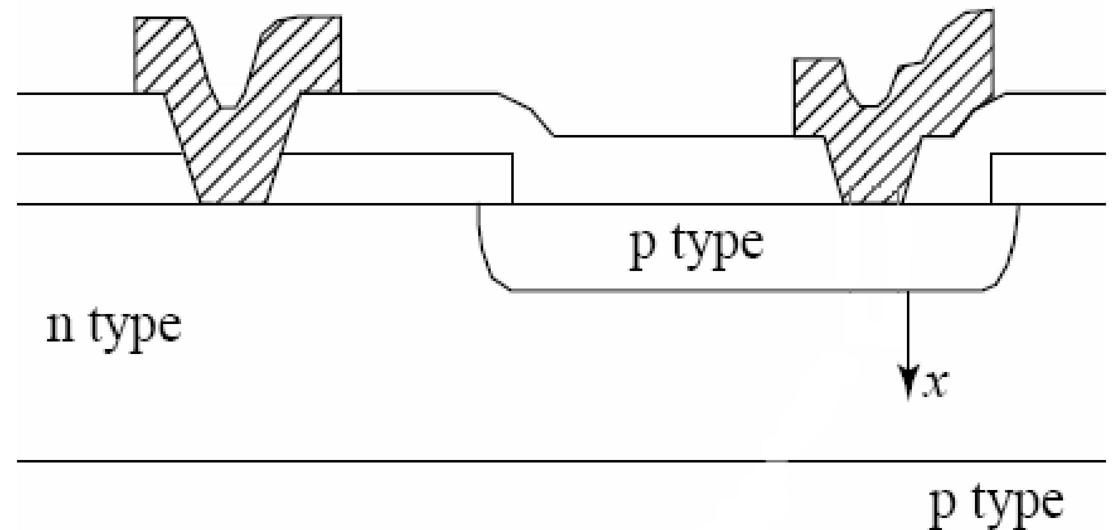
6. pn - Junctions

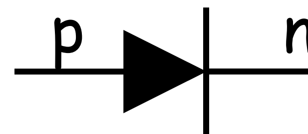
Nov. 6, 2019

pn junctions

pn junctions are found in:

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

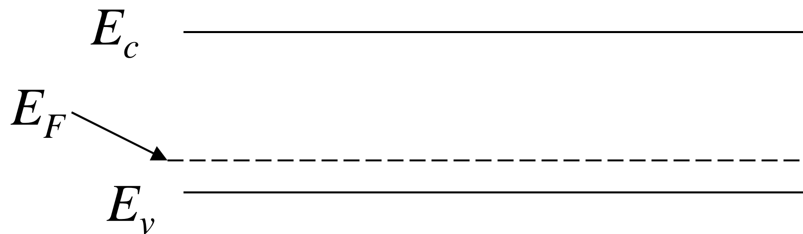




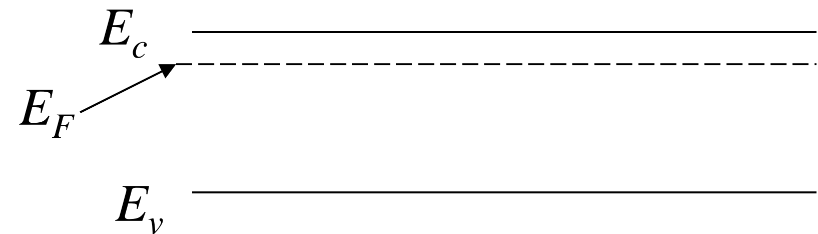
pn junction

isolated semiconductors

p-type



n-type



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

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

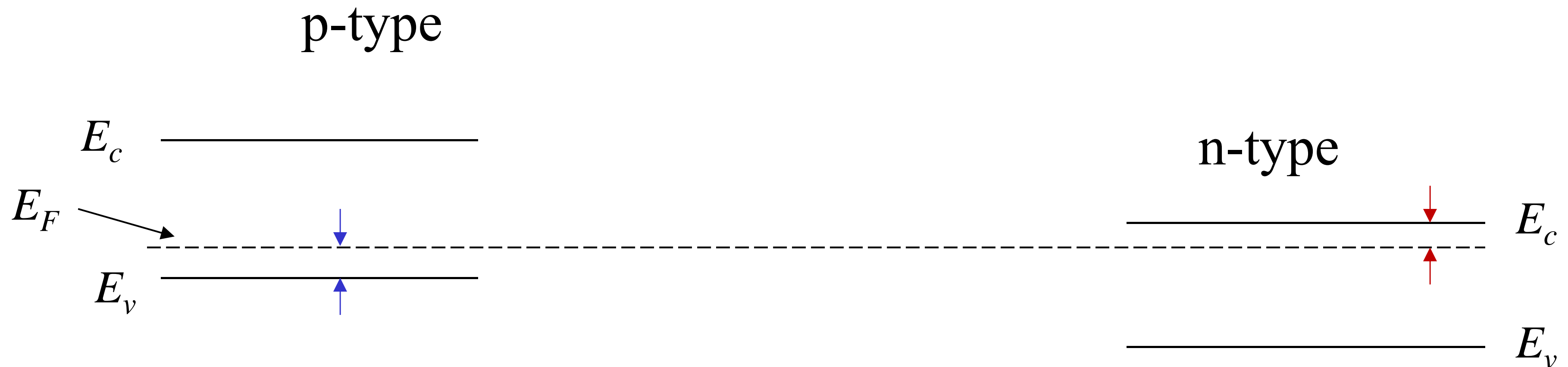
$$p = N_v \exp\left(\frac{E_v - E_F}{k_B T}\right)$$

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



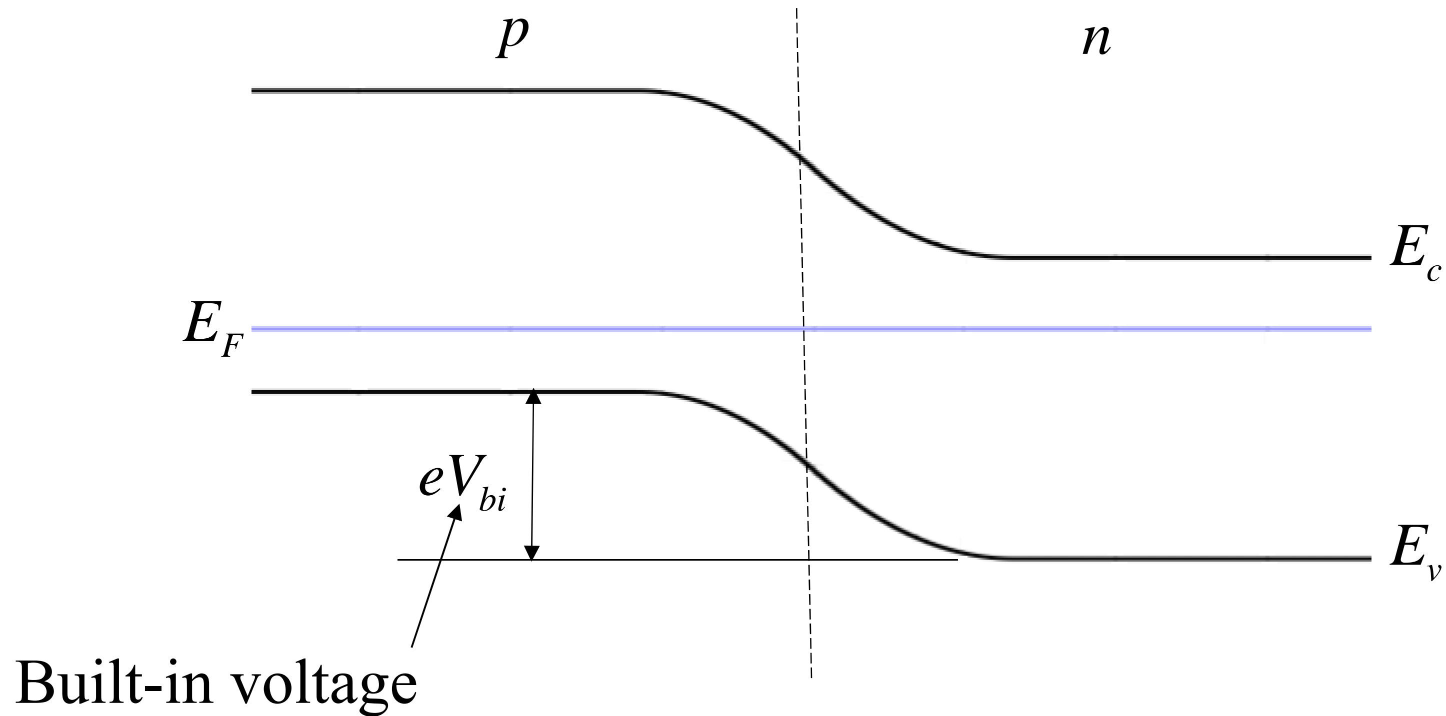
$$n = N_c \exp\left(\frac{E_F - E_c}{k_B T}\right)$$

