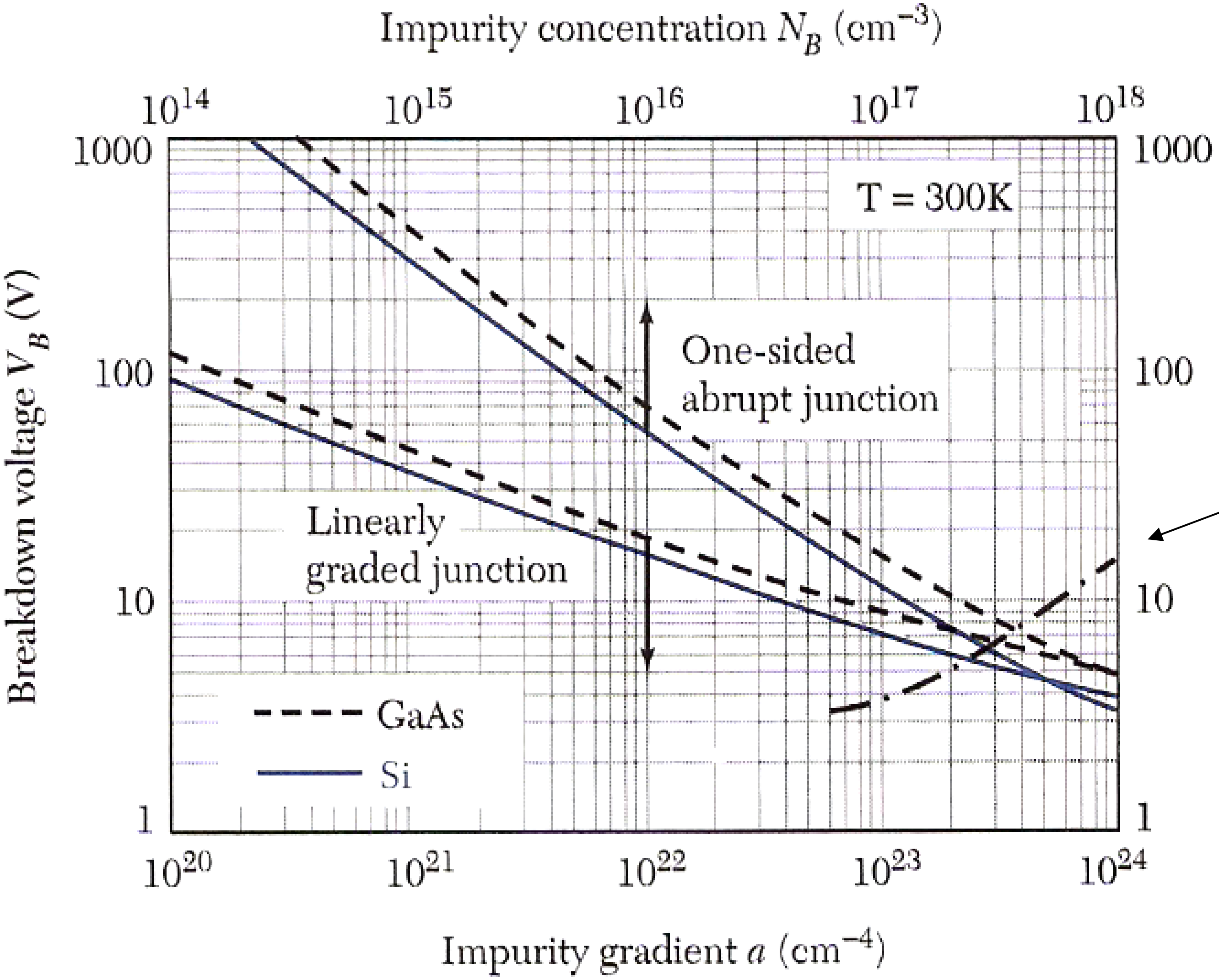
Impact ionization causes an avalanche of current

Occurs at low doping



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

# Avalanche breakdown



Tunneling

# metal - semiconductor contacts

Photoelectric effect
Workfunction
Electron affinity
Interface states
Schottky barriers
Schottky diodes
Ohmic contacts
Thermionic emission
Tunnel contacts