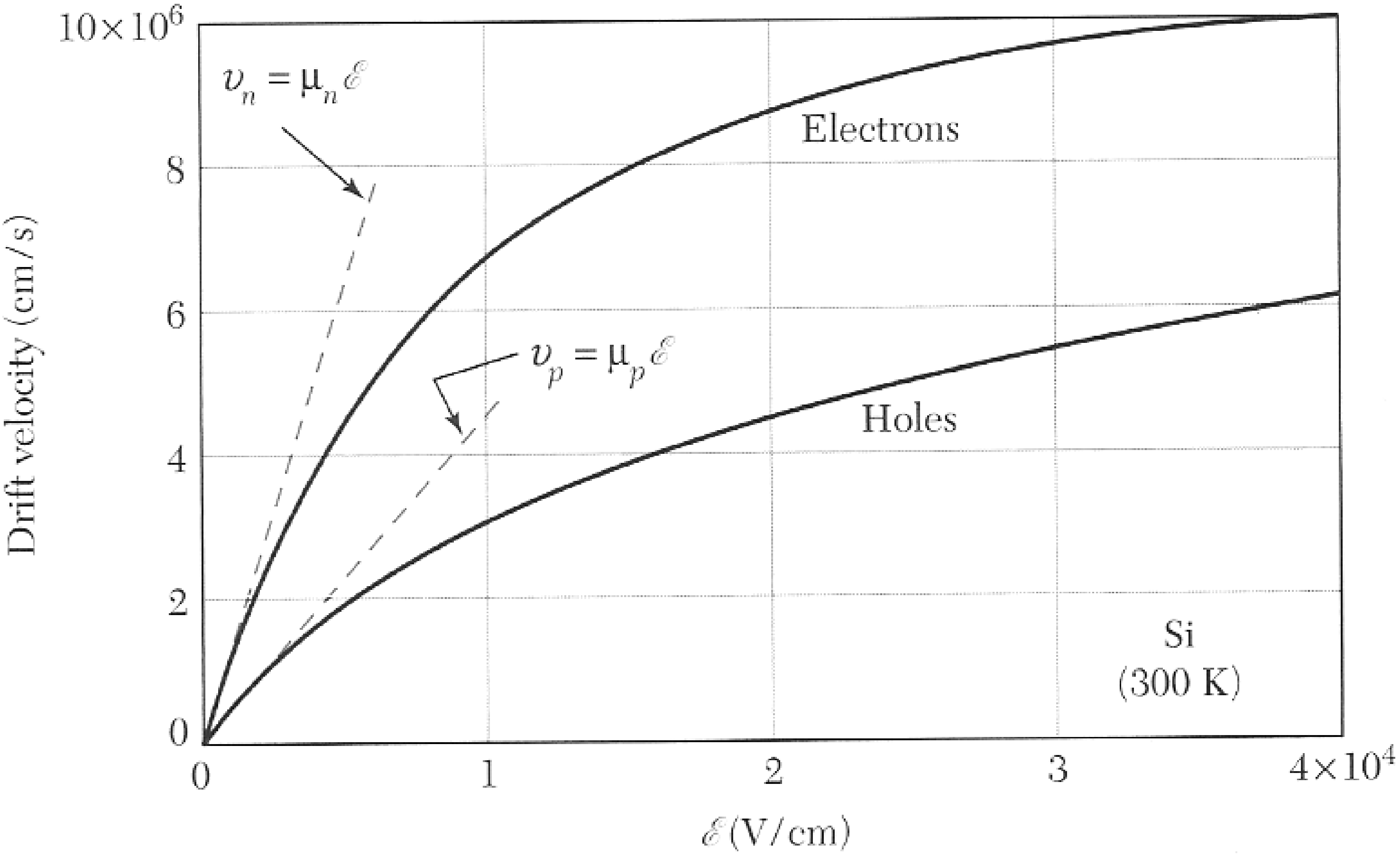
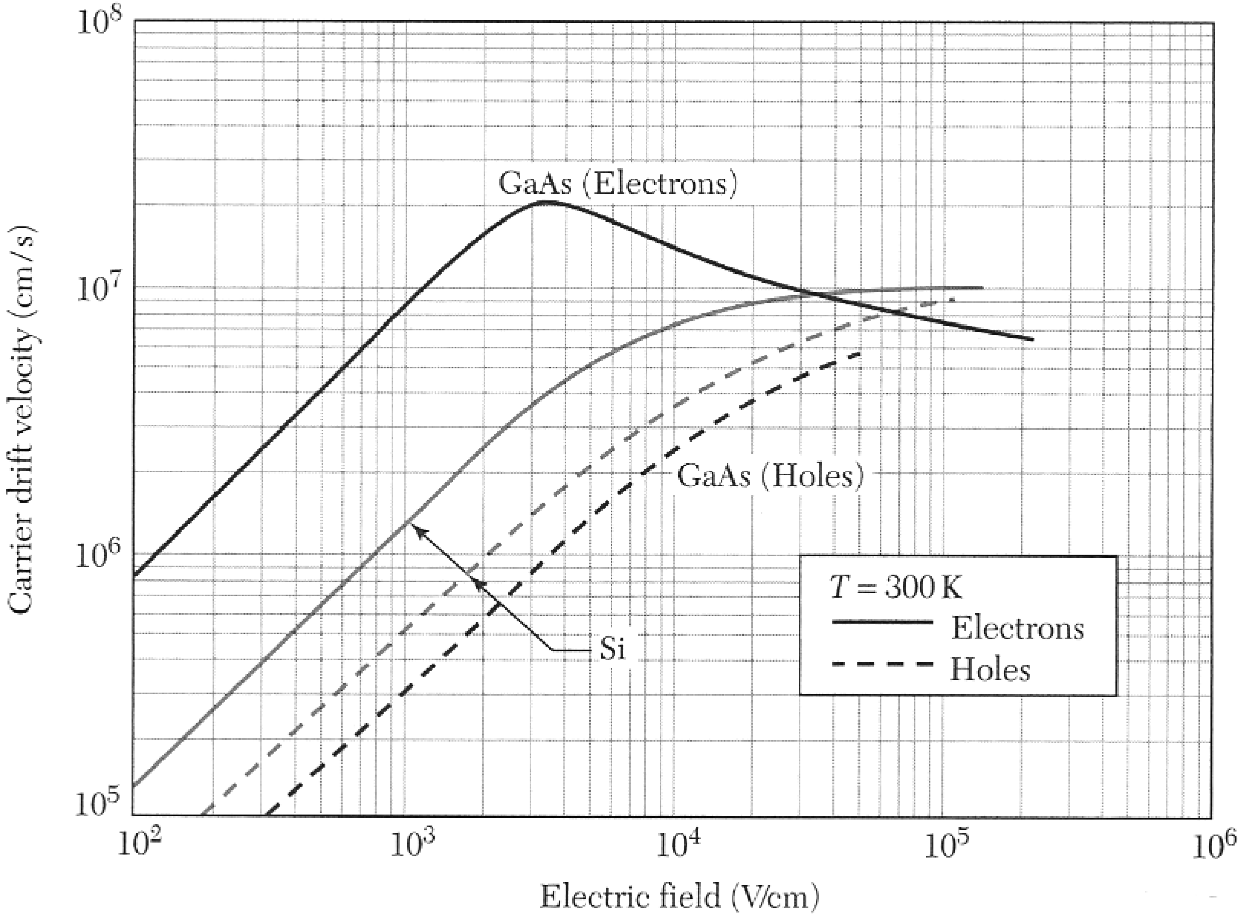
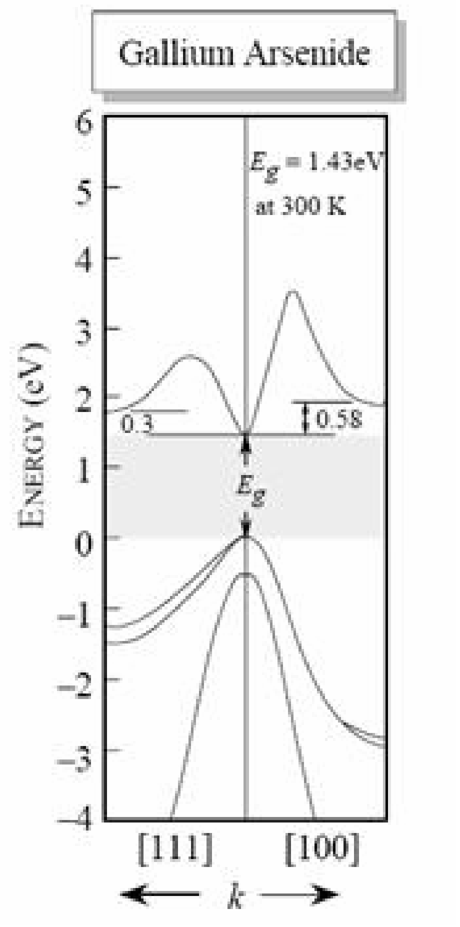
High Fields