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

valid for both n and p doping

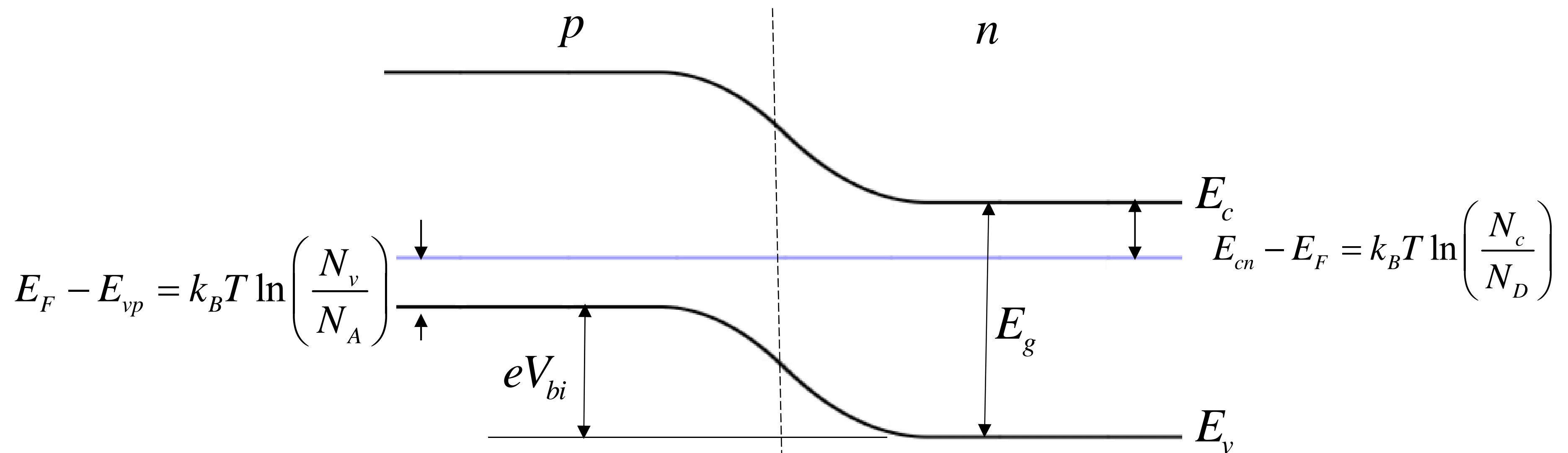
pn junction

semiconductors in contact



Abrupt junction: the doping changes abruptly from p to n

Built-in voltage V_{bi}



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

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

V_{bi}

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

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

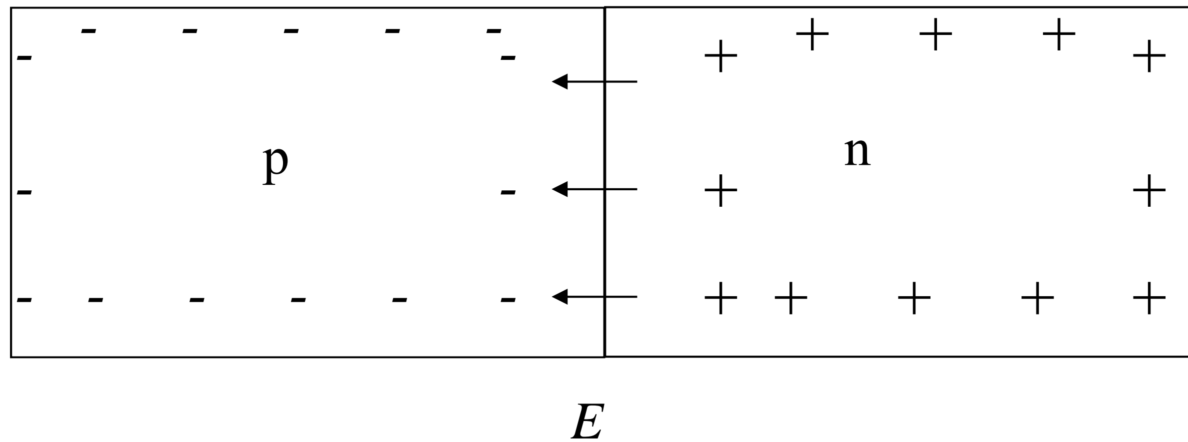
$$eV_{bi} = k_B T \ln\left(\frac{\left(N_{D,n} - N_{A,n}\right)\left(N_{A,p} - N_{D,p}\right)}{n_i^2}\right)$$

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

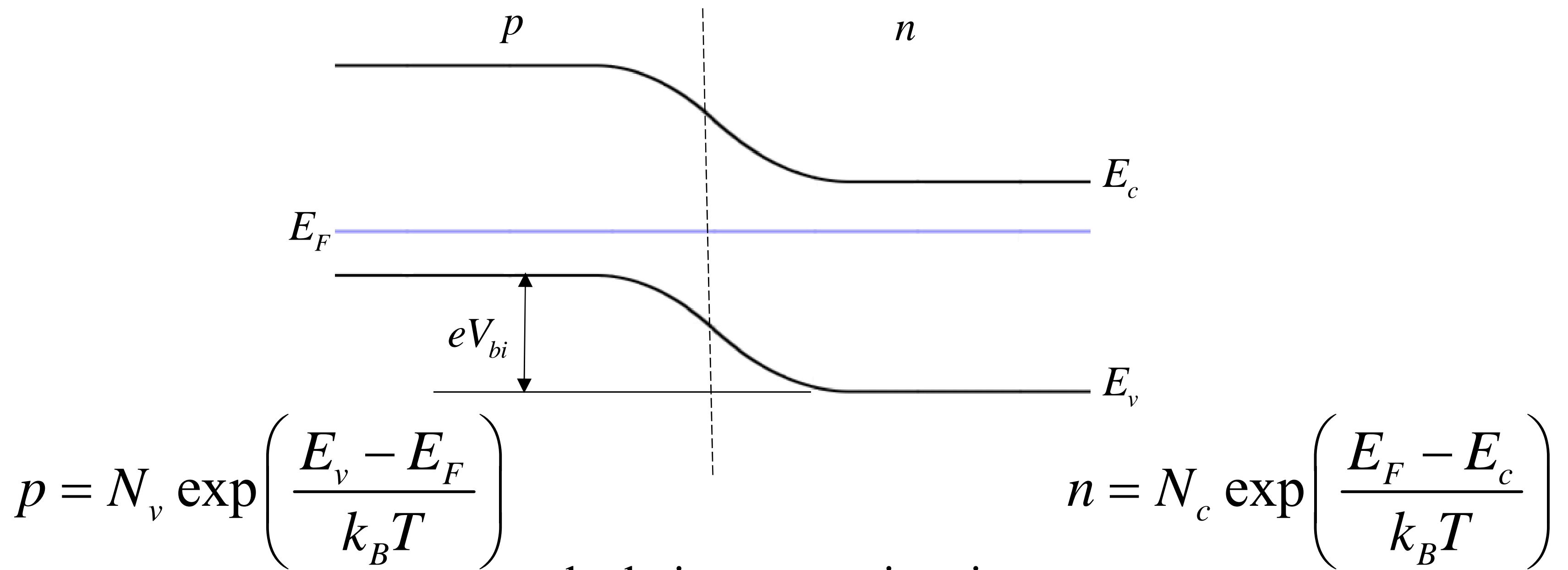
$$\boxed{eV_{bi} = k_B T \ln\left(\frac{N_D N_A}{n_i^2}\right)}$$

