

6. pn - Junctions

Nov. 7, 2018

pn junctions

pn junctions are found in:

diodes

solar cells

LEDs

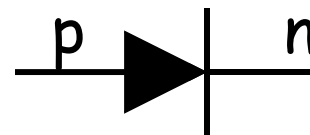
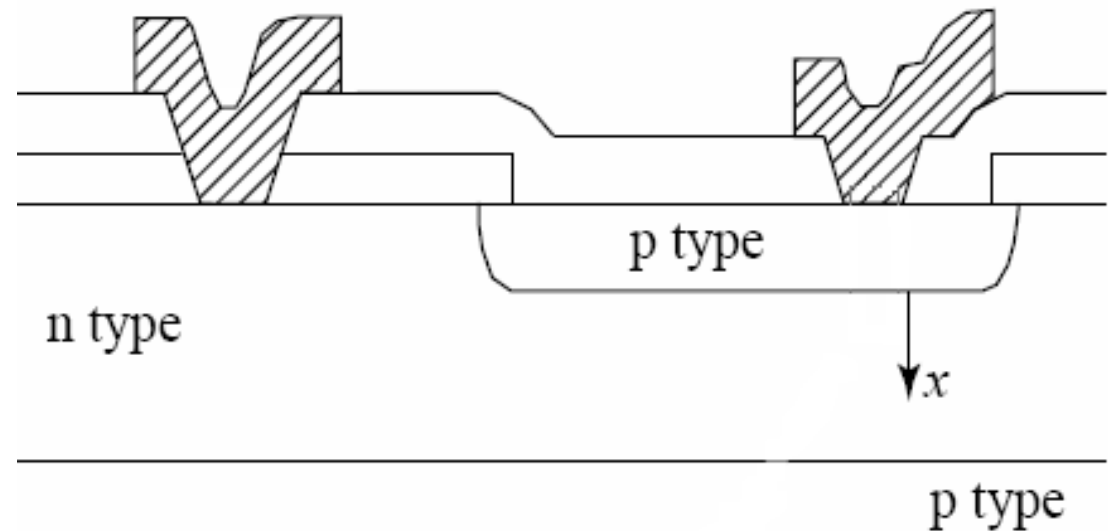
isolation

JFETs

bipolar transistors

MOSFETs

solid state lasers

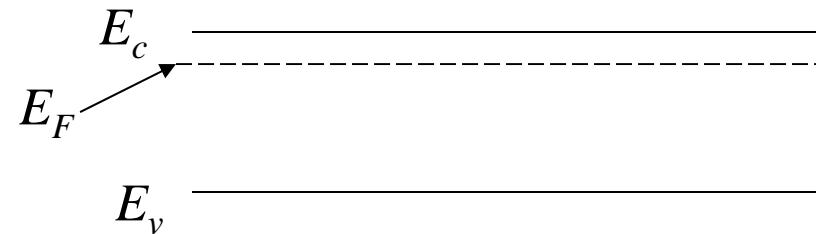
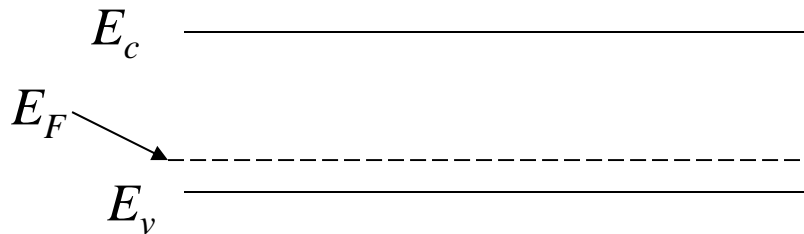


pn junction

isolated semiconductors

p-type

n-type



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

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

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

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

valid for both n and p doping

pn junction

semiconductors in contact
electrons flow from n to p



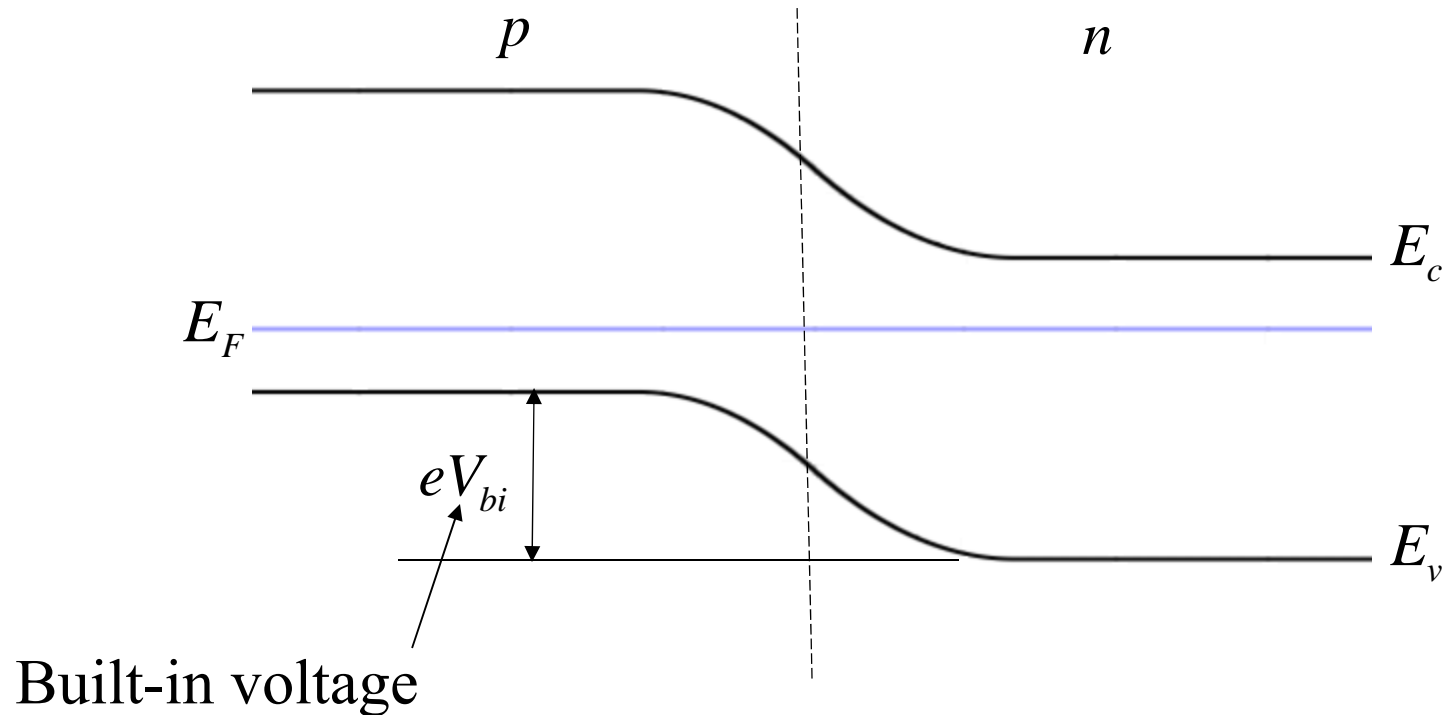
$$E_F = E_v + k_B T \ln \left(\frac{N_v}{N_A} \right)$$