Silicon

High Fields





GaAs

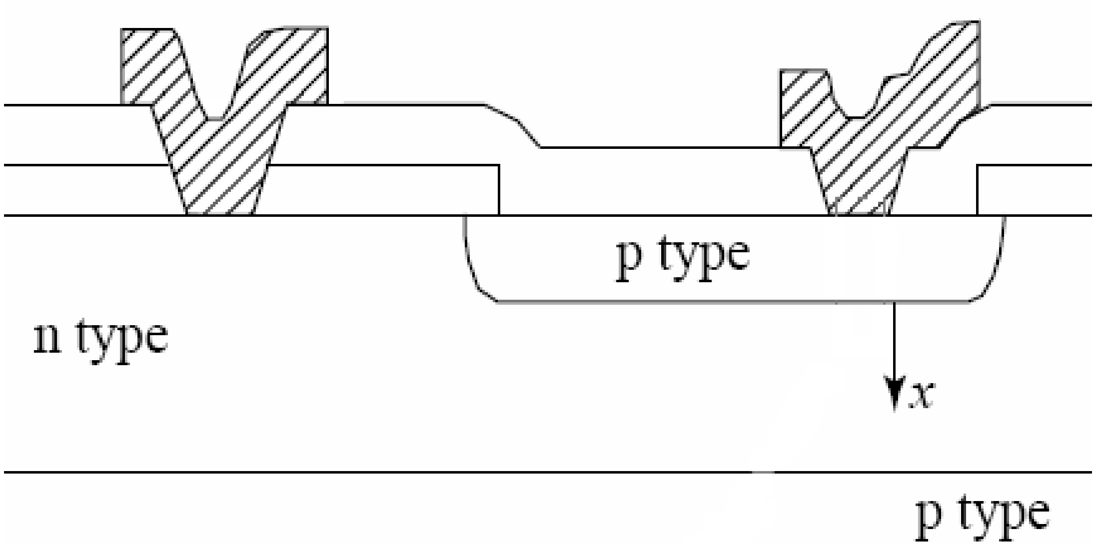
Impact ionization

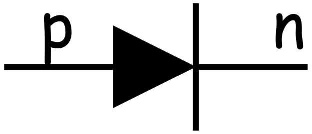
Carriers are accelerated to an energy above the gap before they scatter. They generate more electron-hole pairs. This results in an avalanche breakdown of the device.

pn junctions

pn junctions are found in:

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

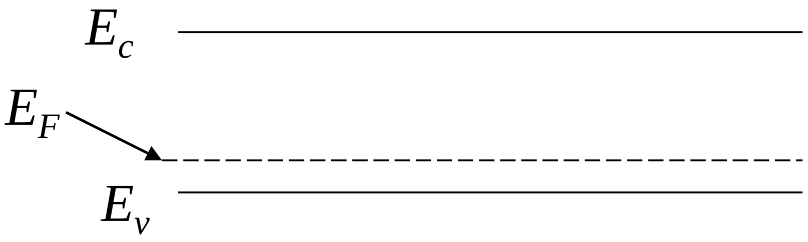




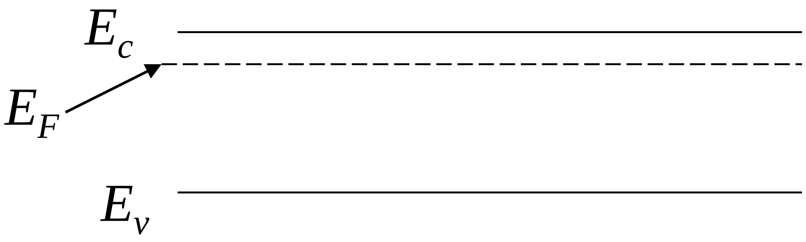
pn junction

isolated semiconductors

p-type



n-type



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

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

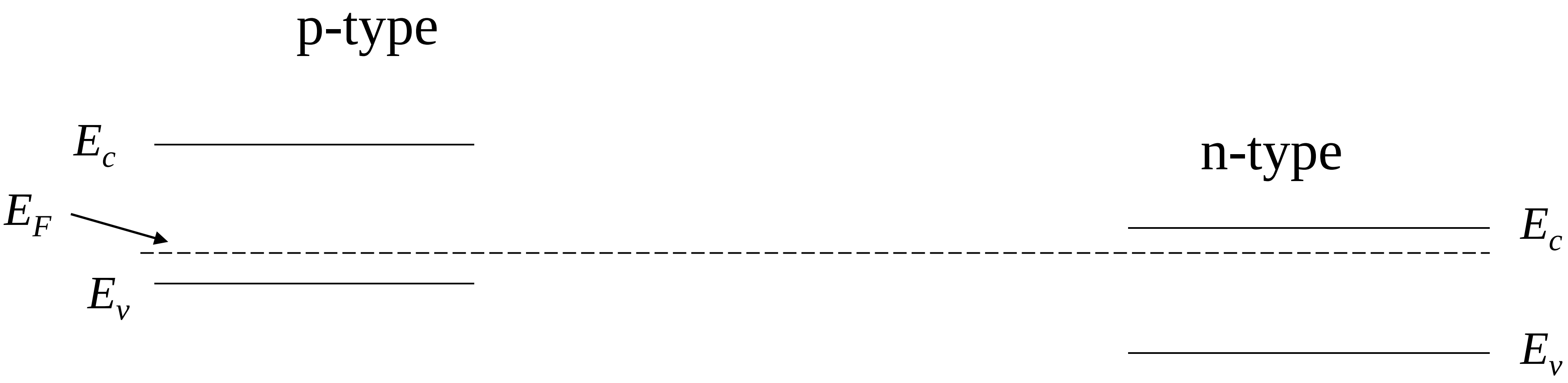
$$p = N_v \exp\left(\frac{E_v - E_F}{k_B T}\right)$$

valid for both n and p doping

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

pn junction

semiconductors in contact
electrons flow from n to p



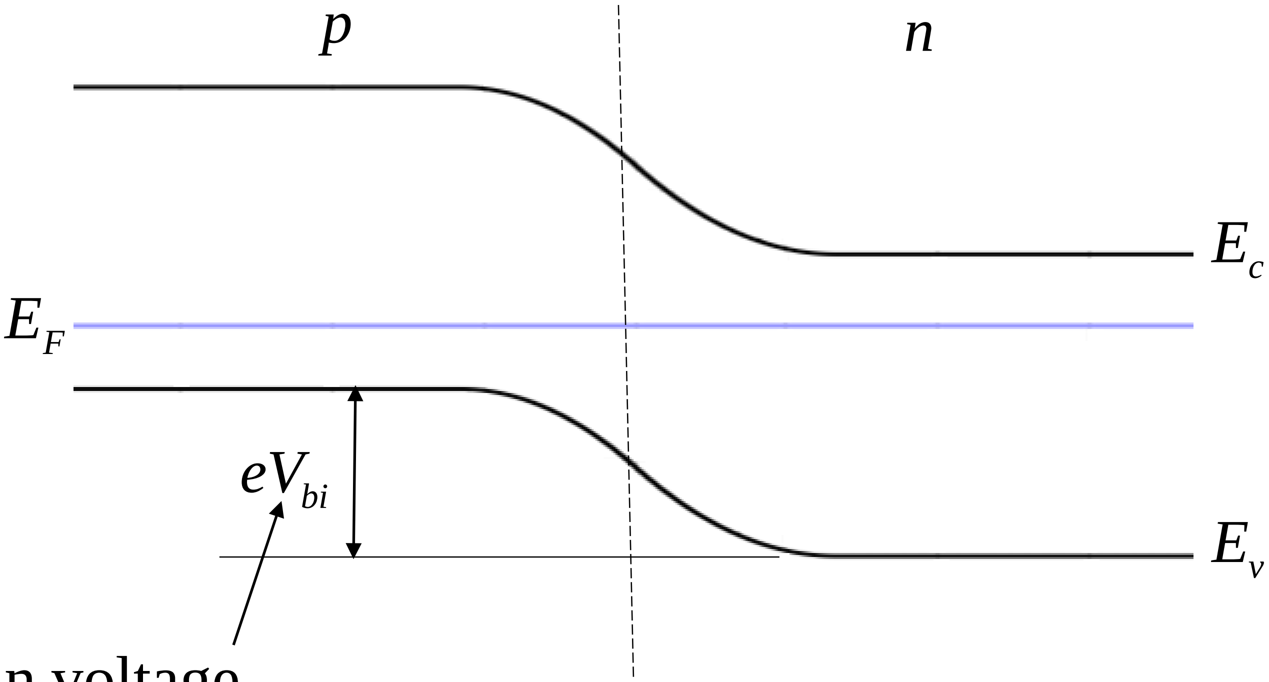
$$E_F = E_v + k_B T \ln\left(\frac{N_v}{N_A}\right)$$