V_{bi}

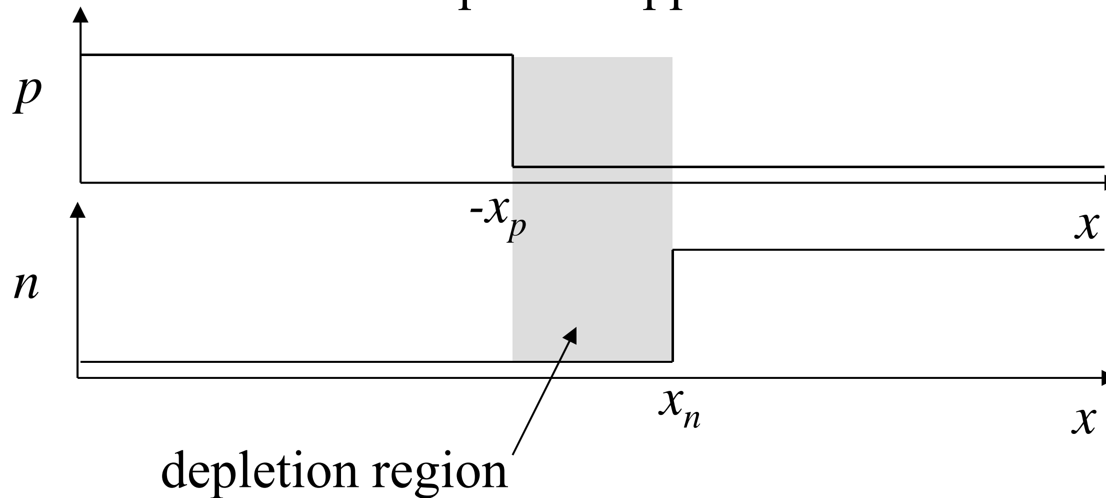
Can V_{bi} perform work?