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

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

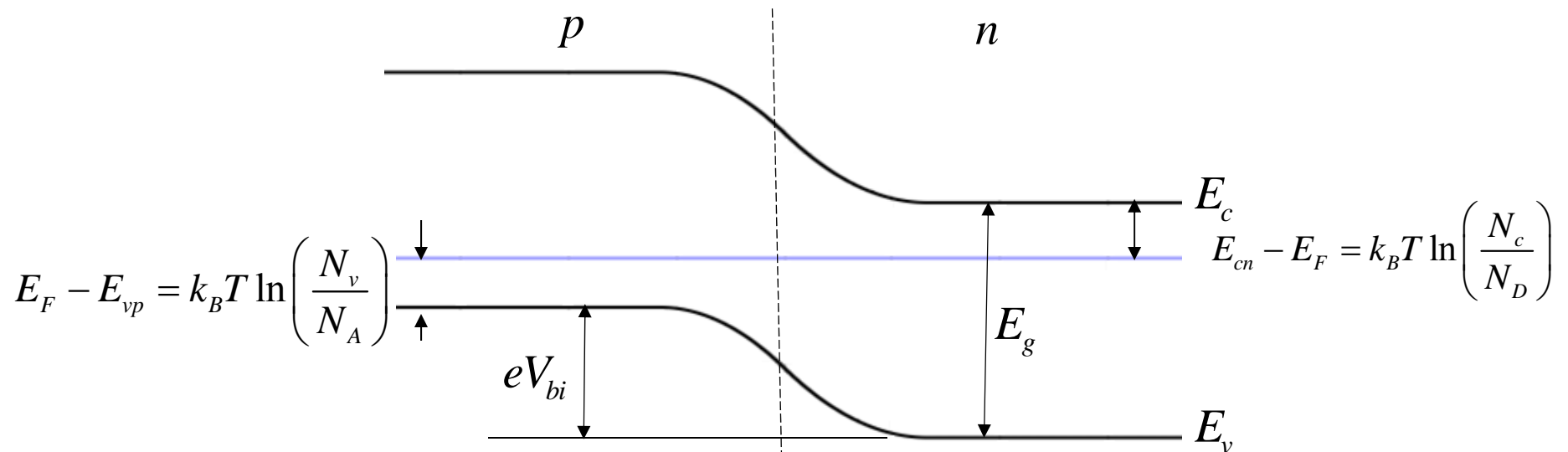
pn junction

semiconductors in contact



Abrupt junction: the doping changes abruptly from p to n

Built-in voltage V_{bi}



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

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

V_{bi}

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

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

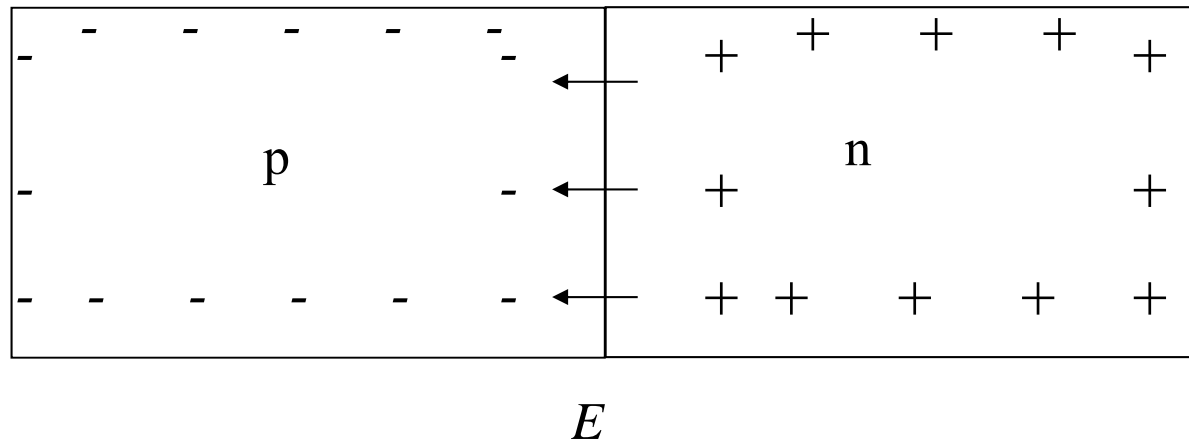
$$eV_{bi} = k_B T \ln \left(\frac{(N_{D,n} - N_{A,n})(N_{A,p} - N_{D,p})}{n_i^2} \right)$$

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

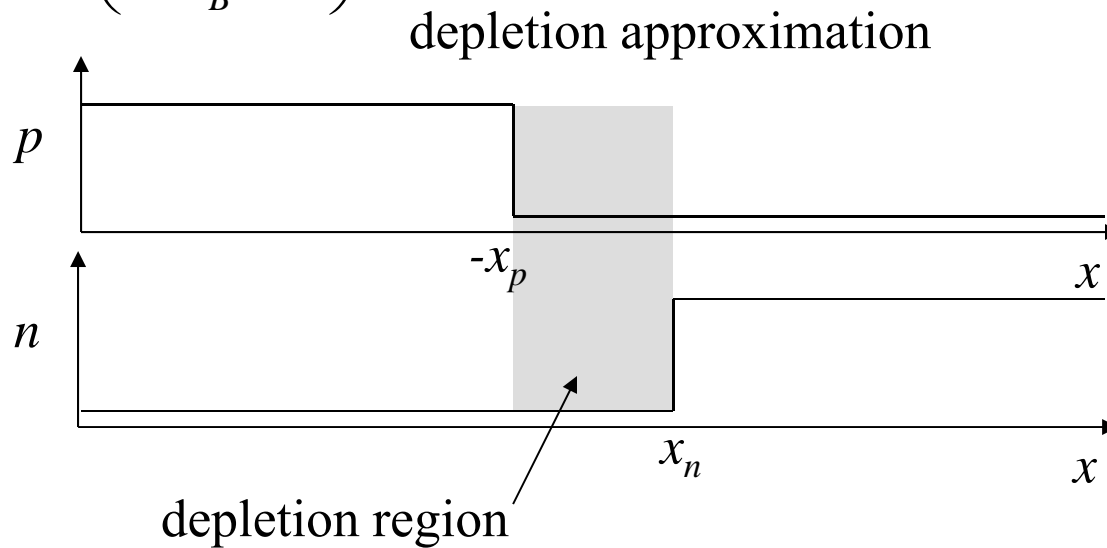
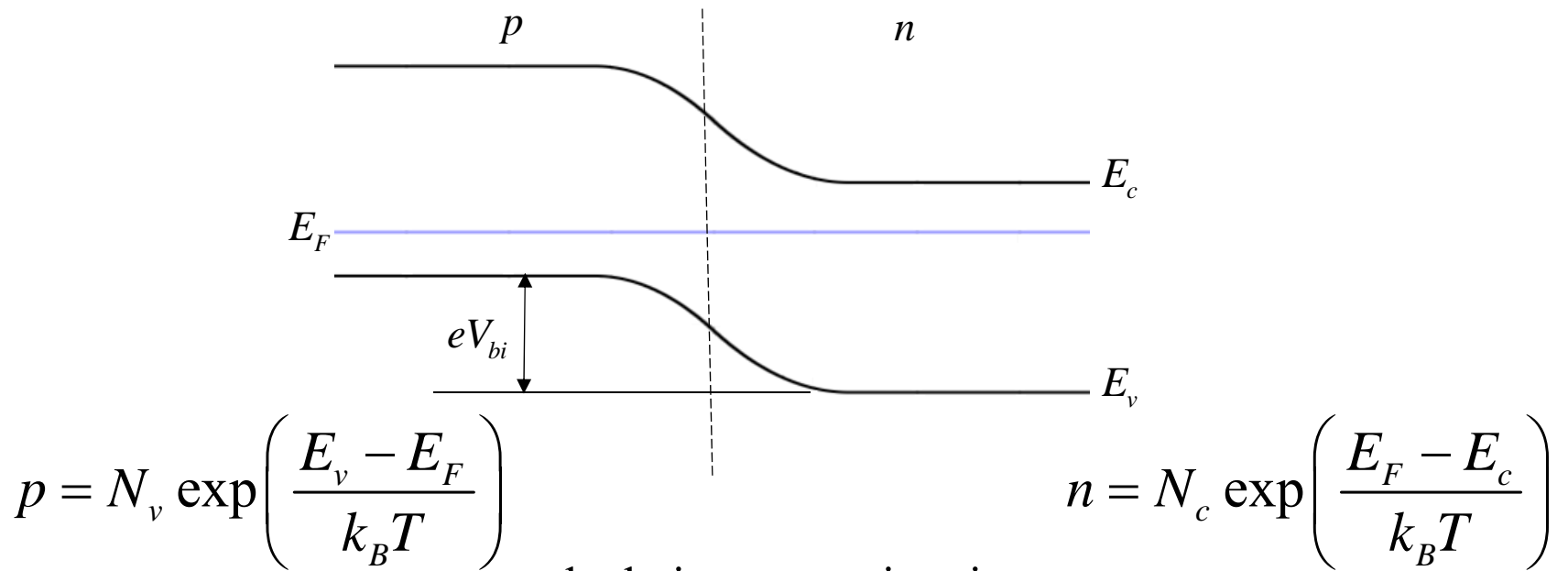
$$eV_{bi} = k_B T \ln \left(\frac{N_D N_A}{n_i^2} \right)$$