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

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

pn junction

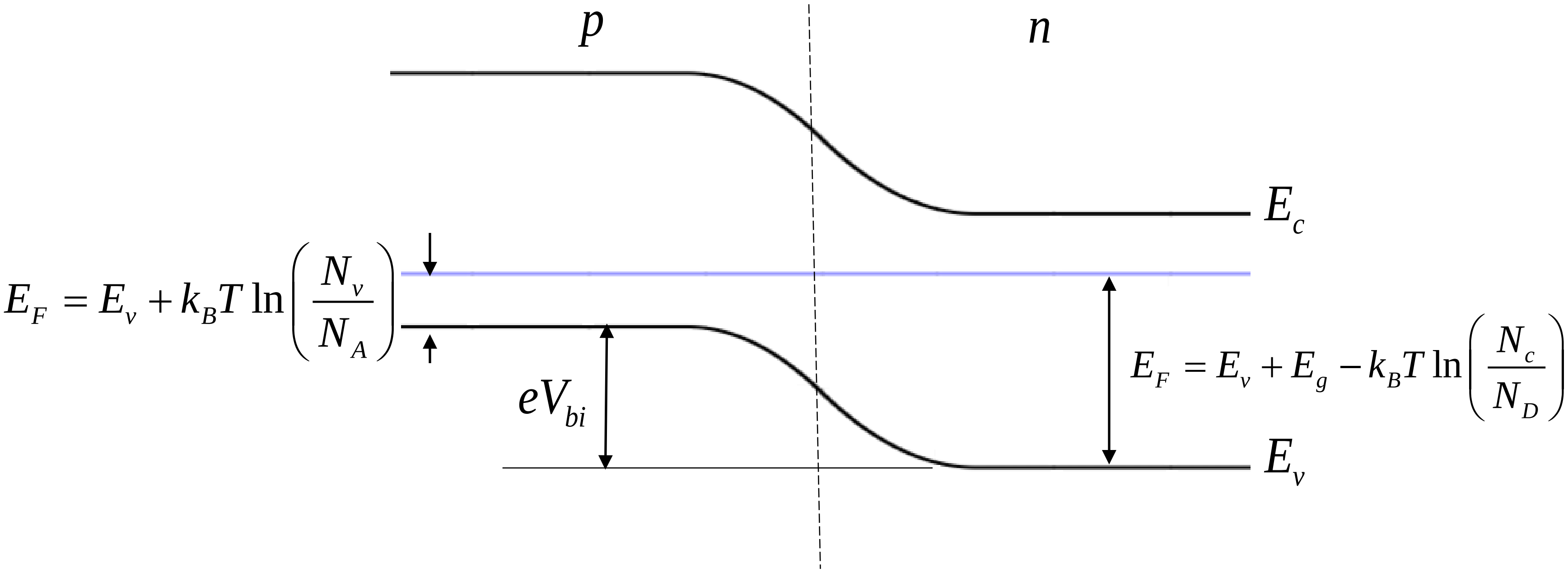
semiconductors in contact



Built-in voltage

Abrupt junction: the doping changes abruptly from p to n

Built-in voltage V_{bi}



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

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

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

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

V$_{bi}$

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

$$n_i^2 = N_v N_c \exp\left(\frac{-E_g}{k_B T}\right)$$

$$E_g = -k_B T \ln\left(\frac{n_i^2}{N_v N_c}\right)$$

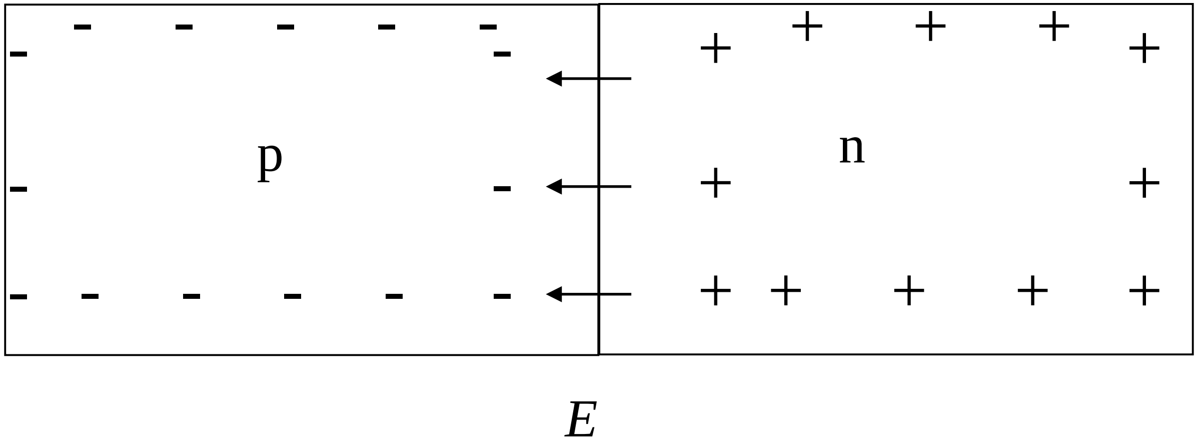
$$eV_{bi} = k_B T \ln\left(\frac{\left(N_{D,n} - N_{A,n}\right)\left(N_{A,p} - N_{D,p}\right)}{n_i^2}\right)$$

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

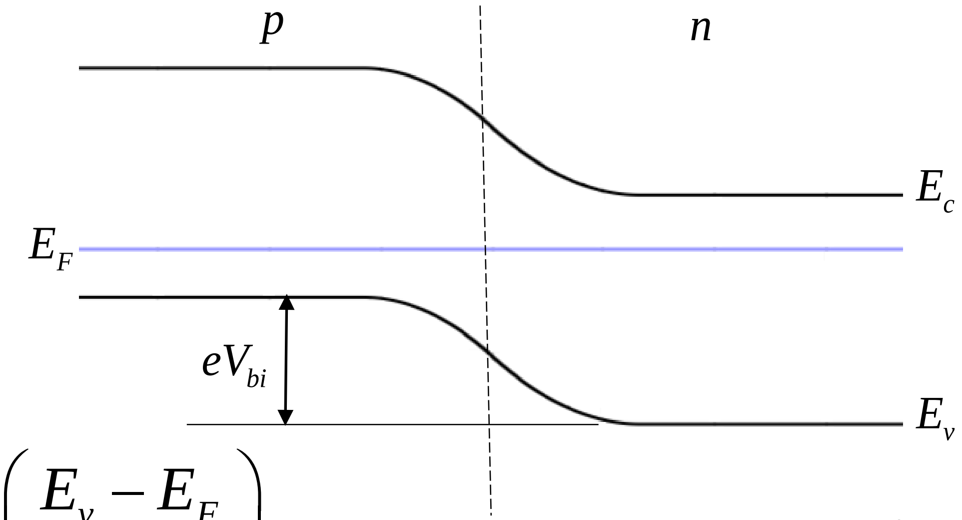
$$\boxed{eV_{bi} = k_B T \ln\left(\frac{N_D N_A}{n_i^2}\right)}$$

V_{bi}

Can V_{bi} perform work?

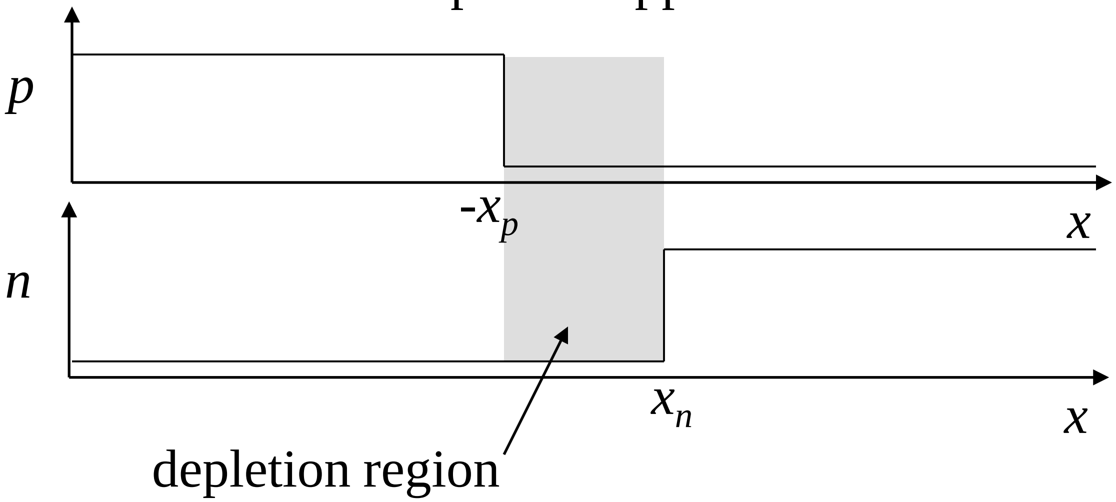


p and n profiles

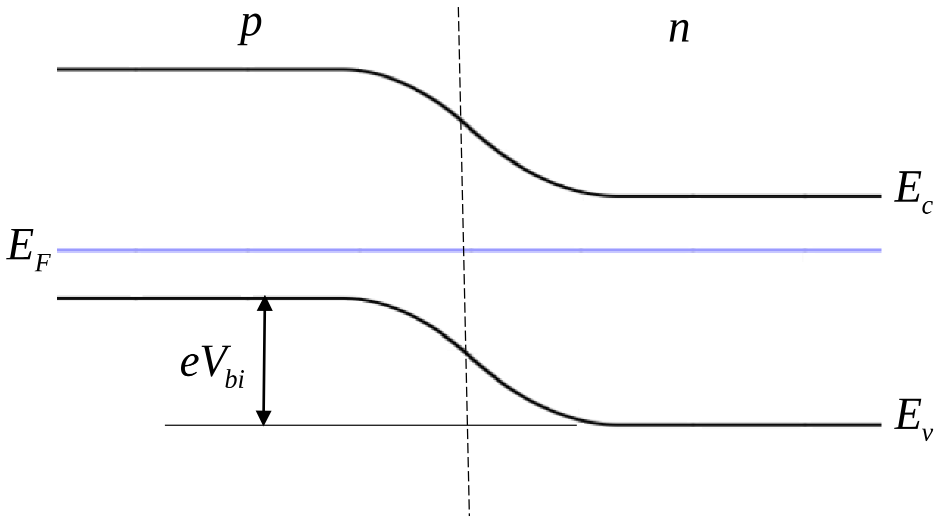


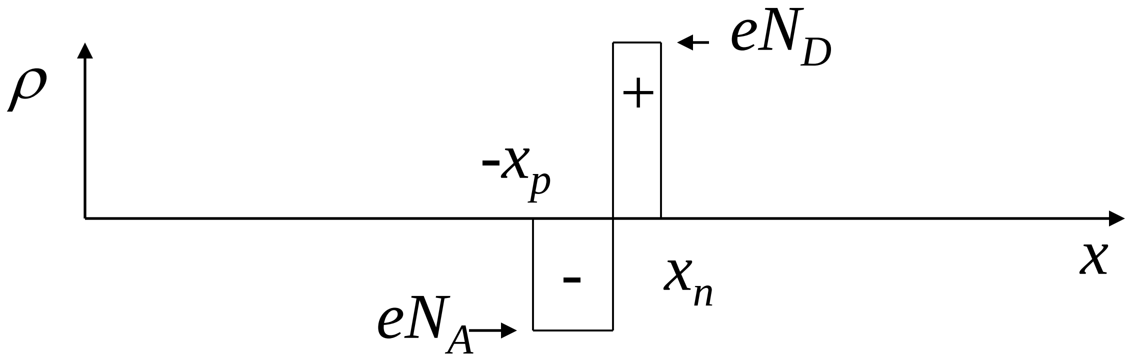
$$p = N_v \exp\left(\frac{E_v - E_F}{k_B T}\right) \qquad n = N_c \exp\left(\frac{E_F - E_c}{k_B T}\right)$$