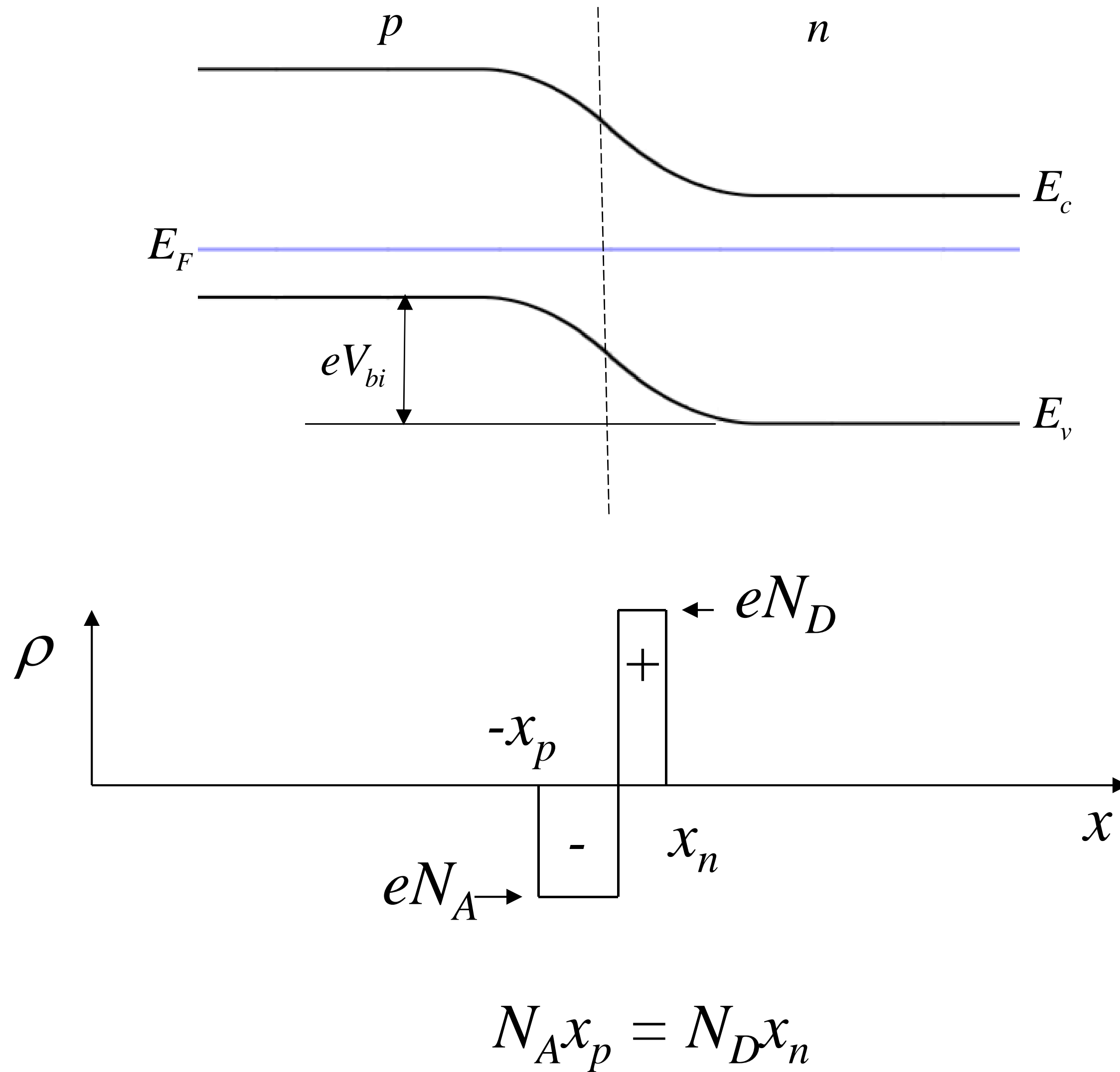
p and n profiles



depletion approximation

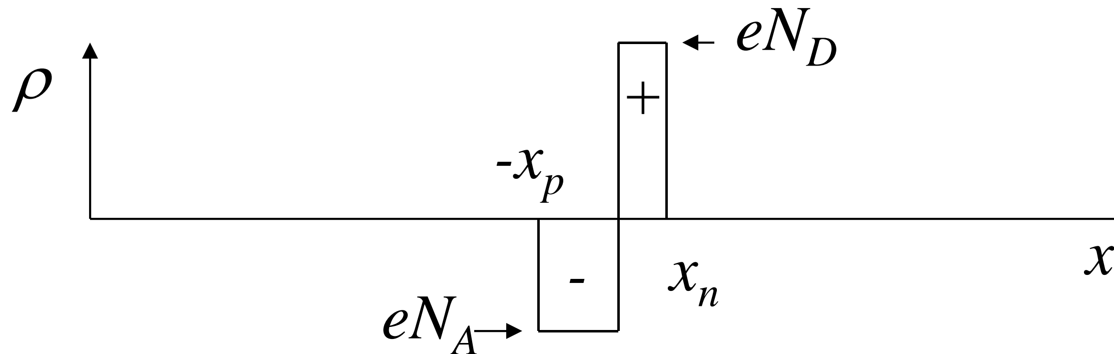


space charge

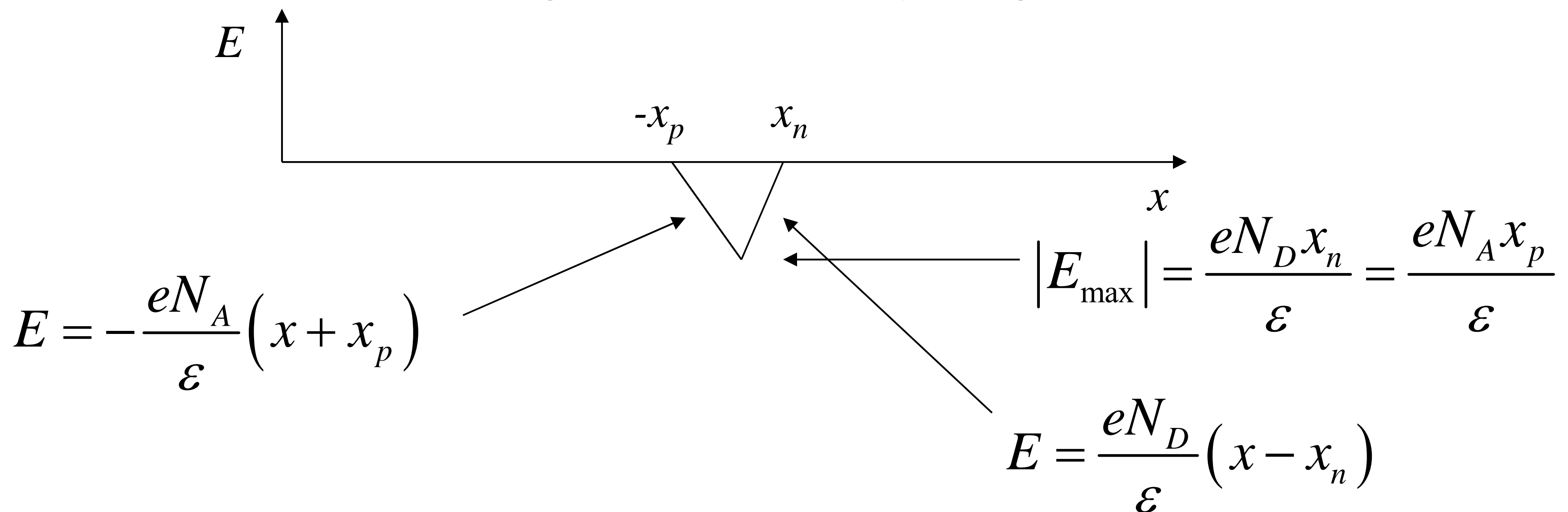


$$N_A x_p = N_D x_n$$

electric field

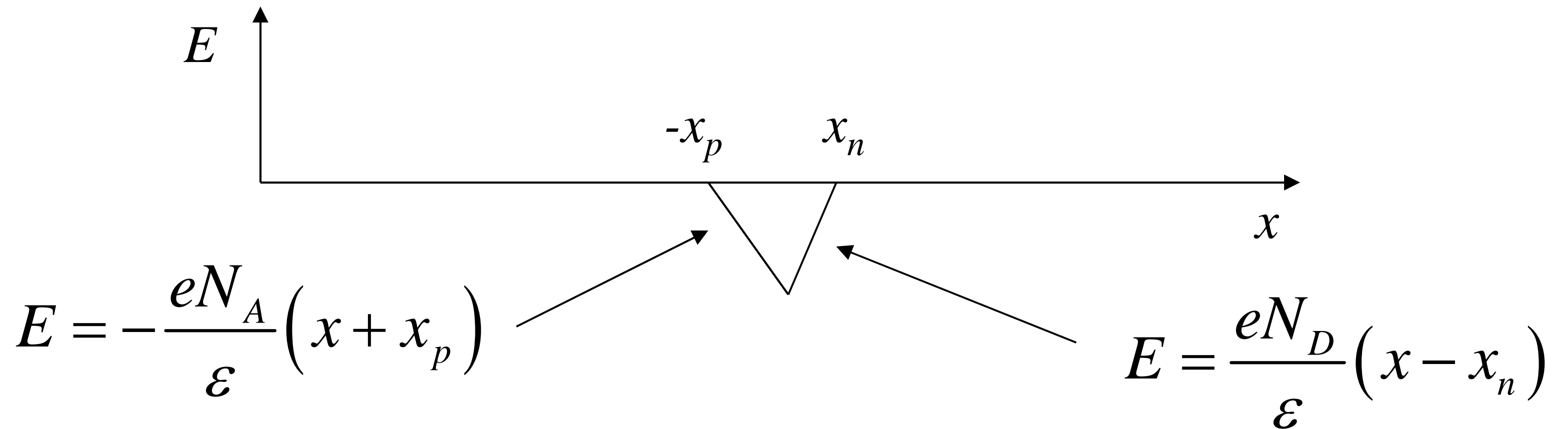


Gauss's law $\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon}$ in 1-D is $\frac{dE}{dx} = \frac{\rho}{\varepsilon}$



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

potential



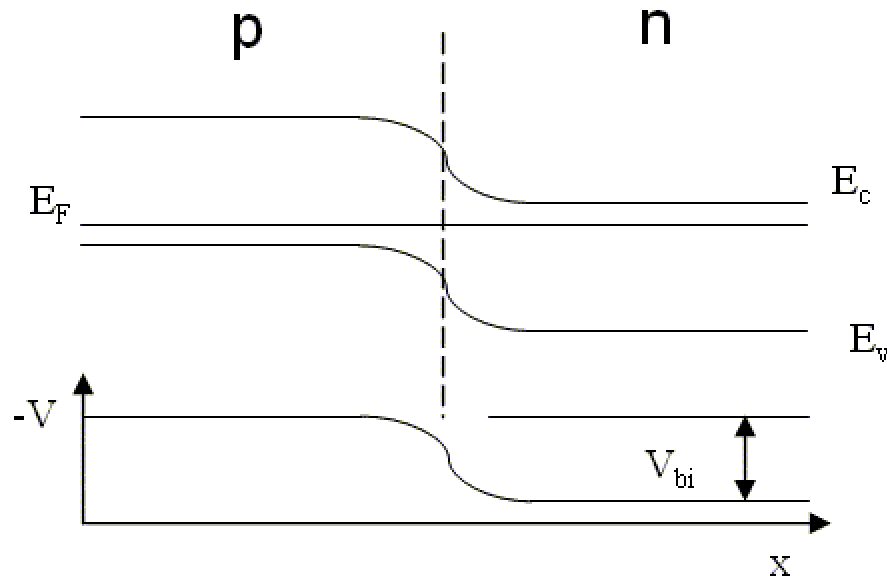
$$\frac{dV}{dx} = -E$$

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

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

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

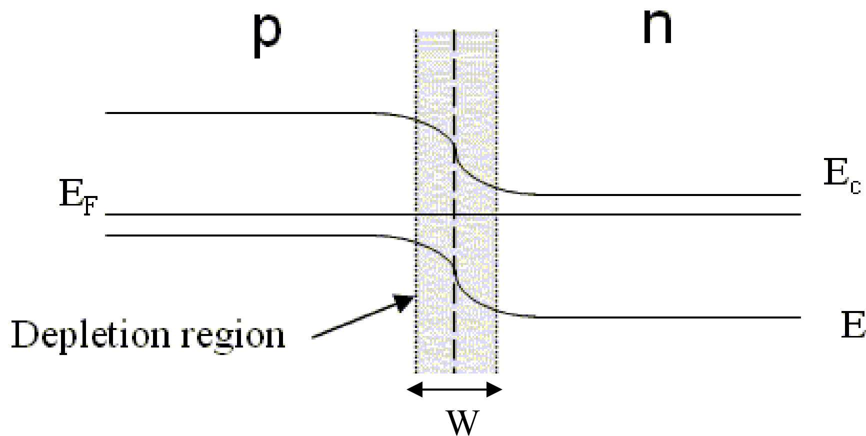
potential



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 = 5E+18 cm^{-3} and N_a = 3E+15 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: $n_i = 1.5 \times 10^{10}$ 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