$$V_{bi}$$

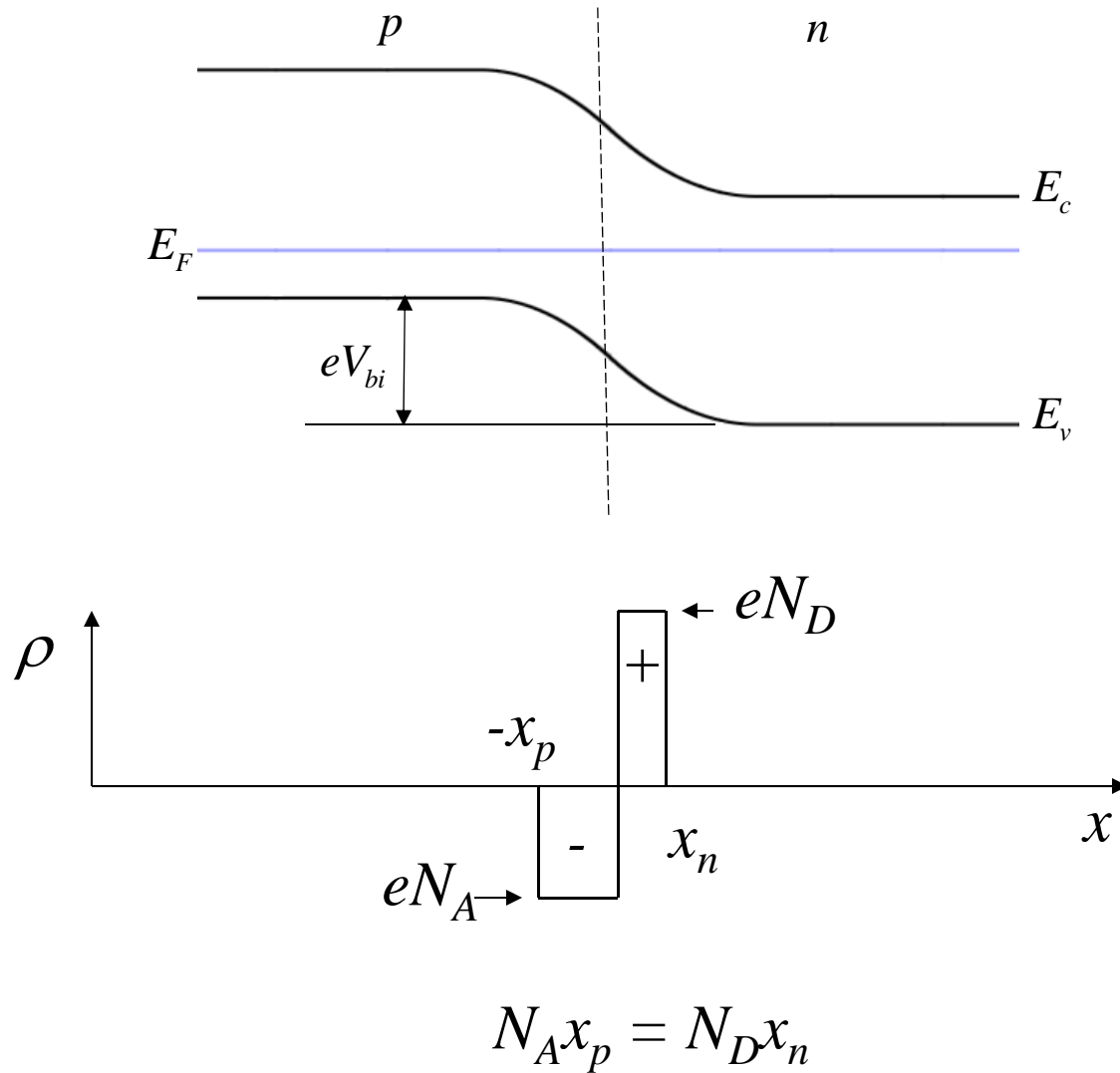
Can V_{bi} perform work?