depletion approximation



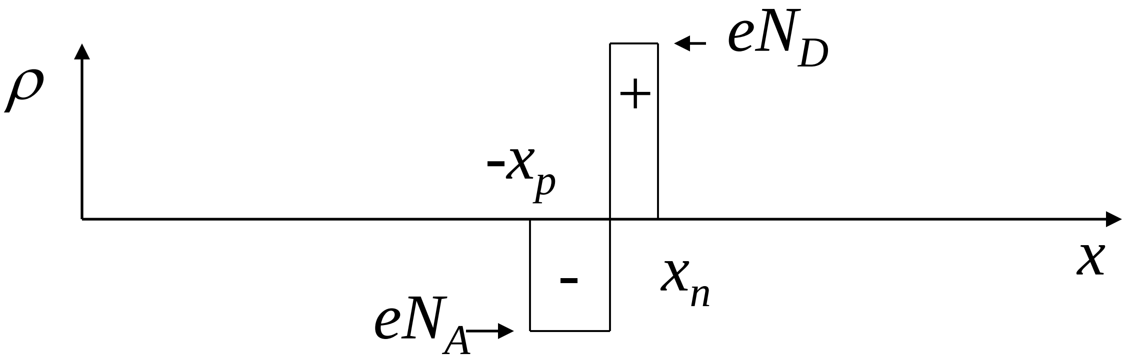
space charge



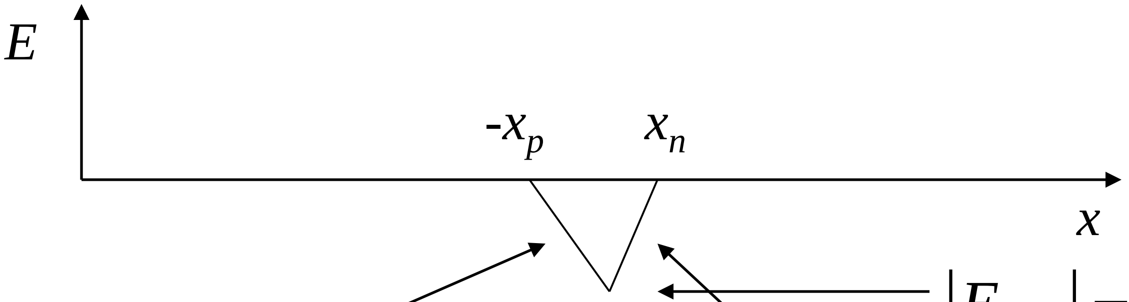


$$N_A x_p = N_D x_n$$

electric field



Gauss's law $\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon}$ in 1-D is $\frac{dE}{dx} = \frac{\rho}{\varepsilon}$



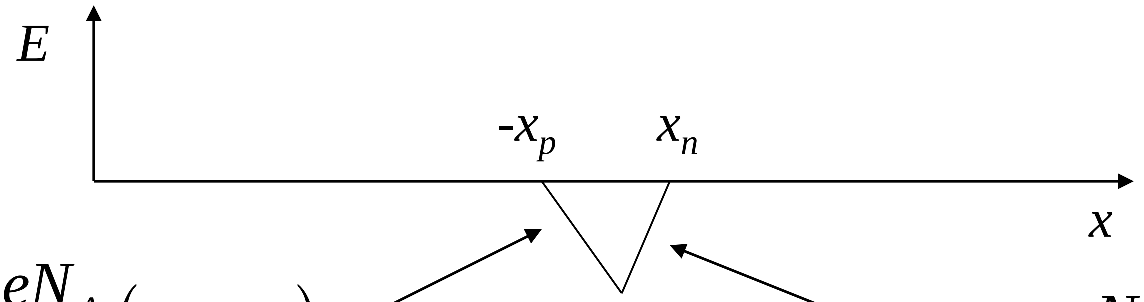
$$E = -\frac{eN_A}{\varepsilon}\left(x + x_p\right)$$

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

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

E pushes the holes towards p and the electrons towards n

potential



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

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

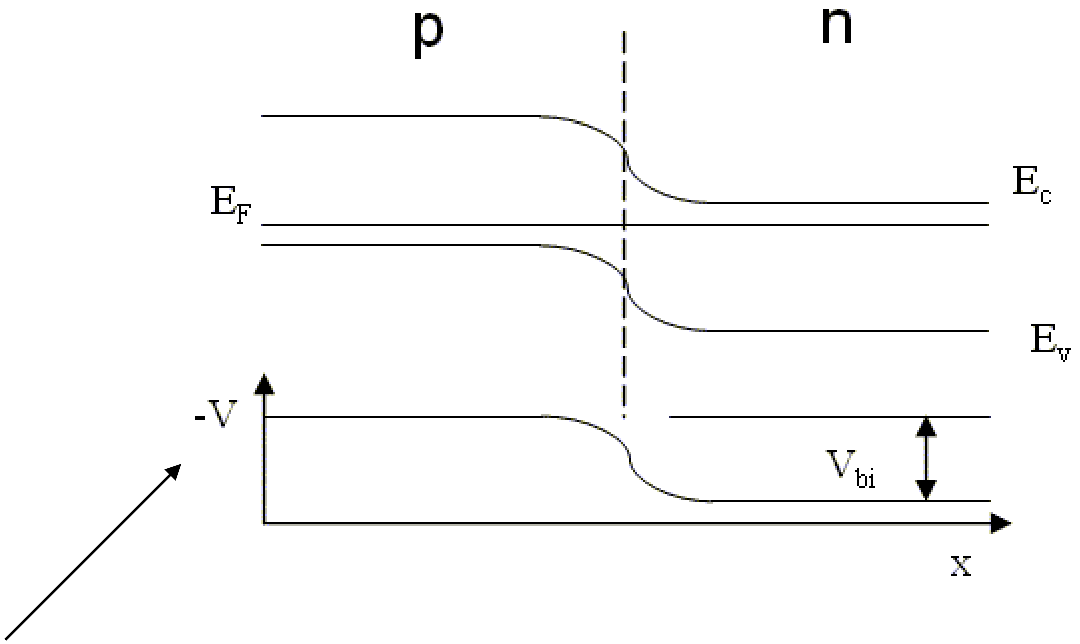
$$\frac{dV}{dx} = -E$$

$$V = \frac{eN_A}{\varepsilon}\left(\frac{x^2}{2} + xx_p\right) \qquad -x_p > x > 0$$

$$V = \frac{-eN_D}{\varepsilon}\left(\frac{x^2}{2} - xx_n\right) \qquad 0 > x > x_n$$

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

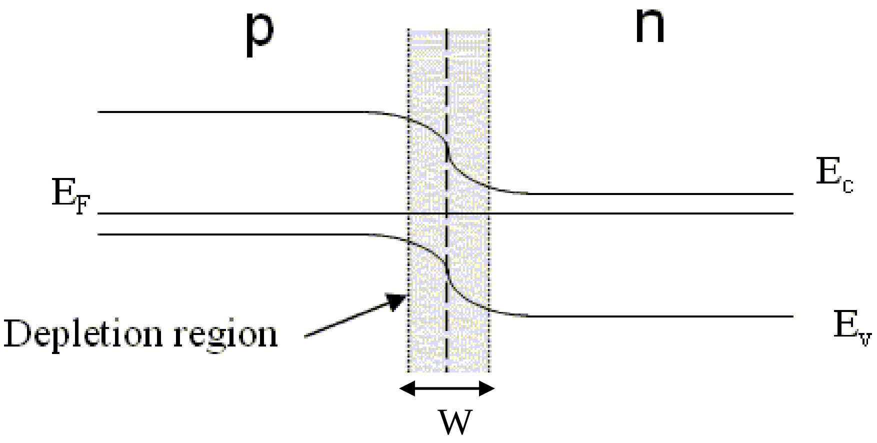
potential



electron energies are plotted in band diagram

$$V_{bi} = \frac{eN_A x_p^2}{2\varepsilon} + \frac{eN_D x_n^2}{2\varepsilon}$$

Depletion width



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

$$N_A x_p = N_D x_n = N_D\left(W - x_p\right) = N_A\left(W - x_n\right)$$

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

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

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

light doping => wide depletion width

p-n junction

A silicon p-n diode has a doping of $N_d = 5\text{E}+18\ \text{cm}^{-3}$ and $N_a = 3\text{E}+15\ \text{cm}^{-3}$. What are the depletion width in the n-region, the depletion width in the p-region, and the built-in potential at 300 K? Use the depletion approximation.