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

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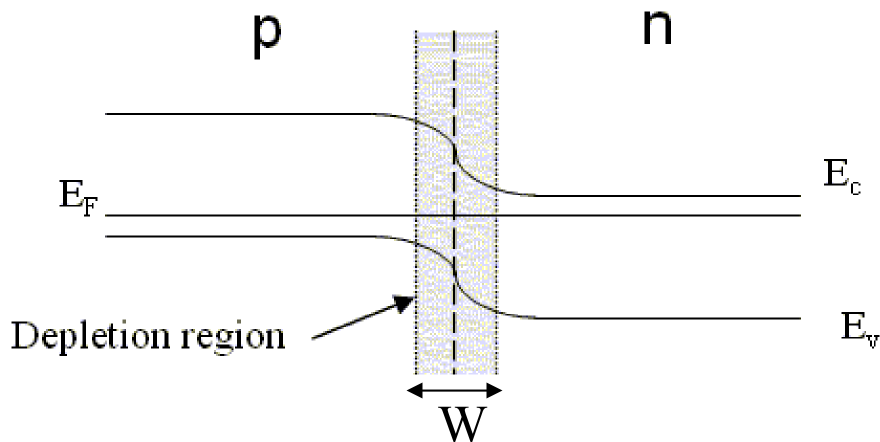
$$x_p = \frac{N_D W}{N_A + N_D} \qquad x_n = \frac{N_A W}{N_A + N_D}$$

Depletion width



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

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

$E_{max} \sim 10^4$ 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

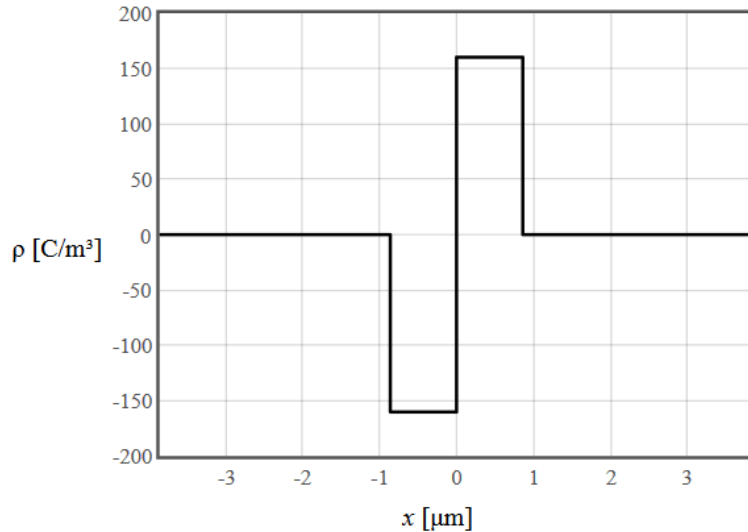
μ_p = 480 cm²/V s μ_n = 1350 cm²/V s τ_p = 1E-10 s τ_n = 1E-10 s

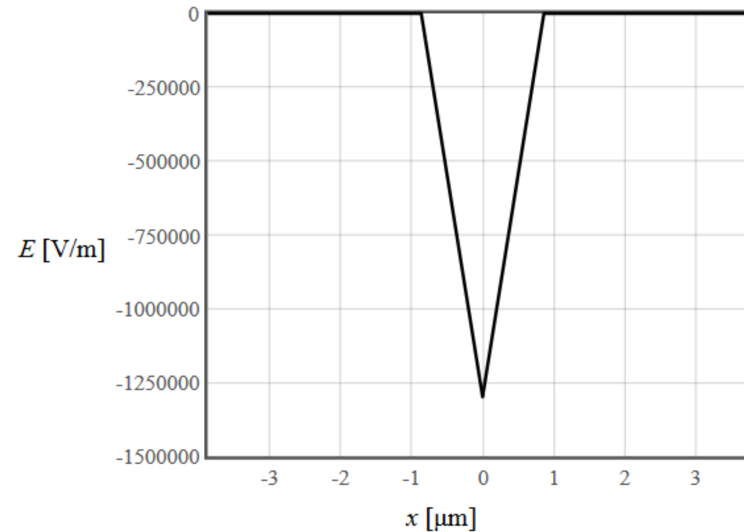
V = -0.5 V

V Submit

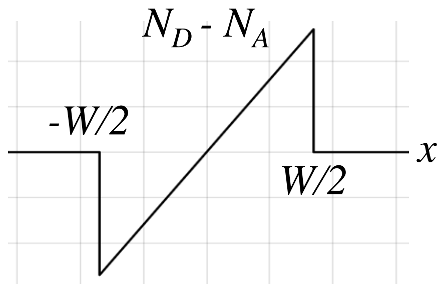
$E_g = 1.12$ eV $W = 1.72$ µm $x_p =$ -0.861 µm $x_n = 0.861$ µm $V_{bi} = 0.618$ V $C_j = 6.17$ nF/cm²

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

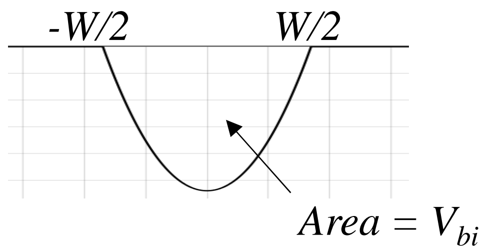




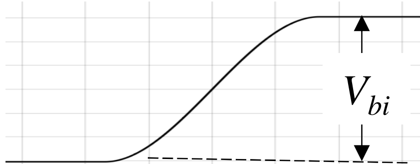
linearly graded junction



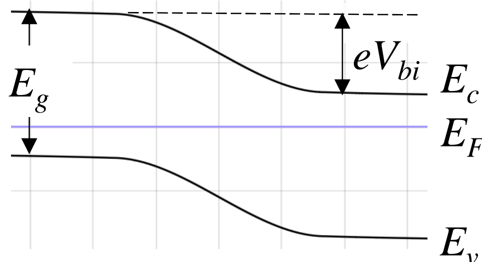
$$\rho = e\left(N_D(x) - N_A(x)\right) = eax$$



$$E = \int \frac{\rho}{\varepsilon} dx = \frac{-ea}{2\varepsilon}\left(\left(\frac{W}{2}\right)^2 - x^2\right) \qquad E_{\max} = \frac{-eaW^2}{8\varepsilon}$$