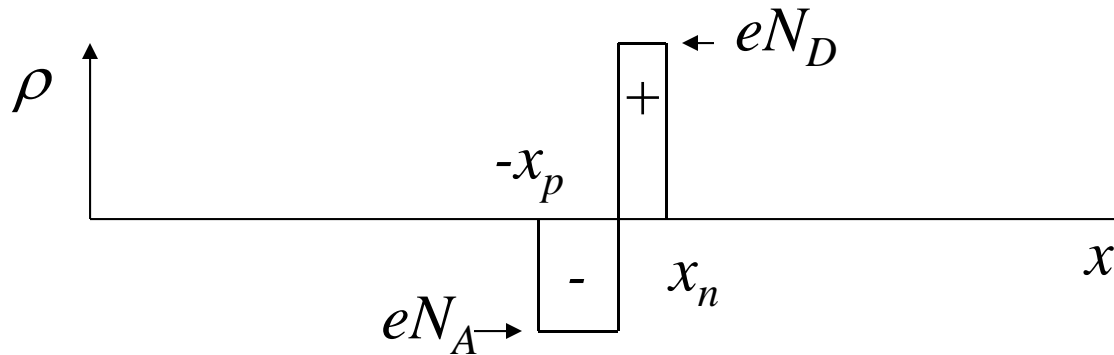
p and n profiles



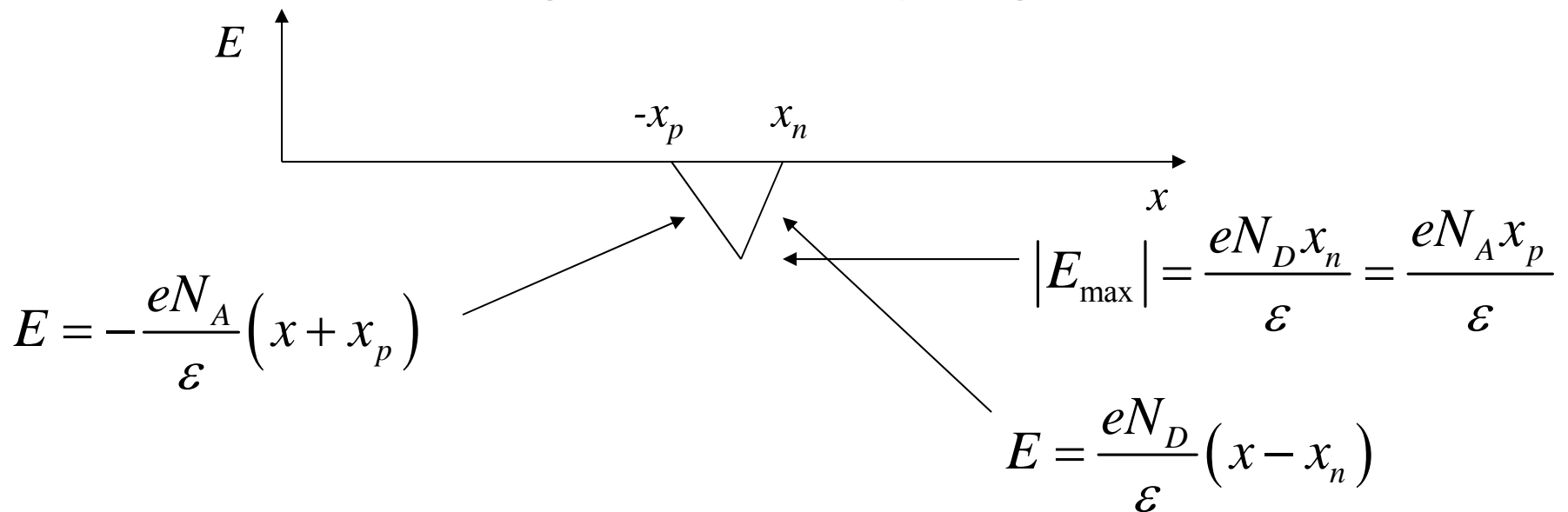
space charge



electric field

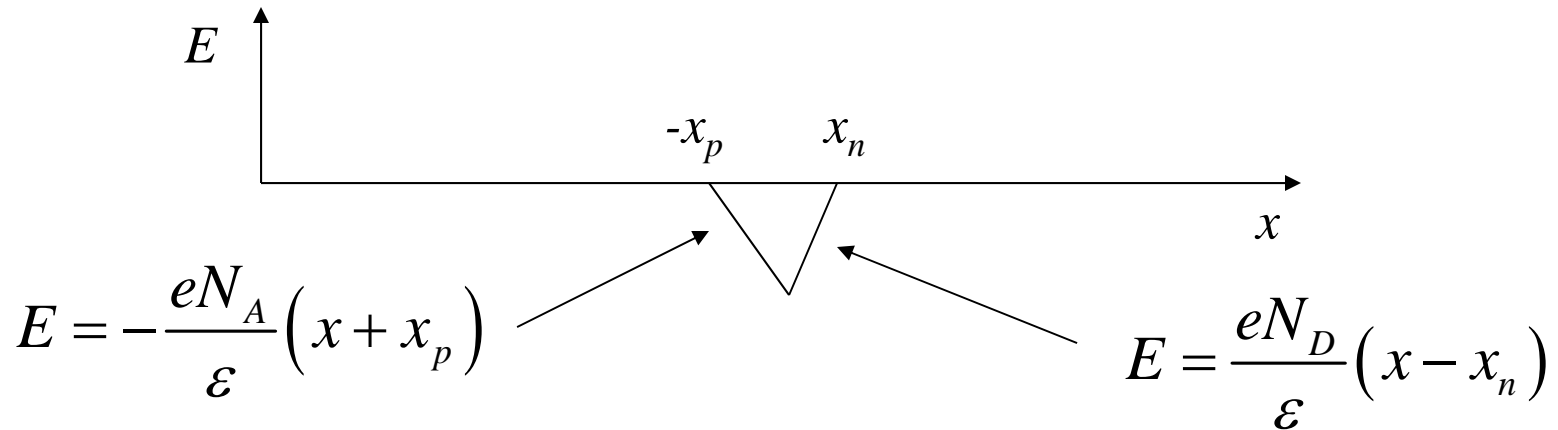


Gauss's law $\nabla \cdot \vec{E} = \frac{\rho}{\epsilon}$ in 1-D is $\frac{dE}{dx} = \frac{\rho}{\epsilon}$



E pushes the holes towards p and the electrons towards n

potential



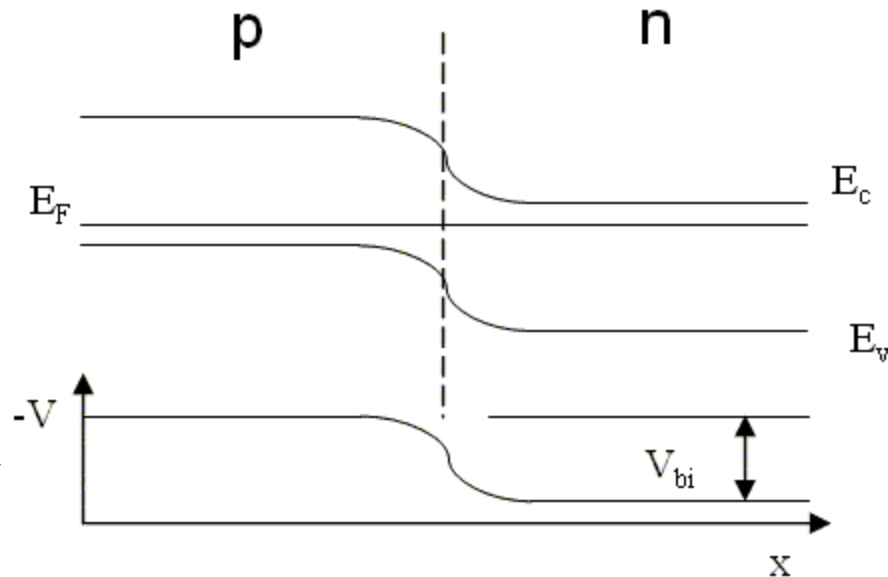
$$\frac{dV}{dx} = -E$$

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

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

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

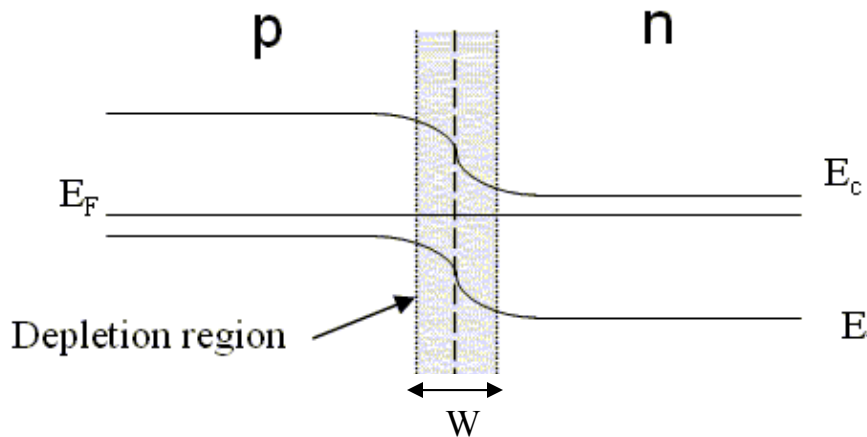
potential



electron energies are plotted in band diagram

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

Depletion width



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

$$N_A x_p = N_D x_n = N_D (W - x_p) = N_A (W - x_n)$$

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

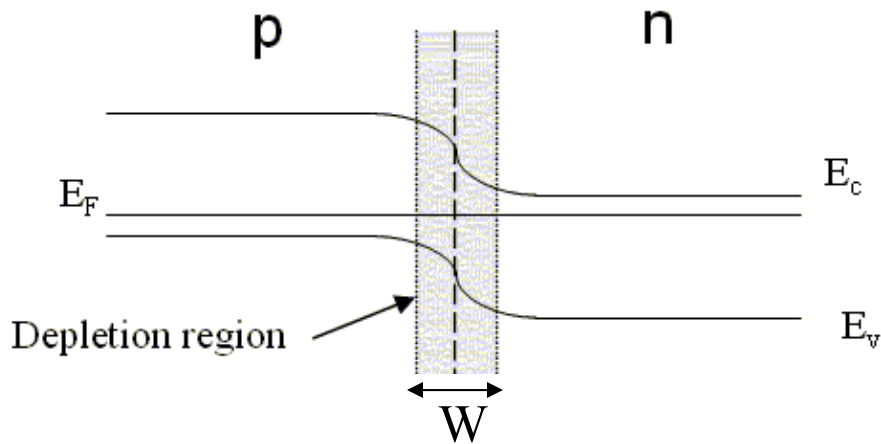
$$x_n = \frac{N_A W}{N_A + N_D}$$

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

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

light doping => wide depletion width

Depletion width



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

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

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

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

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

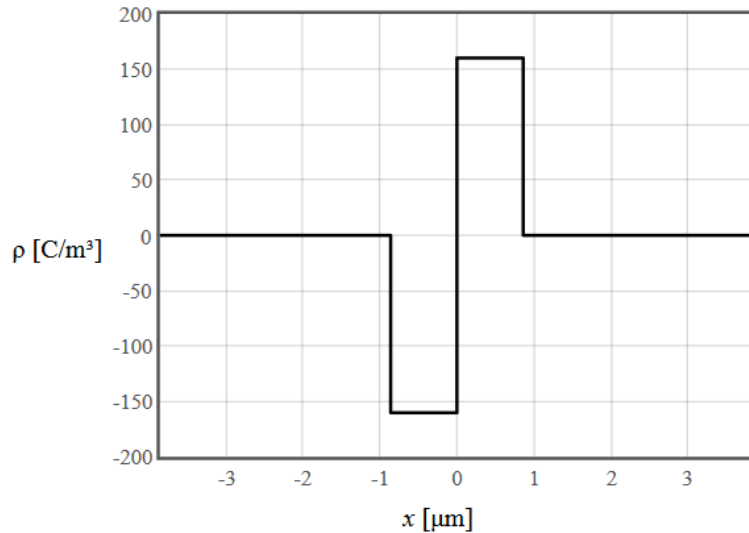
In an abrupt pn junction, the doping changes abruptly from p to n. It is common to solve for the band bending, the local electric field, the carrier concentration profiles, and the local conductivity in the depletion approximation. In this approximation it is assumed that there is a depletion width W 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.