For Si: $n_i = 1.5 \times 10^{10}\ \text{cm}^{-3}$, $\varepsilon_r = 11.9$.

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

$W_n =$ ______ m

$W_p =$ ______ m

$V_{bi} =$ ______ V

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

Submit answer   Clear

Upload solutions, questions, or comments with the buttons below.

Upload text

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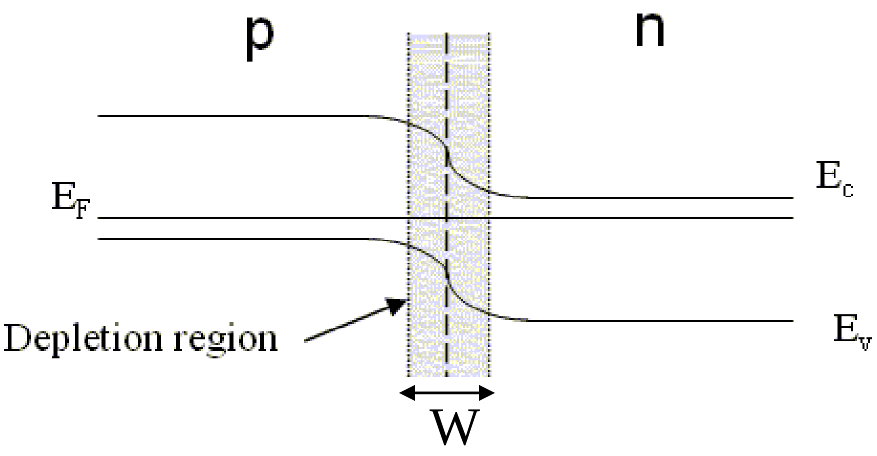
$$x_p = \frac{N_D W}{N_A + N_D} \qquad x_n = \frac{N_A W}{N_A + N_D}$$

Depletion width



$V_{bi} \sim 1\mathrm{V}$

$W \sim 1\mu\mathrm{m}$

$E_{max} \sim 10^4\ \mathrm{V/cm}$

$v_{sat} \sim 10^7\ \mathrm{cm/sec}$

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

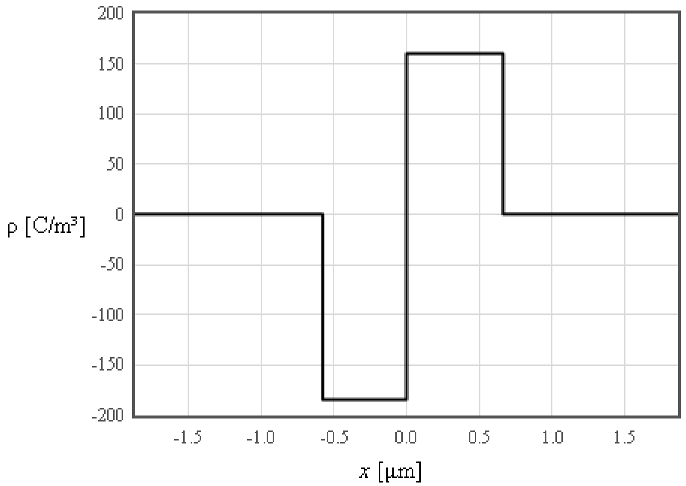
Diffusion sends electrons towards the p-region and holes towards the n-region.

Abrupt pn junctions in the depletion approximation

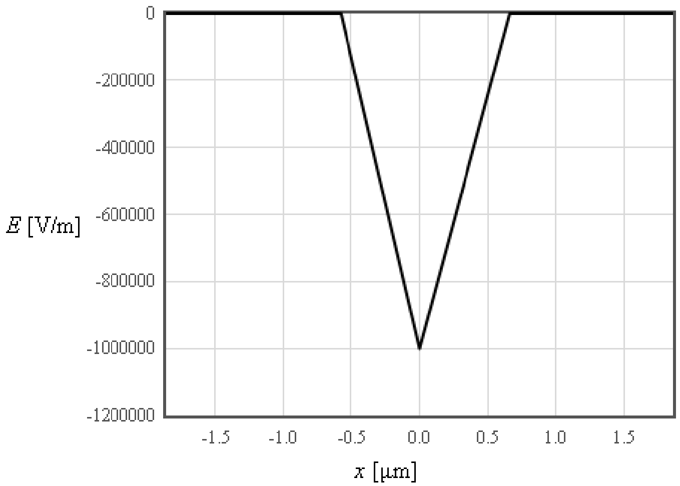
In an abrupt pn junction, the doping changes abruptly from p to n. It is common to solve for the band bending, the local electric field, the carrier concentration profiles, and the local conductivity in the depletion approximation. In this approximation it is assumed that there is a depletion width W 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 = 1.15E15 1/cm³ N_D = 1E15 1/cm³ T = 300 K [Start]