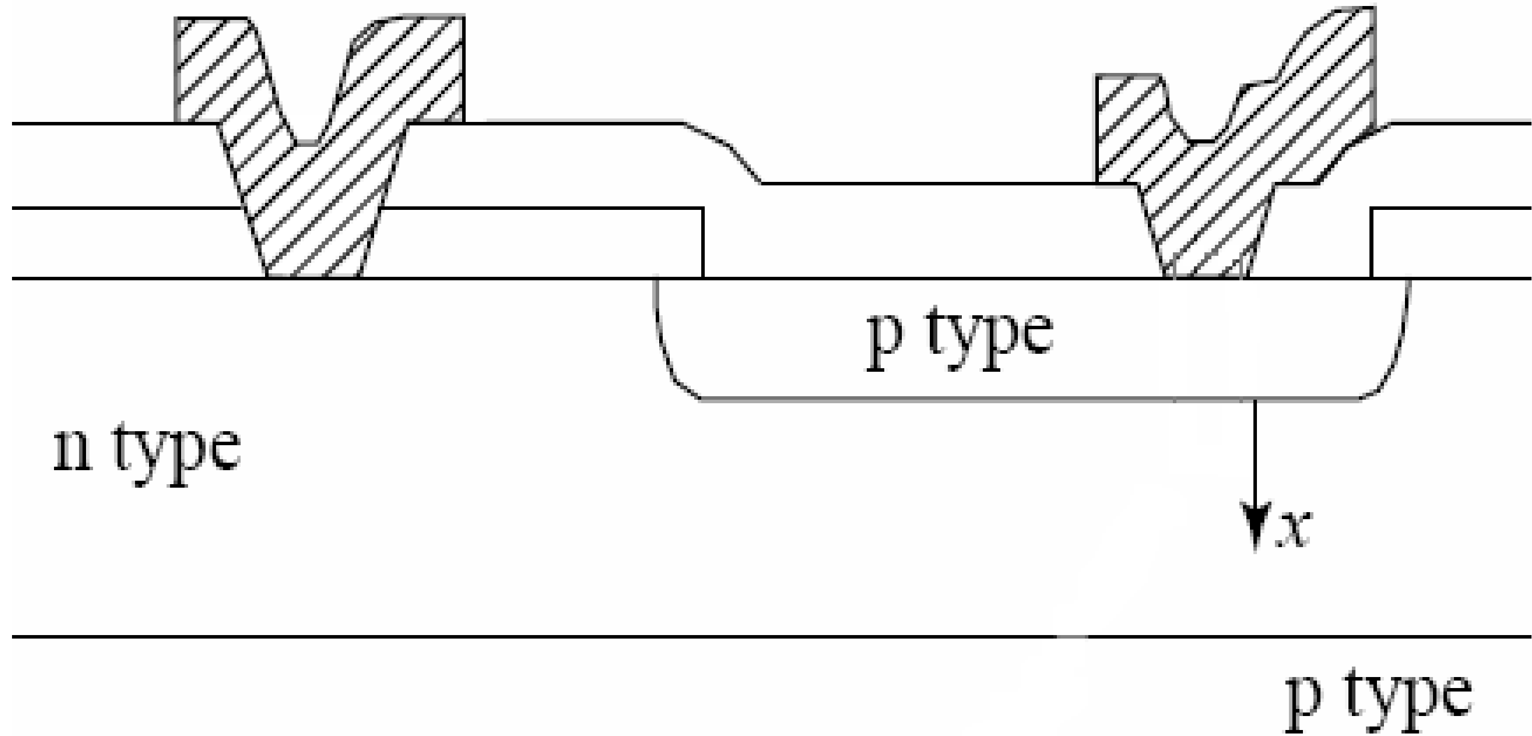
$$V = \int E dx = \frac{ea}{2\varepsilon}\left(\left(\frac{W}{2}\right)^2 x - \frac{x^3}{3}\right)$$



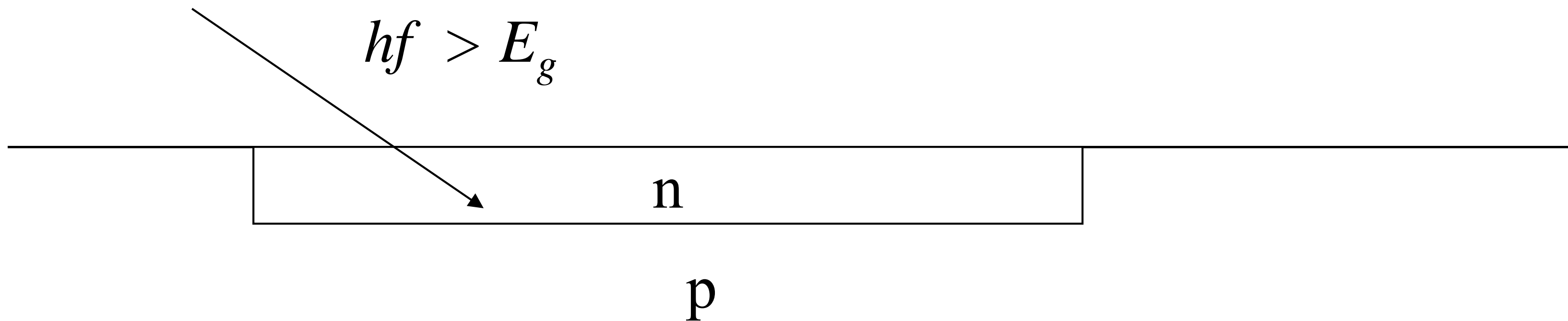
$$V_{bi} = \frac{eaW^3}{12\varepsilon}$$