$N_A =$ <input type="text" value="1E15"/> $1/\text{cm}^3$	$N_D =$ <input type="text" value="1E15"/> $1/\text{cm}^3$	$E_g =$ <input type="text" value="1.166-4.73E-4*T*(T+636)"/> eV
$N_v(300) =$ <input type="text" value="9.84E18"/> $1/\text{cm}^3$	$N_c(300) =$ <input type="text" value="2.78E19"/> $1/\text{cm}^3$	$\epsilon_r =$ <input type="text" value="12"/> $T =$ <input type="text" value="300"/> K
$\mu_p =$ <input type="text" value="480"/> $\text{cm}^2/\text{V s}$	$\mu_n =$ <input type="text" value="1350"/> $\text{cm}^2/\text{V s}$	$\tau_p =$ <input type="text" value="1E-10"/> s $\tau_n =$ <input type="text" value="1E-10"/> s
$V =$ <input type="text" value="-0.5"/> V		<input type="button" value="Submit"/>

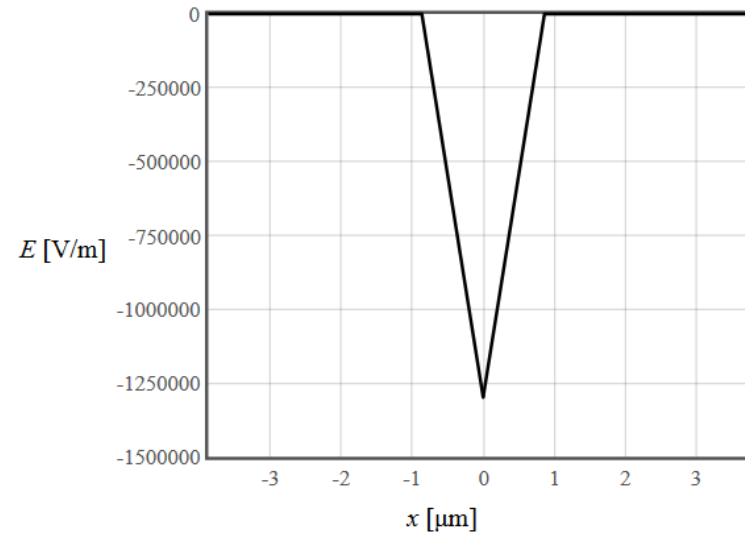
$$E_g = 1.12 \text{ eV} \quad W = 1.72 \text{ } \mu\text{m} \quad x_p = -0.861 \text{ } \mu\text{m} \quad x_n = 0.861 \text{ } \mu\text{m} \quad V_{bi} = 0.618 \text{ V} \quad C_j = 6.17 \text{ nF/cm}^2$$

$$D_p = 12.4 \text{ cm}^2/\text{s} \quad D_n = 34.9 \text{ cm}^2/\text{s} \quad L_p = 0.352 \text{ } \mu\text{m} \quad L_n = 0.591 \text{ } \mu\text{m}$$