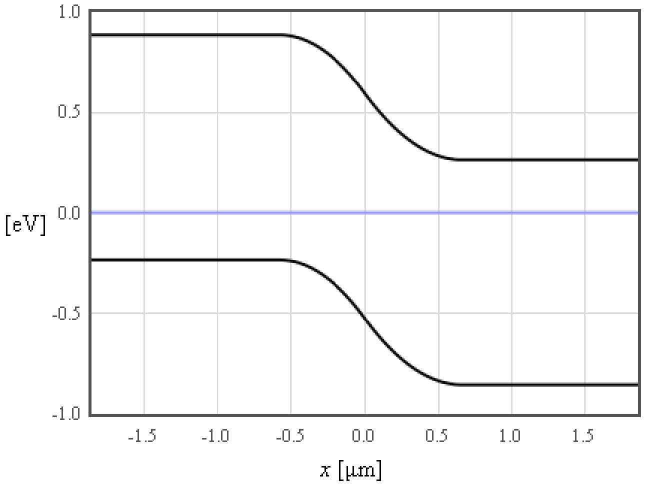
Charge density



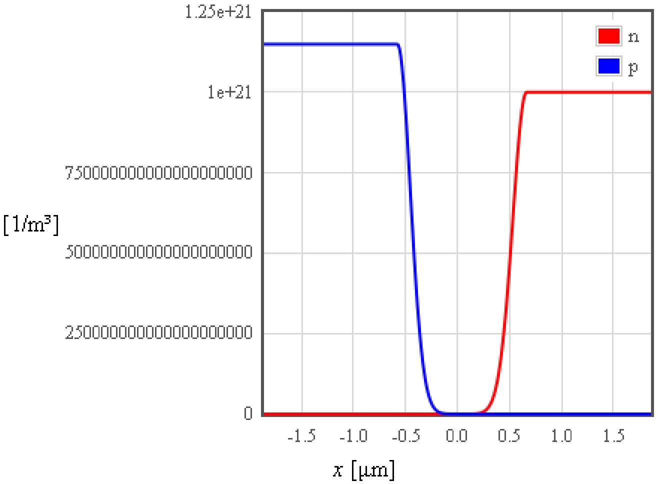
Electric field

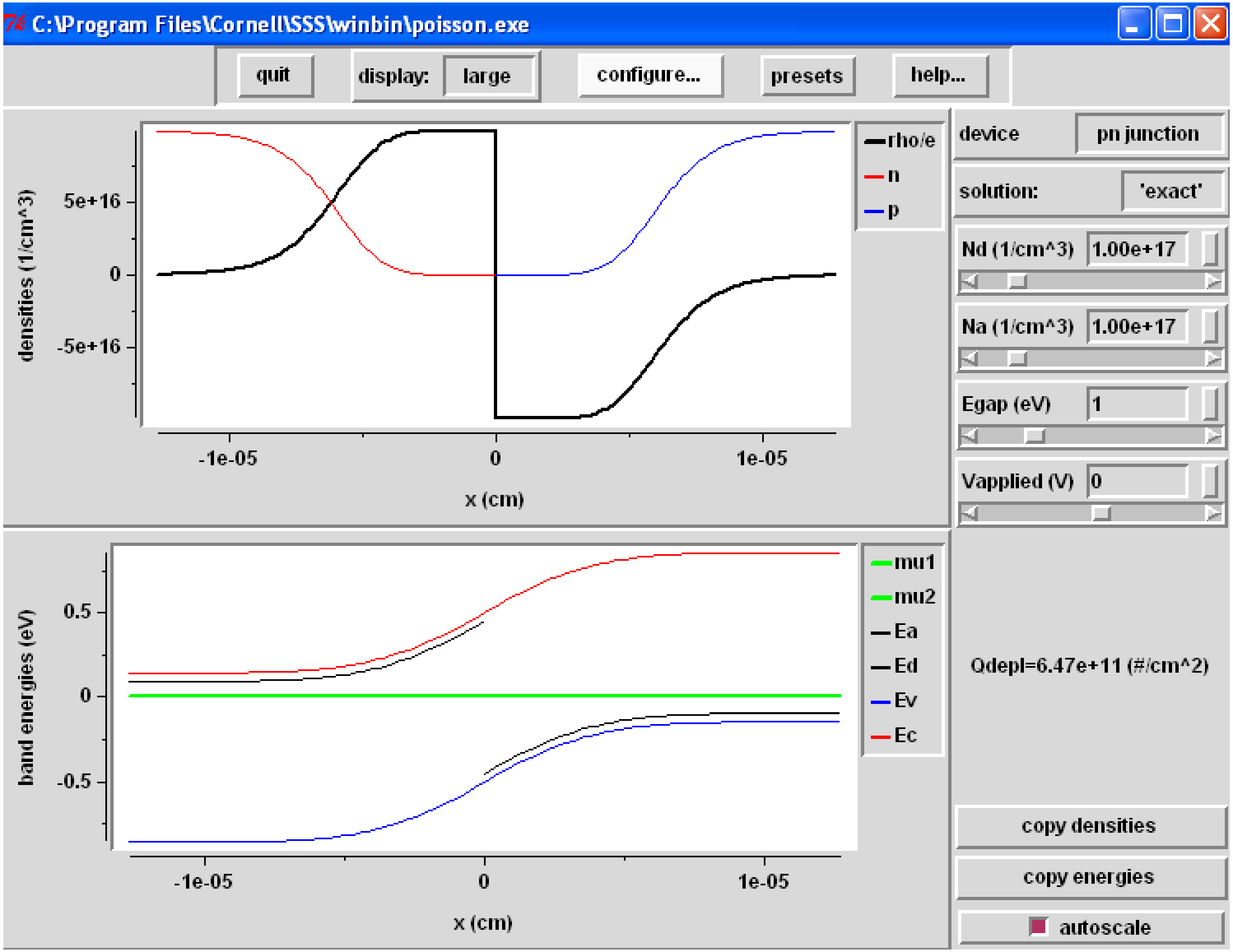


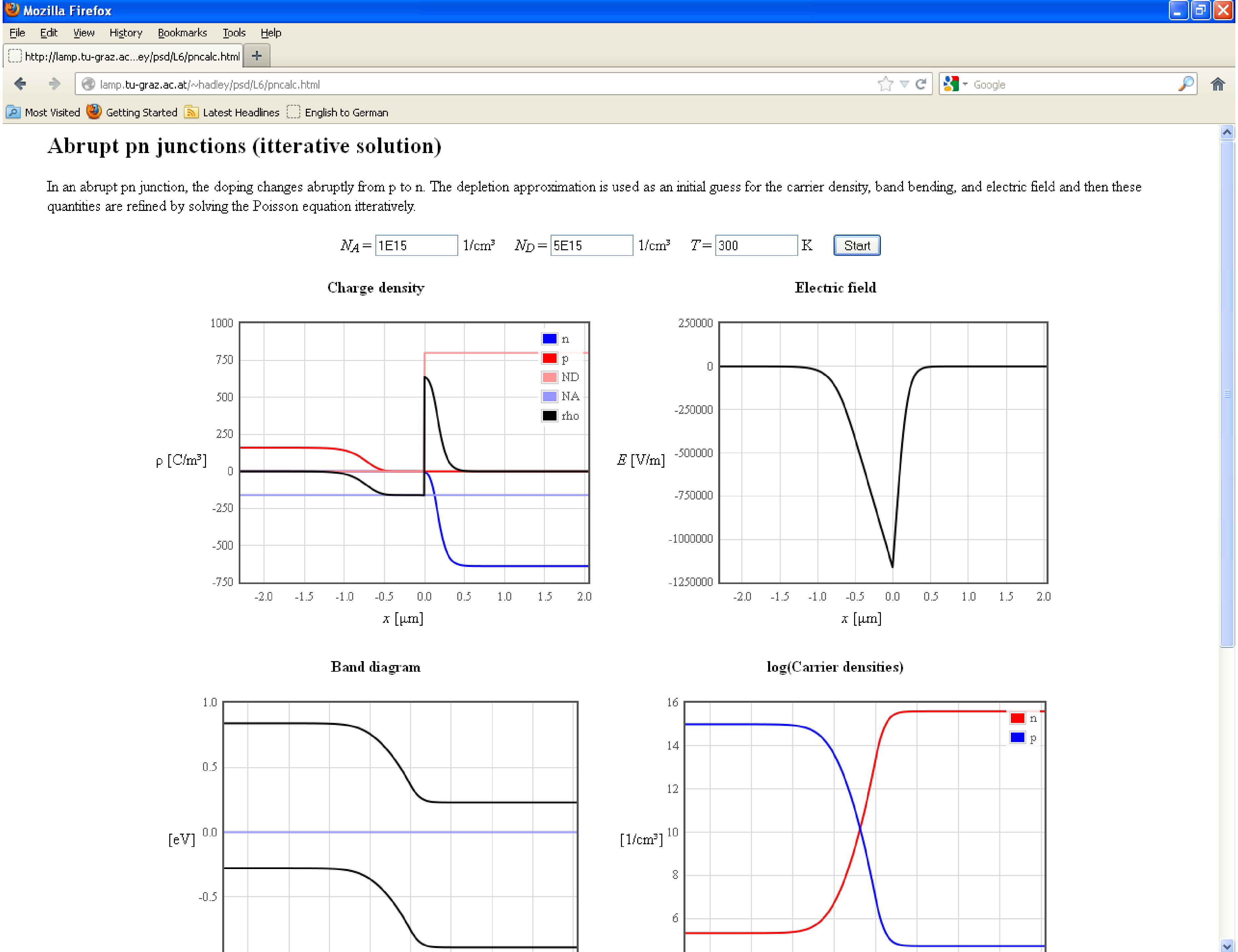
Band diagram



Carrier densities







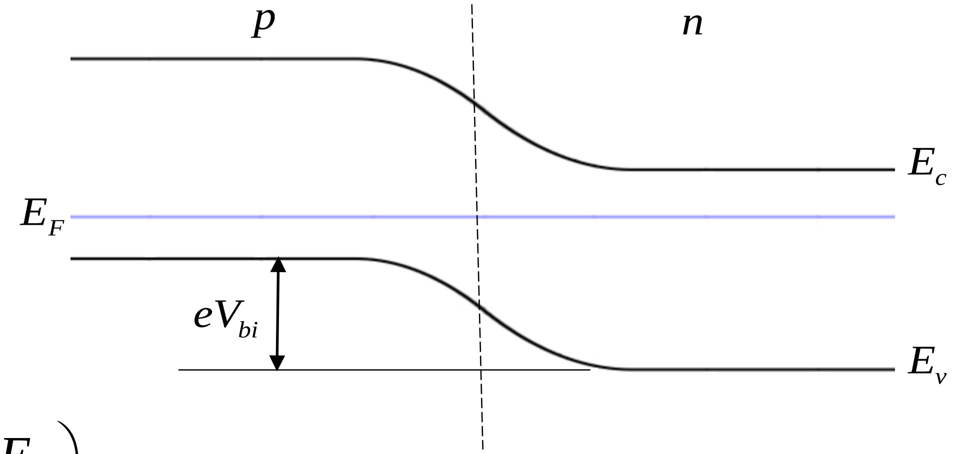
Abrupt pn junctions (itterative solution)

In an abrupt pn junction, the doping changes abruptly from p to n. The depletion approximation is used as an initial guess for the carrier density, band bending, and electric field and then these quantities are refined by solving the Poisson equation itteratively.

N_A = 1E15 1/cm³ N_D = 5E15 1/cm³ T = 300 K

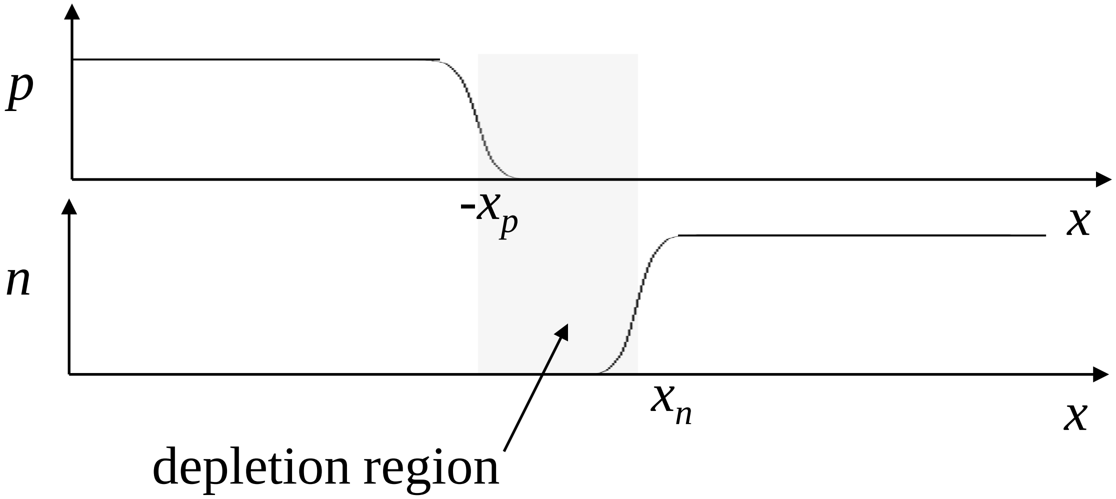
p and n profiles (again)

Knowing the voltage profile we can calculate n and p.