http://lampx.tugraz.at/~hadley/psd/L6/linearly_graded.html

Isolation

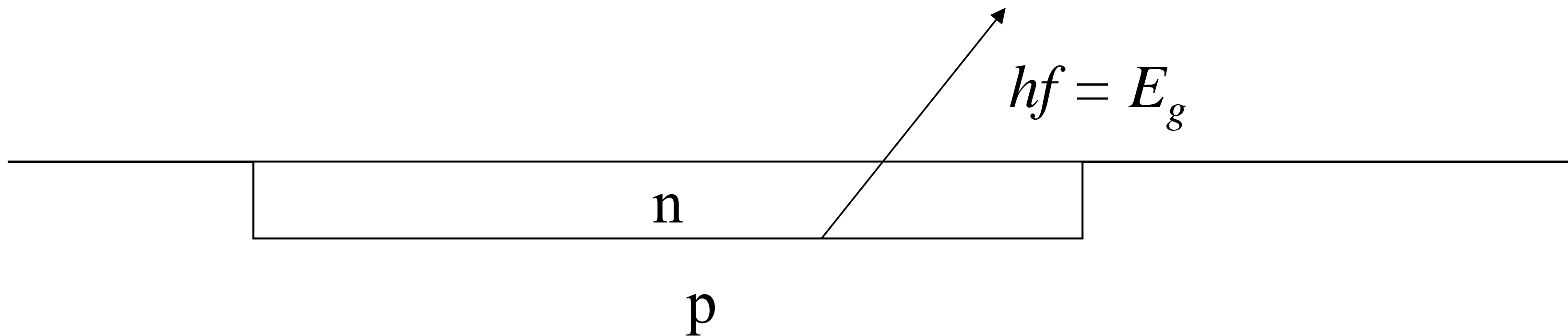


Solar cell



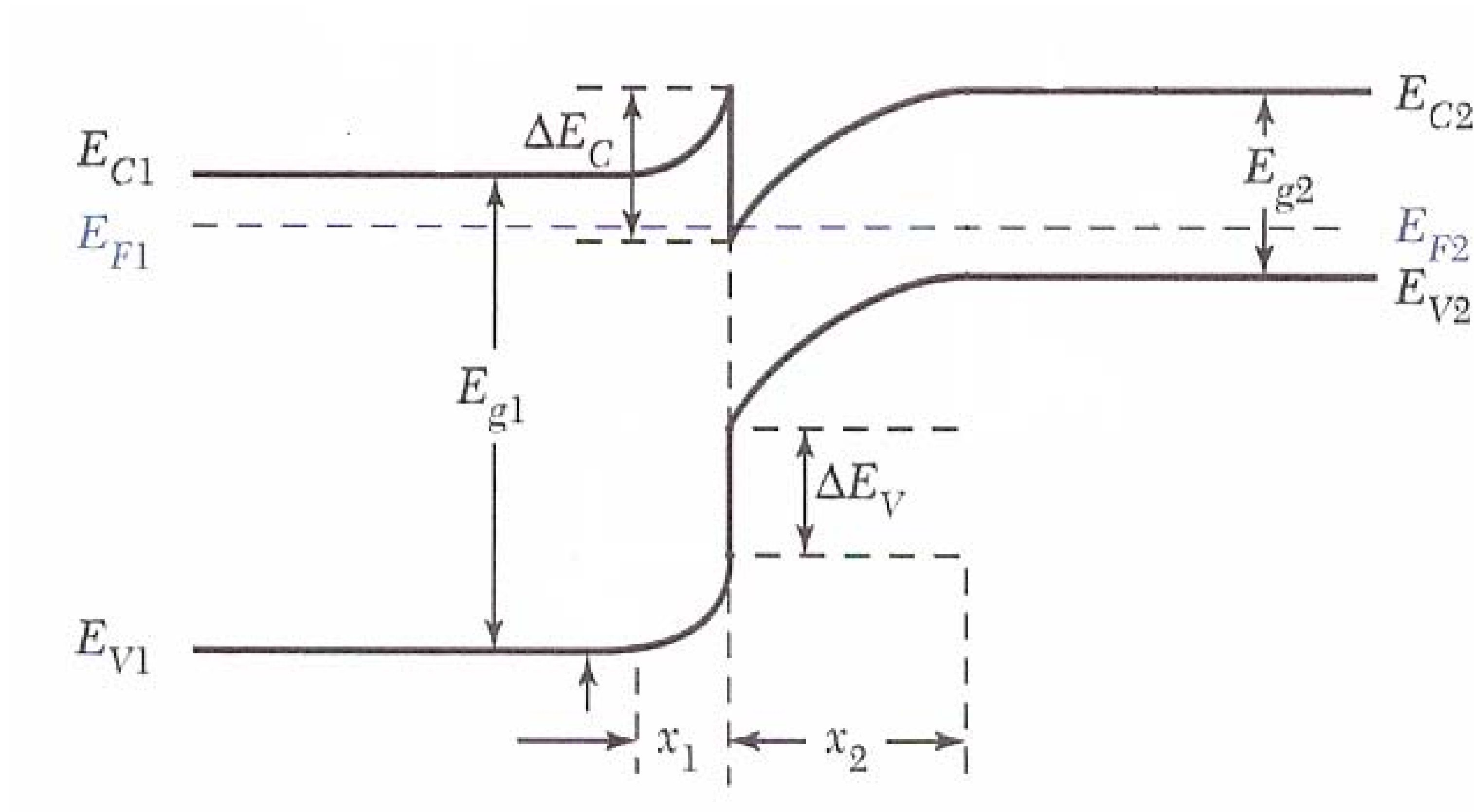
Light creates an electron-hole pair in the depletion region. The electric field sweeps the electrons towards the n-region and the holes towards the p-region.

Light emitting diode

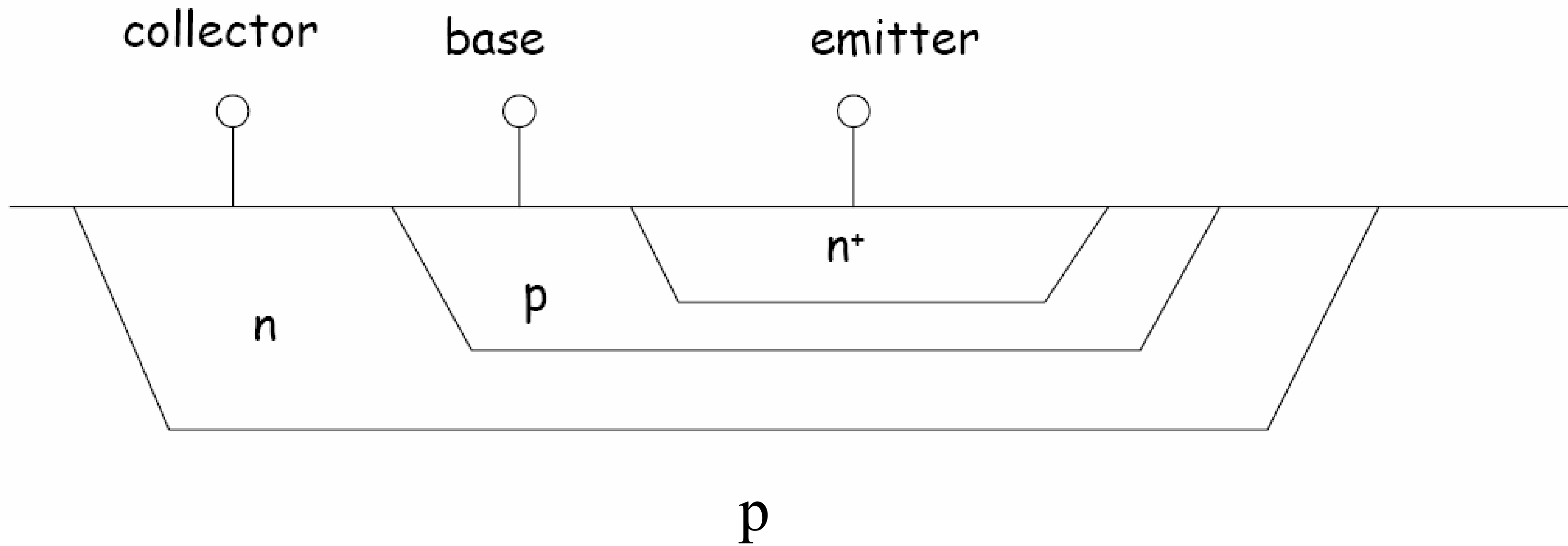


Electrons and holes are injected into the depletion region by forward biasing the junction. The electrons fall in the holes. For direct bandgap semiconductors, photons are emitted. For indirect bandgap semiconductors, phonons are emitted.