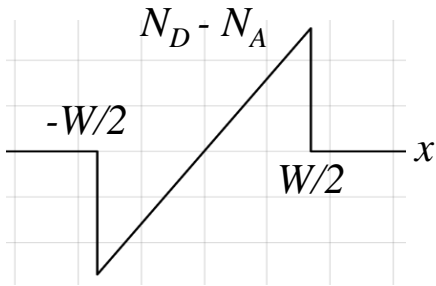
Charge density



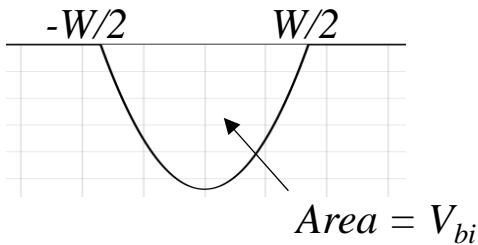
Electric field



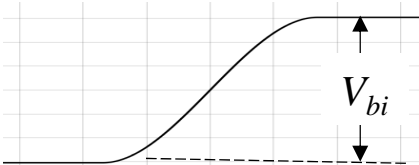
linearly graded junction



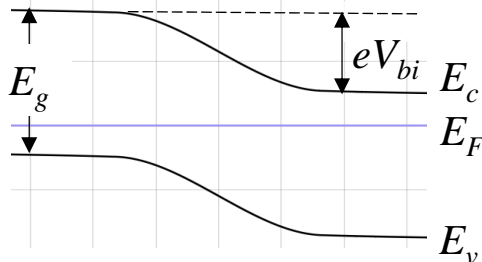
$$\rho = e(N_D(x) - N_A(x)) = eax$$



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

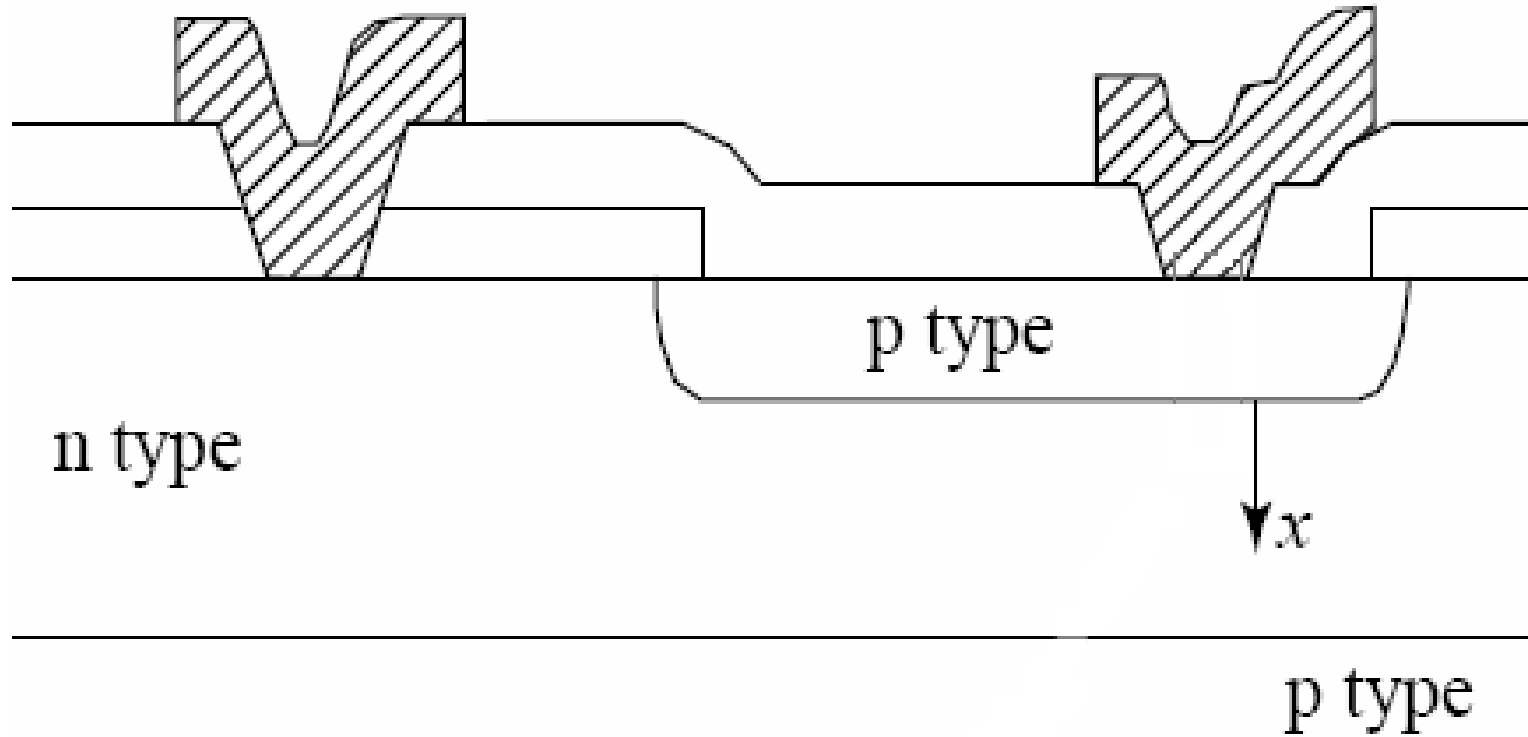


$$V = \int E dx = \frac{ea}{2\epsilon} \left(\left(\frac{W}{2} \right)^2 x - \frac{x^3}{3} \right)$$

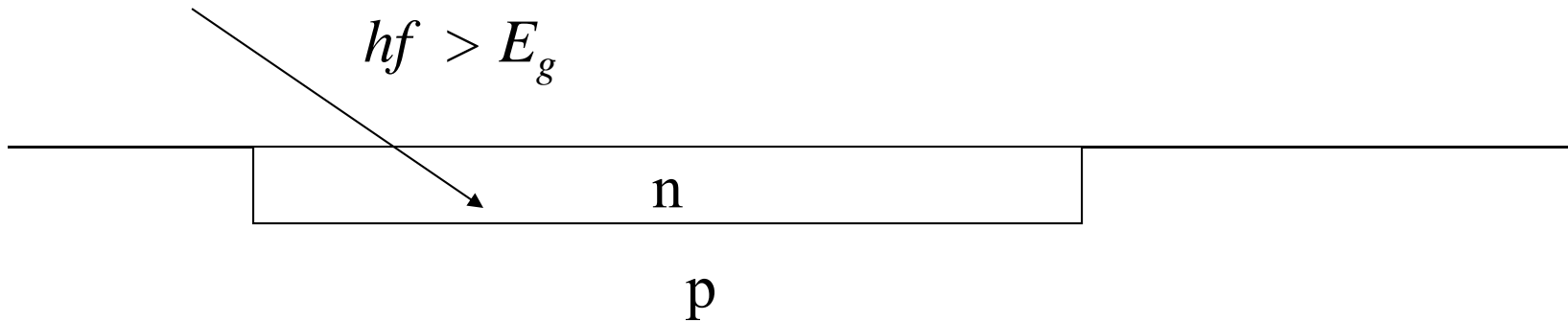


$$V_{bi} = \frac{eaW^3}{12\epsilon}$$

Isolation

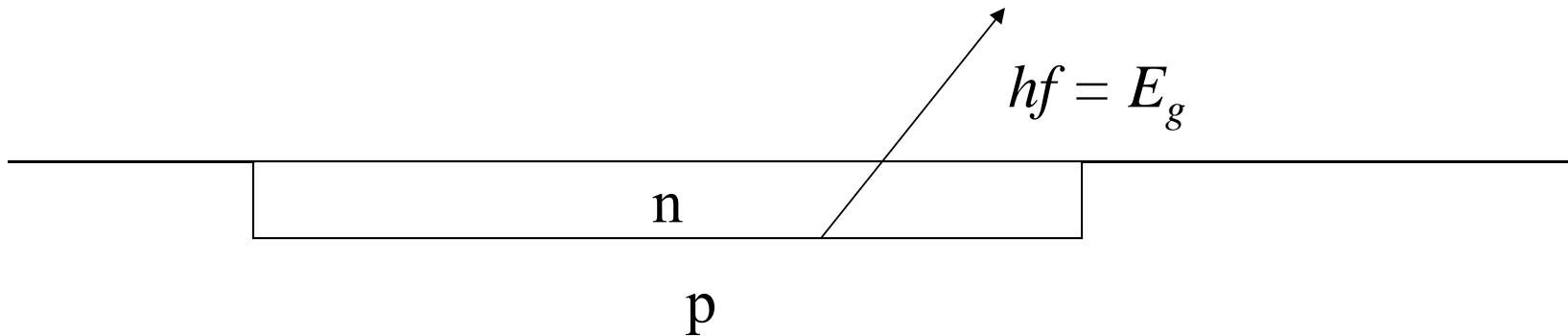


Solar cell



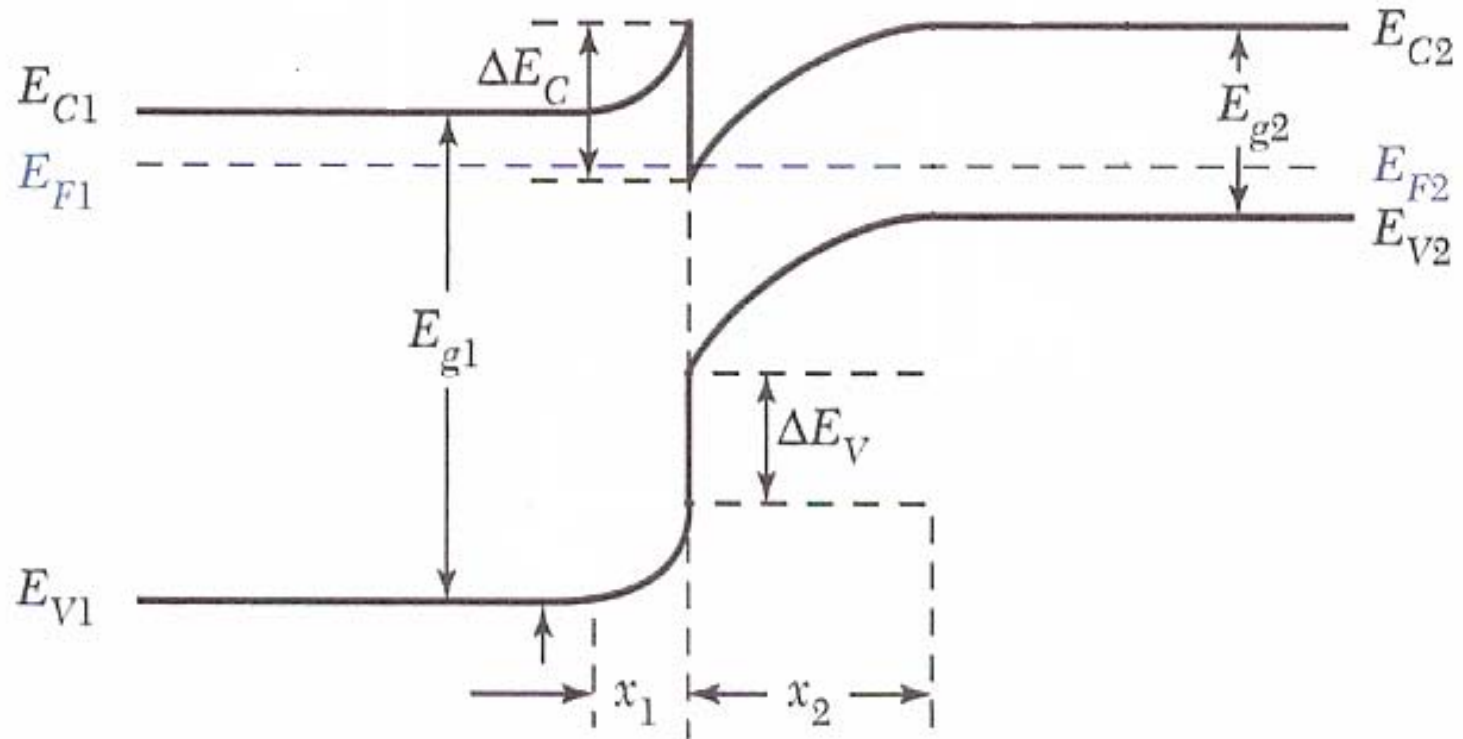
Light creates an electron-hole pair in the depletion region. The electric field sweeps the electrons towards the n-region and the holes towards the p-region.