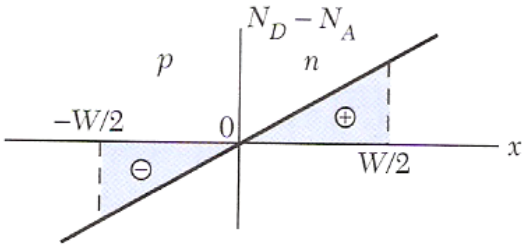


$$p = N_v \exp\left(\frac{E_F - E_v}{k_B T}\right)$$

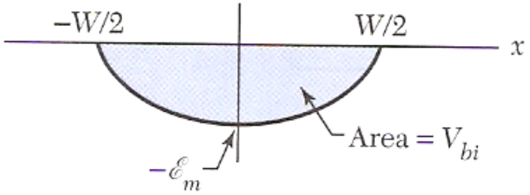
$$n = N_c \exp\left(\frac{E_c - E_F}{k_B T}\right)$$



linearly graded junction

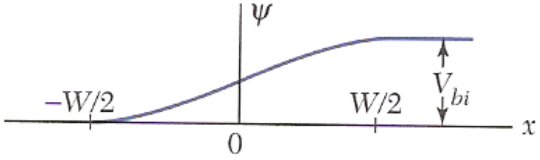


$$\rho = e\left(N_D(x) - N_A(x)\right) = eax$$

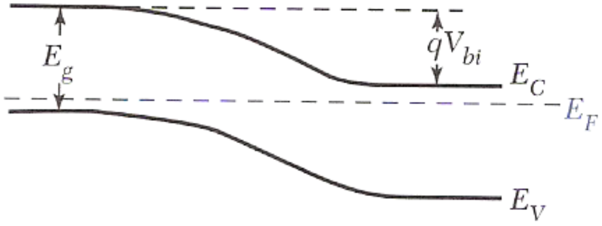


$$E = \int \frac{\rho}{\varepsilon} dx = \frac{-ea}{2\varepsilon}\left(\left(\frac{W}{2}\right)^2 - x^2\right)$$

$$E_{\max} = \frac{-eaW^2}{8\varepsilon}$$

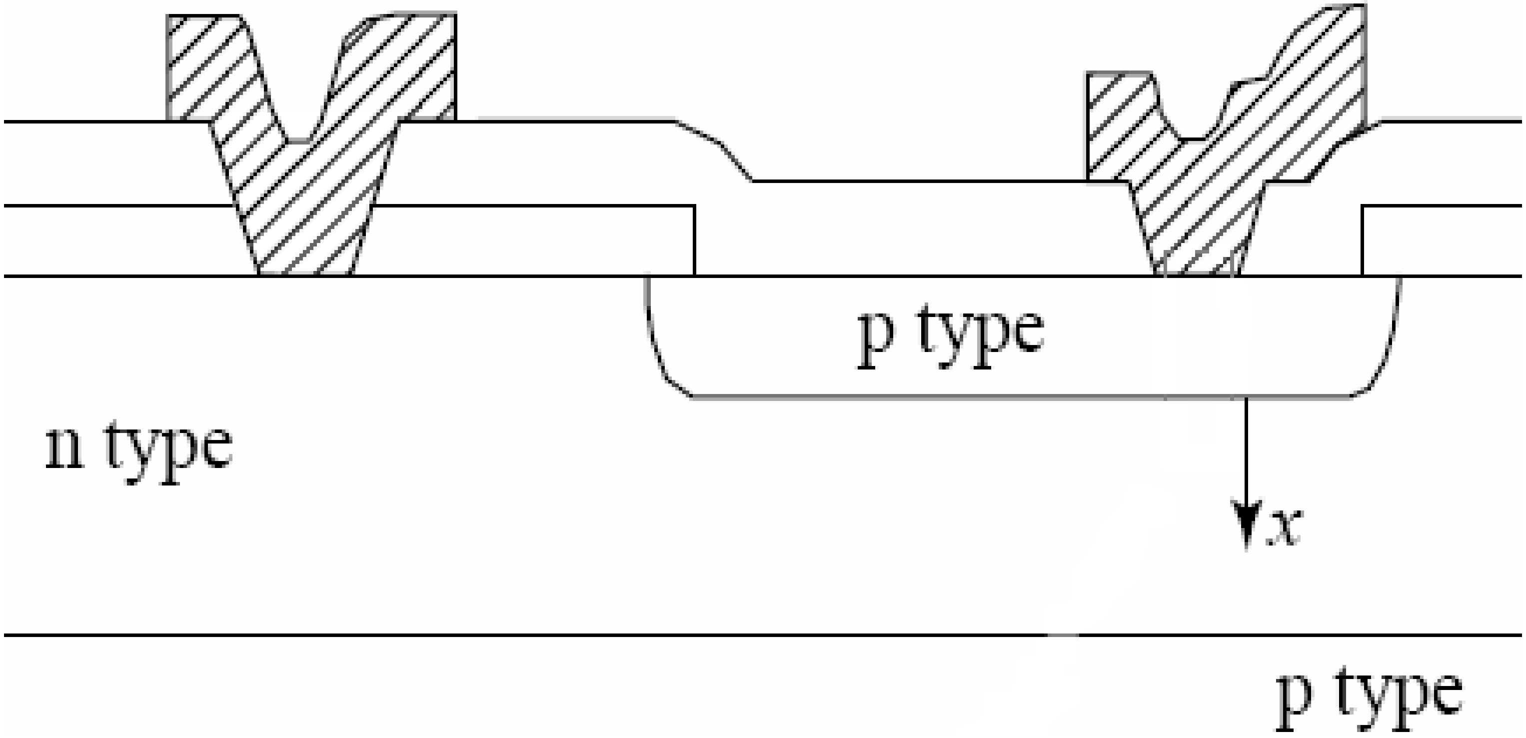


$$V = \int E dx = \frac{ea}{2\varepsilon}\left(\left(\frac{W}{2}\right)^2 x - \frac{x^3}{3}\right)$$