Heterojunctions

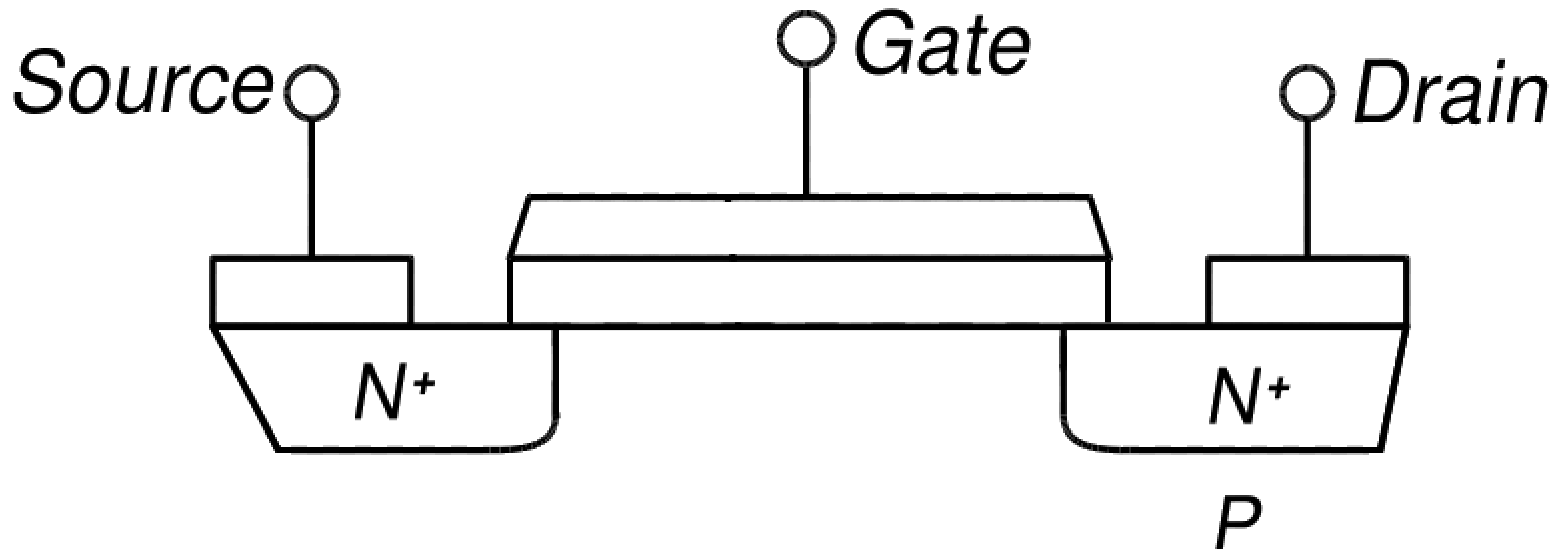


Bipolar transistor



MOSFET

Metal Oxide Semiconductor Field Effect Transistor

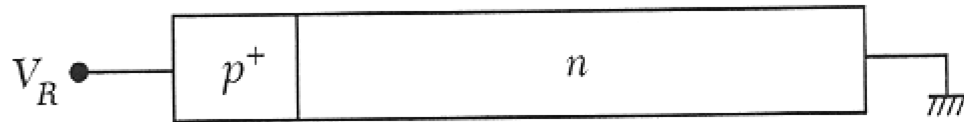


functions as a switch

~ 1 billion /chip

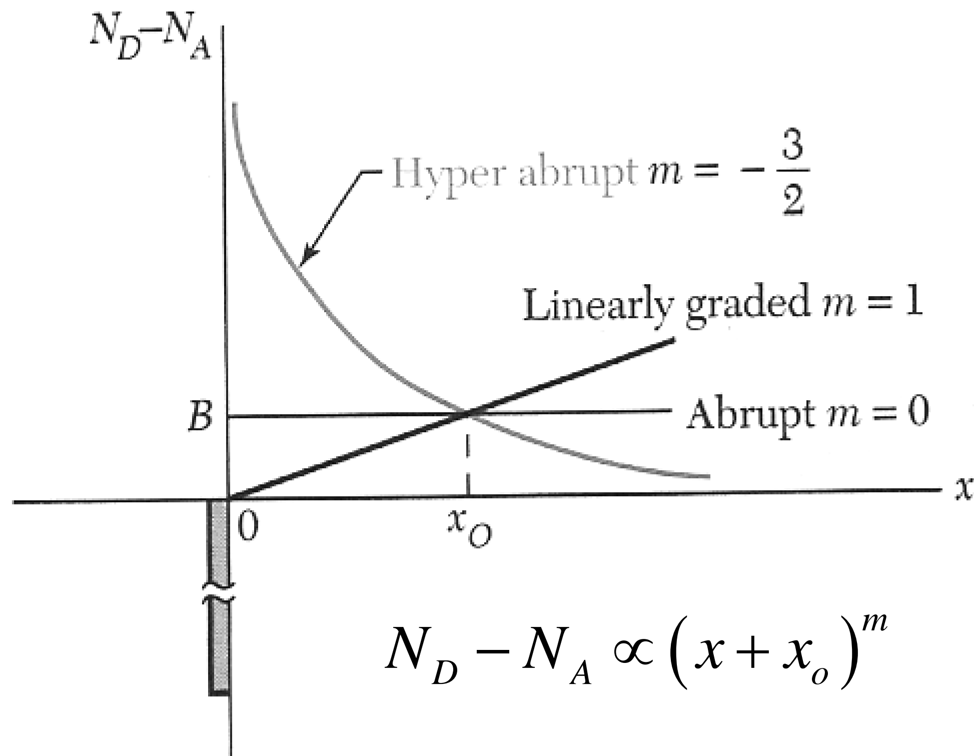
http://en.wikipedia.org/wiki/Image:Mosfet_linear.svg

Varactor



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

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



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

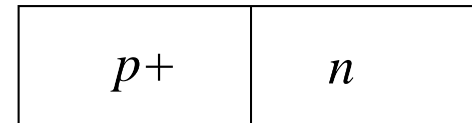
$n = 1/(m+2)$

Capacitance-voltage characteristics

specific capacitance $C_j = \dfrac{\varepsilon}{W}$ F m^{-2}

abrupt junction: $W = \dfrac{\varepsilon}{C_j} = \sqrt{\dfrac{2\varepsilon(N_D + N_A)(V_{bi} - V)}{eN_DN_A}}$

a one sided abrupt junction in reverse bias:



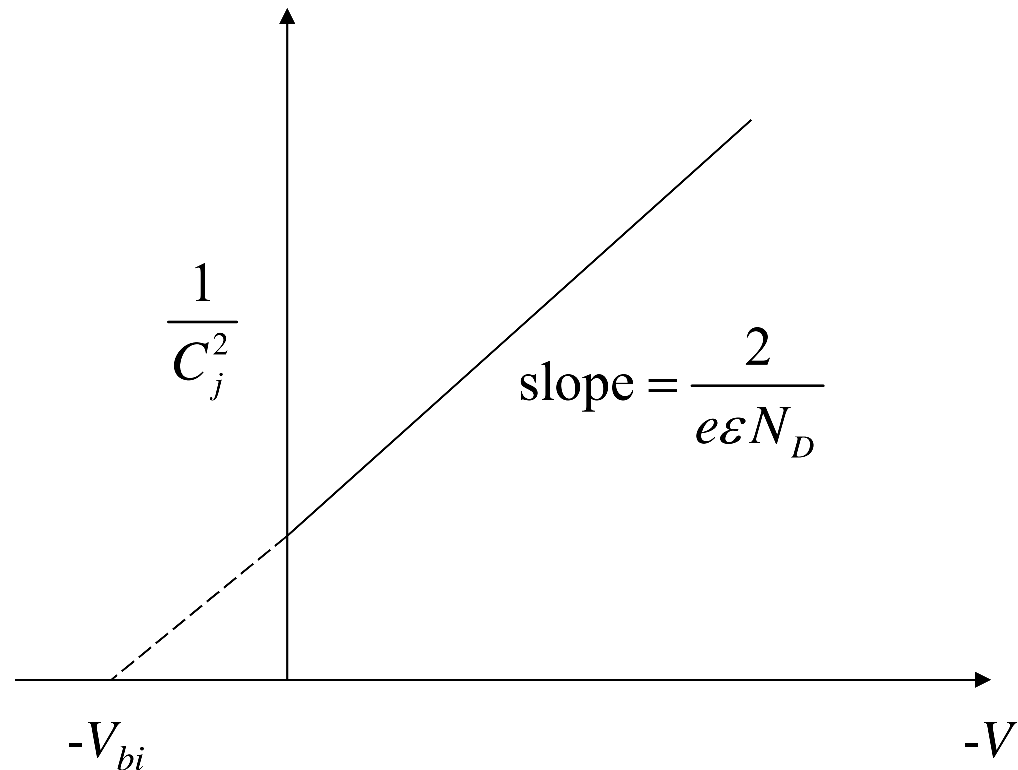
$$\frac{1}{C_j^2} = \frac{2(V_{bi} - V)}{e\varepsilon N_D}$$

Capacitance-voltage characteristics

a one sided abrupt junction in reverse bias:

$p+$	n

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



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