Light emitting diode

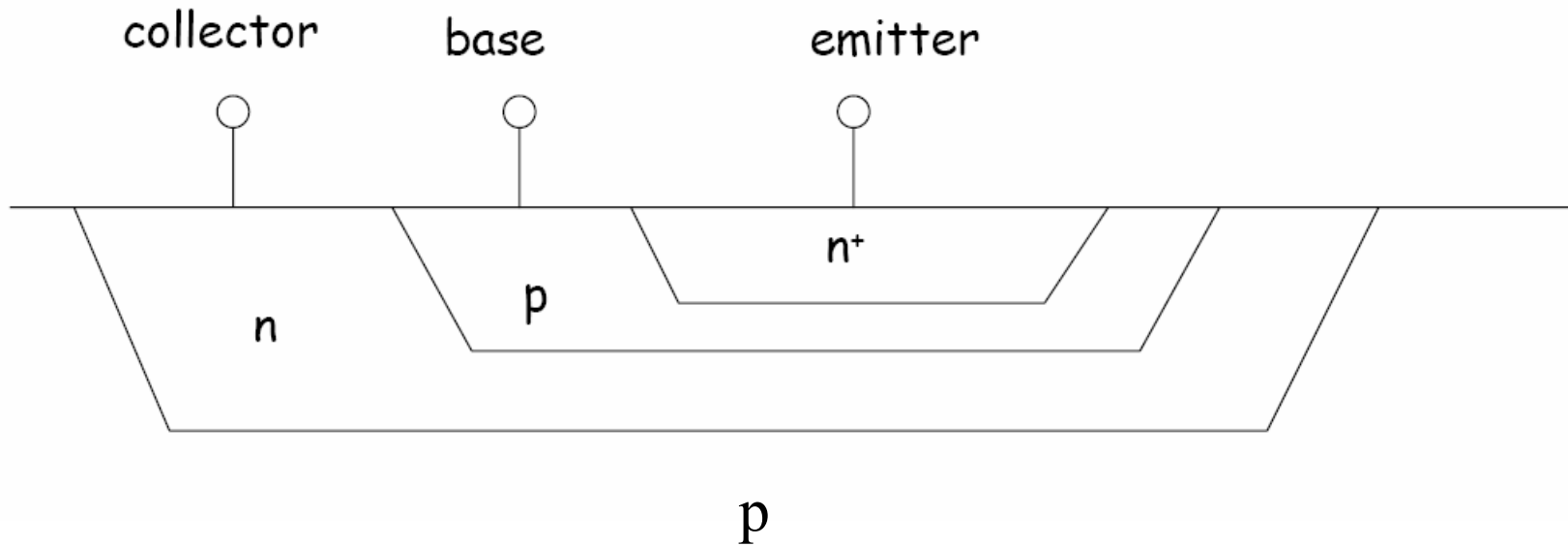


Electrons and holes are injected into the depletion region by forward biasing the junction. The electrons fall in the holes. For direct bandgap semiconductors, photons are emitted. For indirect bandgap semiconductors, phonons are emitted.