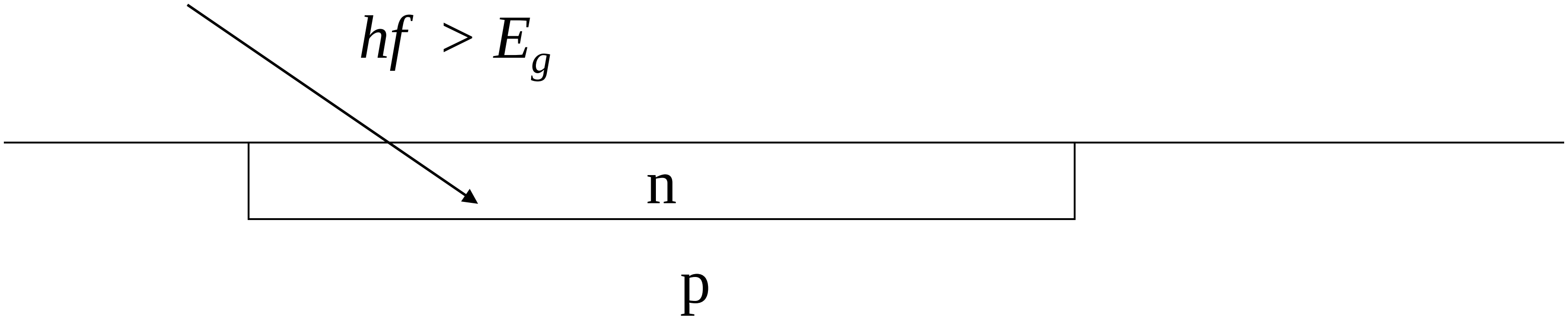


$$V_{bi} = \frac{eaW^3}{12\varepsilon}$$

Isolation

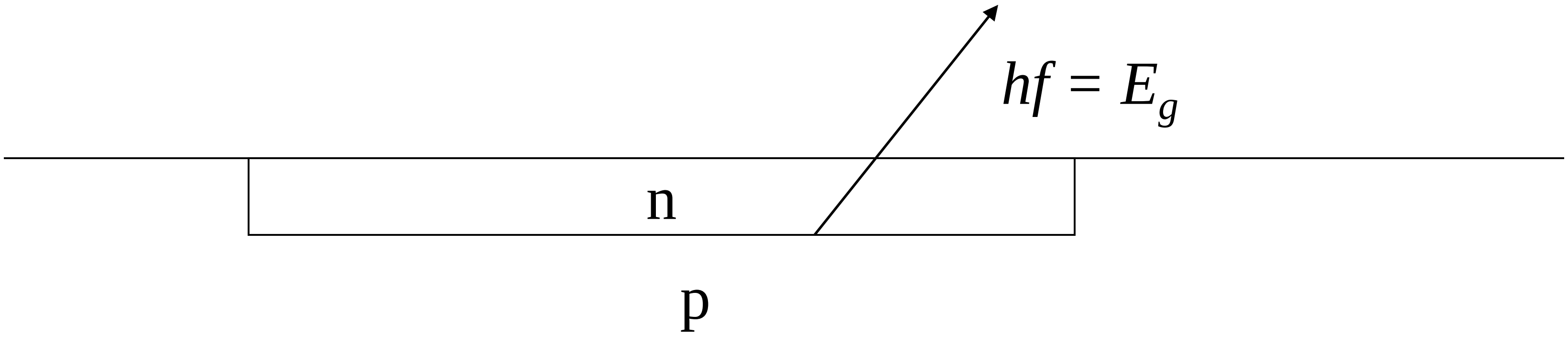


Solar cell



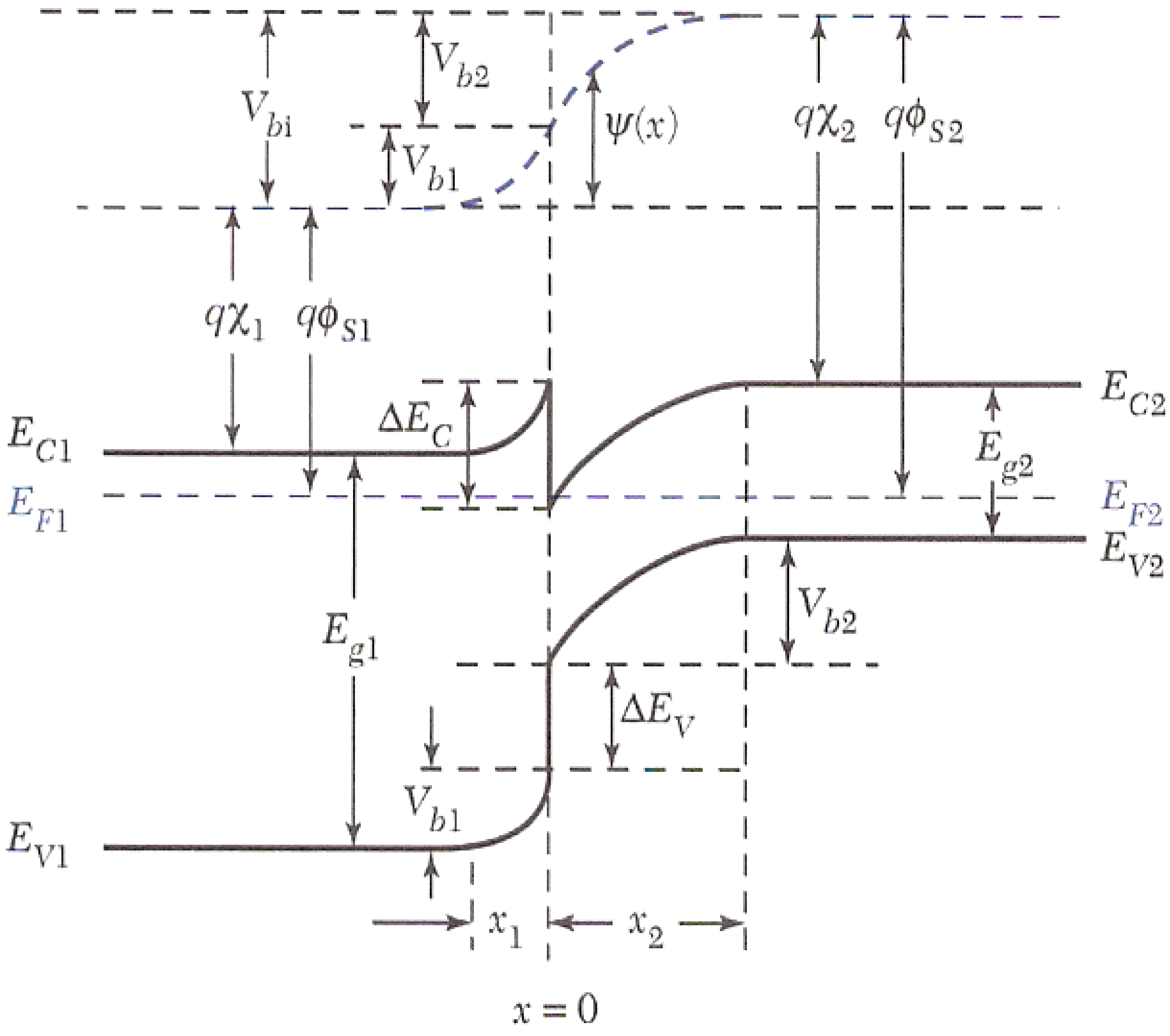
Light creates an electron-hole pair in the depletion region. The electric field sweeps the electrons towards the n-region and the holes towards the p-region.

Light emitting diode

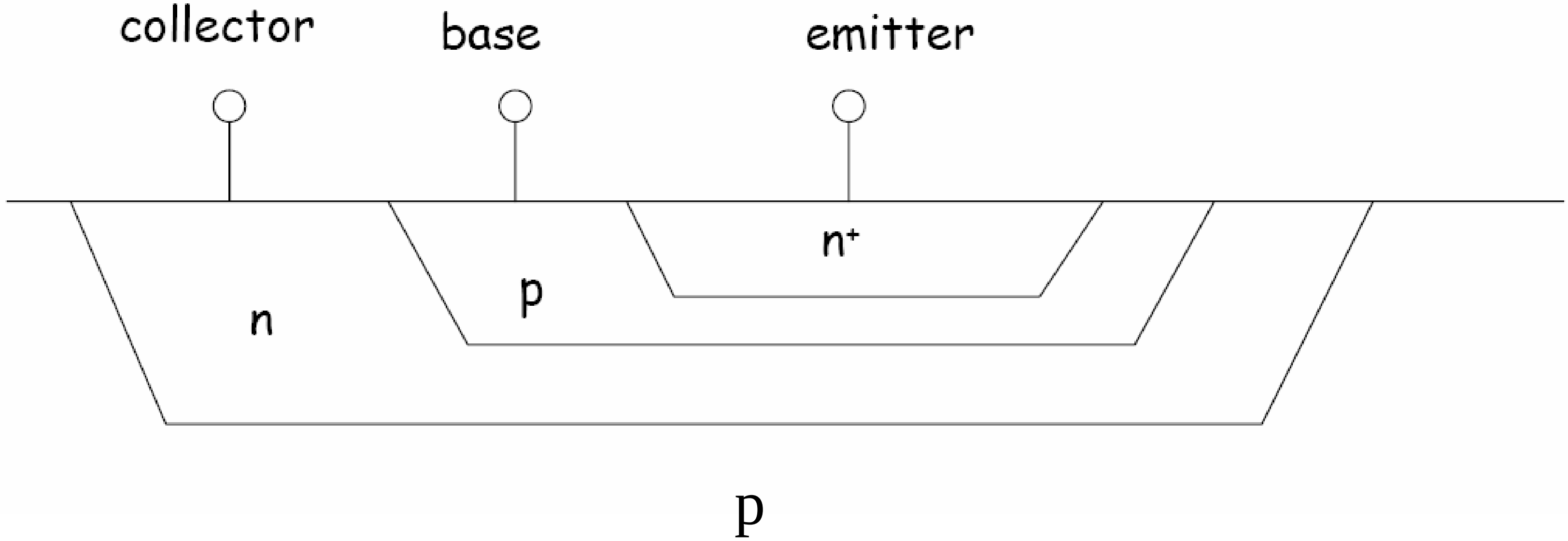


Electrons and holes are injected into the depletion region by forward biasing the junction. The electrons fall in the holes. For direct bandgap semiconductors, photons are emitted. For indirect bandgap semiconductors, phonons are emitted.

Heterojunctions

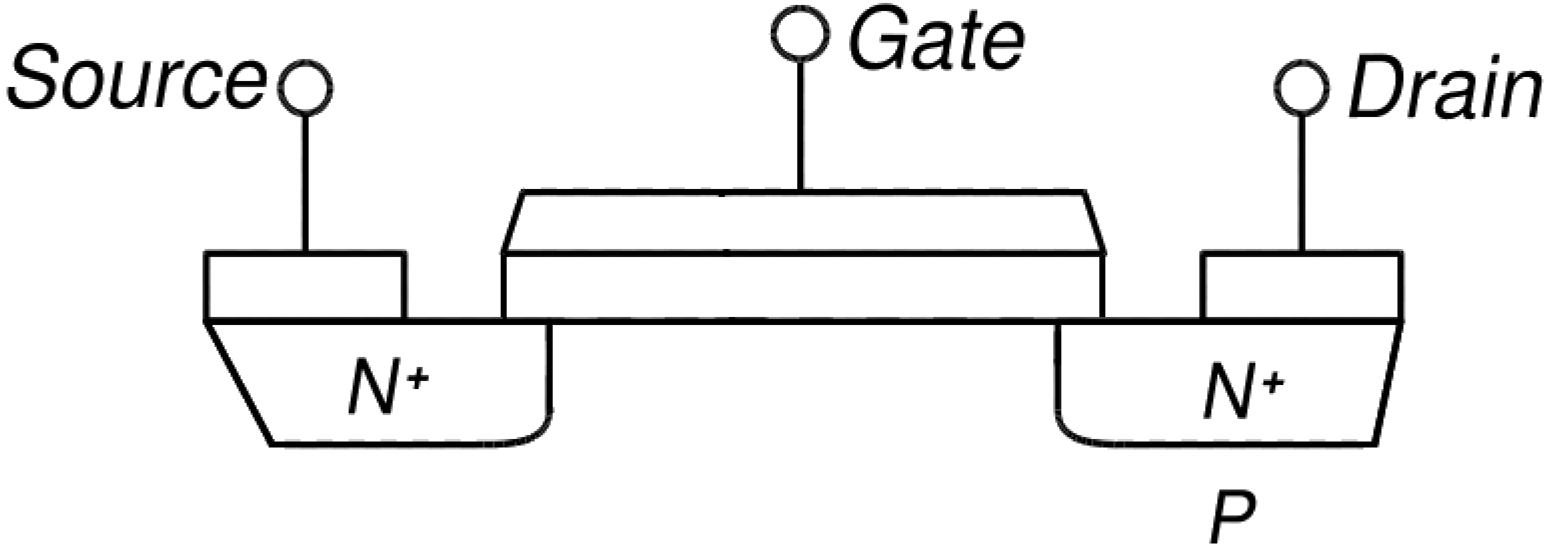


Bipolar transistor



MOSFET

Metal Oxide Semiconductor Field Effect Transistor



functions as a switch
~ 1 billion /chip

http://en.wikipedia.org/wiki/Image:Mosfet linear.s