Heterojunctions

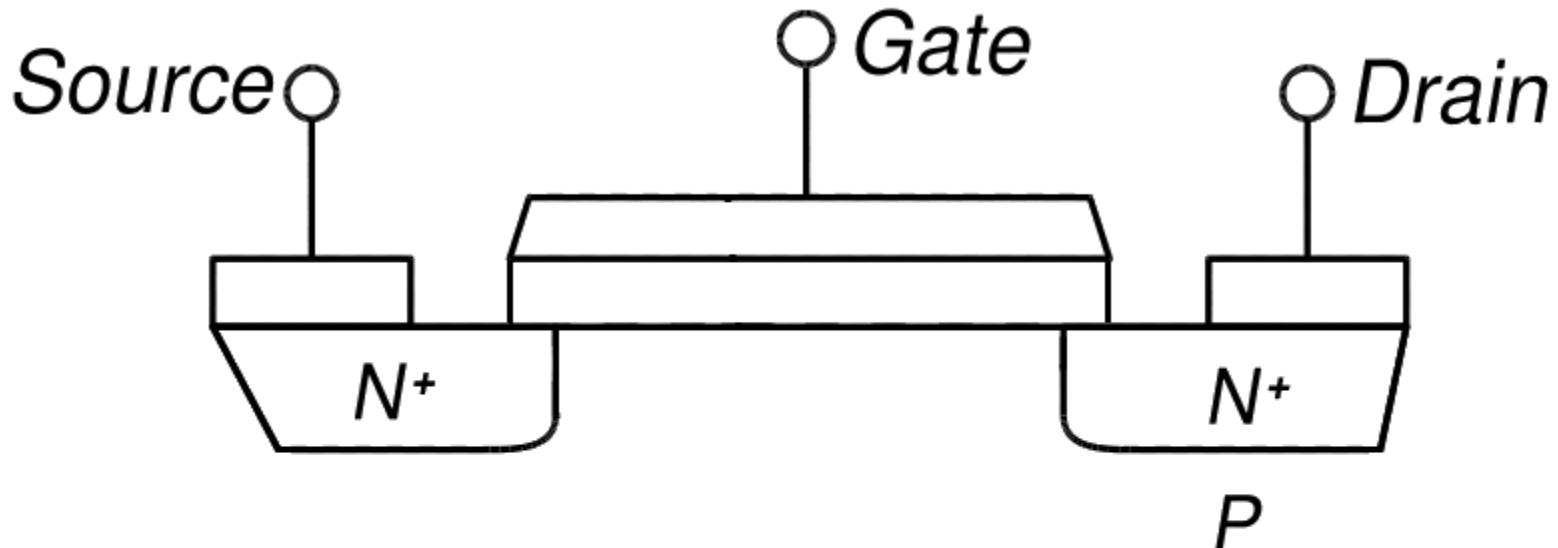


Bipolar transistor



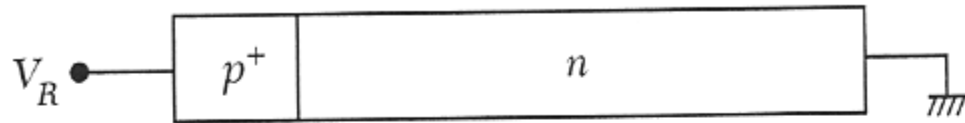
MOSFET

Metal Oxide Semiconductor Field Effect Transistor



functions as a switch
~ 1 billion /chip

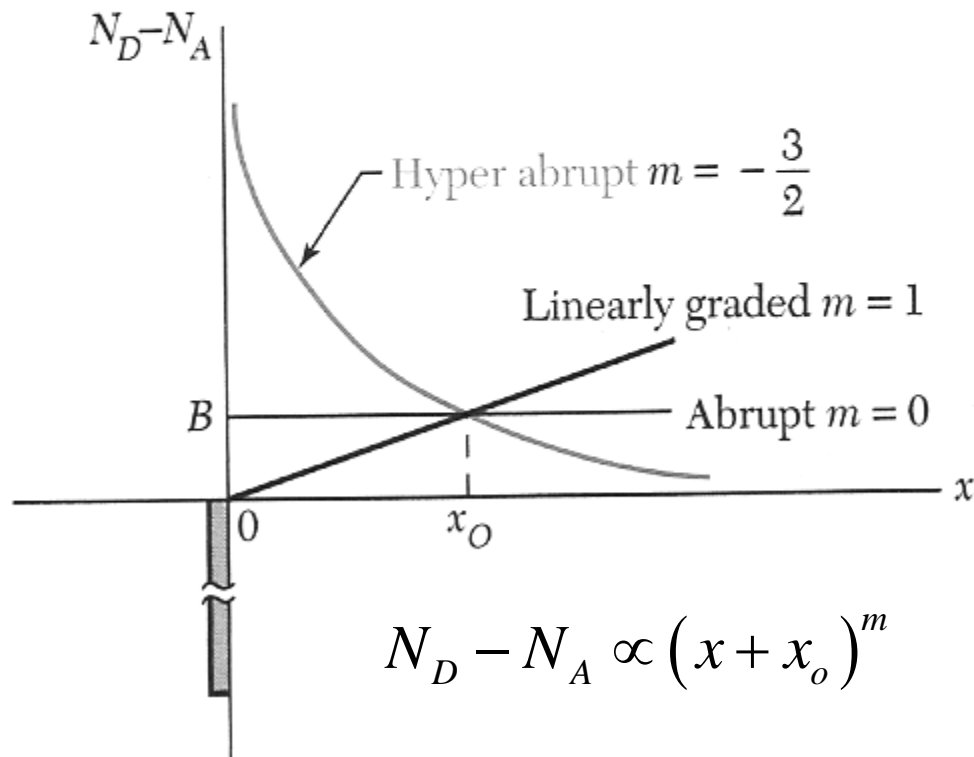
Varactor



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

abrupt: $n = 1/2$

linearly graded: $n = 1/3$



$$n = 1/(m+2)$$



Capacitance-voltage characteristics

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

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

a one sided abrupt junction in reverse bias:



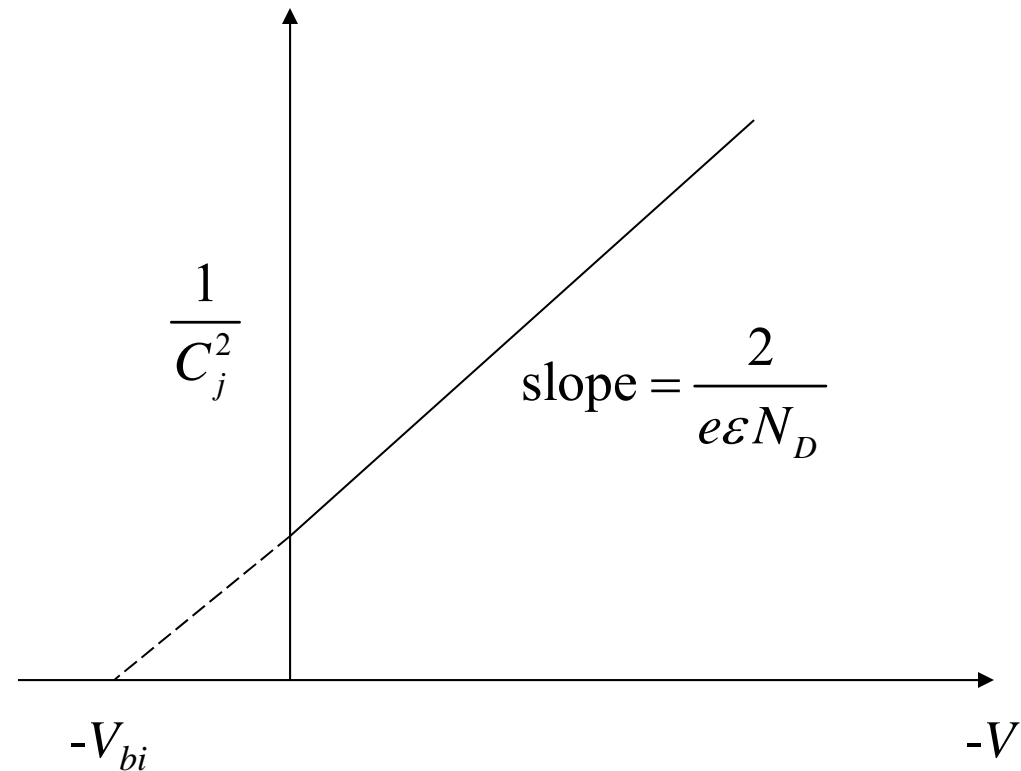
$$\frac{1}{C_j^2} = \frac{2(V_{bi} - V)}{e\epsilon N_D}$$

Capacitance-voltage characteristics

a one sided abrupt
junction in reverse
bias:

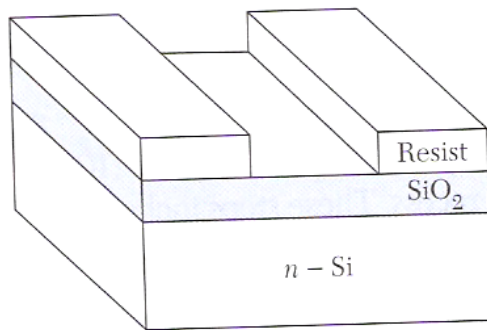
$p+$	n
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$$\frac{1}{C_j^2} = \frac{2(V_{bi} - V)}{e\epsilon N_D}$$

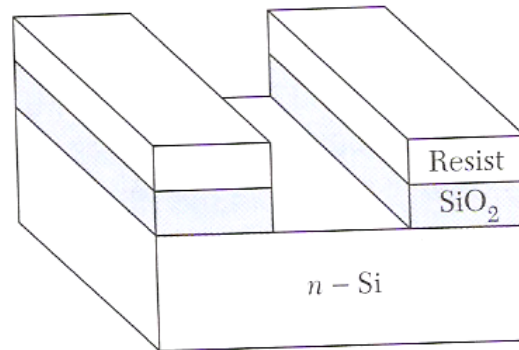


slope gives impurity concentration and the intercept gives V_{bi}

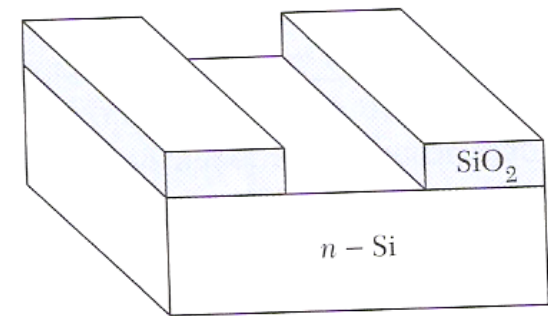
diode fabrication



(a)

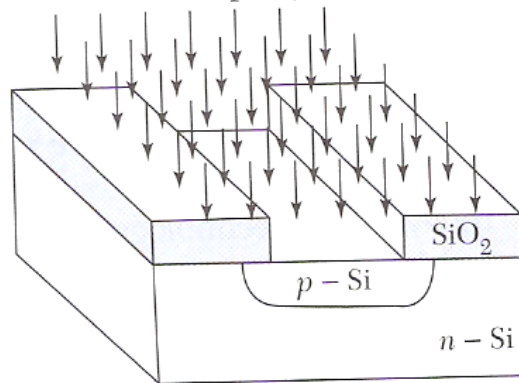


(b)

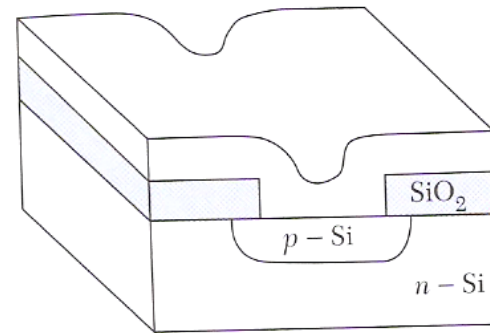


(c)

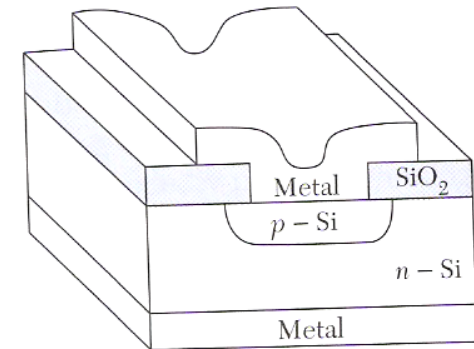
Dopant gas
or
accelerated impurity ions



(d)



(e)



(f)