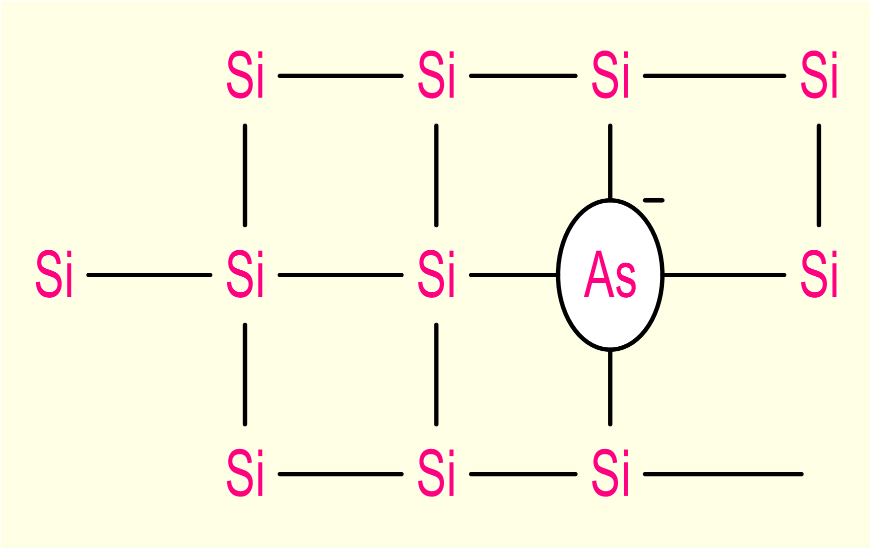
ESC201T : Introduction to Electronics

Lecture 20: Diodes

B. Mazhari
Dept. of EE, IIT Kanpur

Doping

N-Type Semiconductor



$$N_D \longrightarrow N_D^{+} + e^{-}$$

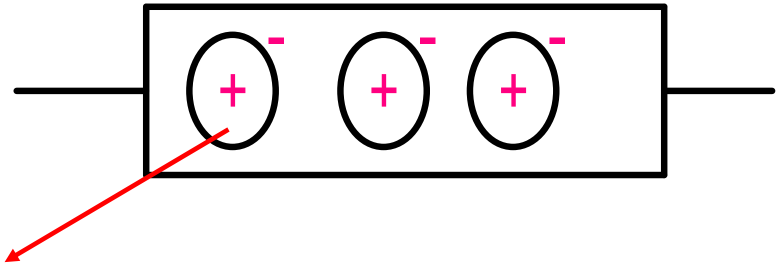
$$In\ equilibrium: \quad n \times p = n_i^2$$

$$n_i = 1.45 \times 10^{10} \mathrm{cm}^{-3} at T = 300°K$$

$$N_D = 10^{16} \mathrm{cm}^{-3}$$

$$n \approx N_D = 10^{16} \mathrm{cm}^{-3}$$

$$p = \frac{n_i^2}{n} = n_i^2 / N_D \approx 2 \times 10^4 \mathrm{cm}^{-3}$$



Positively charged donor atoms

$$n >> p$$

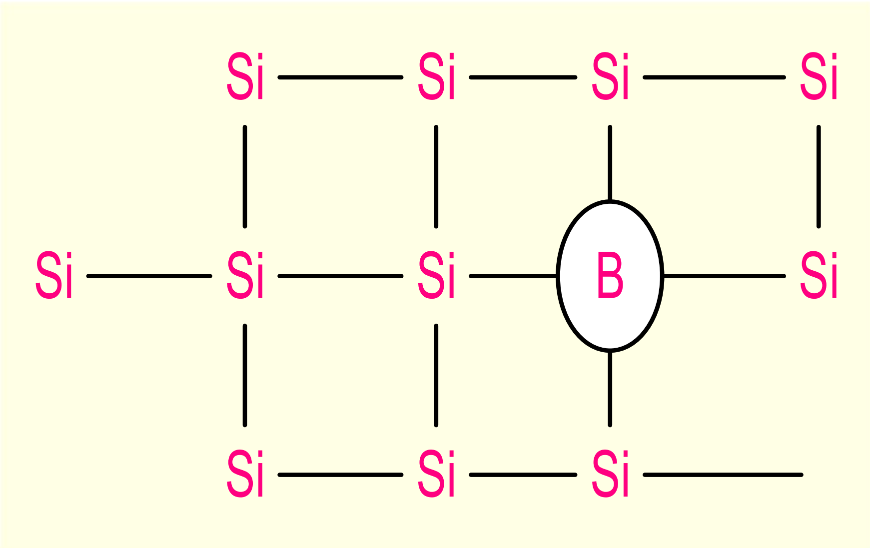
Small amount of impurity results in large change in resistivity !

No. of Silicon atoms / volume = $5 \times 10^{22}\ cm^{-3}$

$$\frac{10^{16}}{5 \times 10^{22}} = 2 \times 10^{-7}$$ (0.2PPM)

$$\rho :\quad 2 \times 10^{5}\ \Omega\ cm \xrightarrow{N_D = 10^{16}\ cm^{-3}} \mathbf{1.5}\ \Omega\ cm$$

P-Type Semiconductor

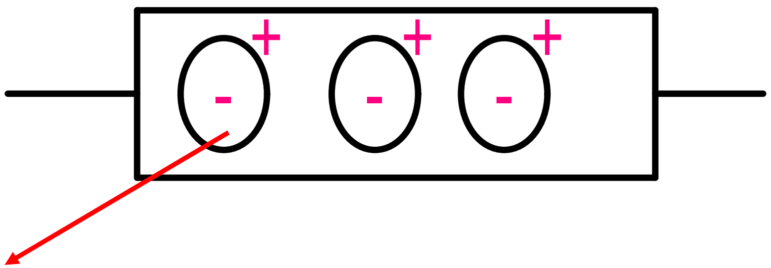


$$N_A + e^- \longrightarrow N_A^- + h^+$$

$$N_A = 10^{16}\mathrm{cm}^{-3}$$

$$p \approx N_A = 10^{16}\mathrm{cm}^{-3}$$

$$n = \frac{n_i^2}{p} = n_i^2/N_A = 2 \times 10^4\mathrm{cm}^{-3}$$

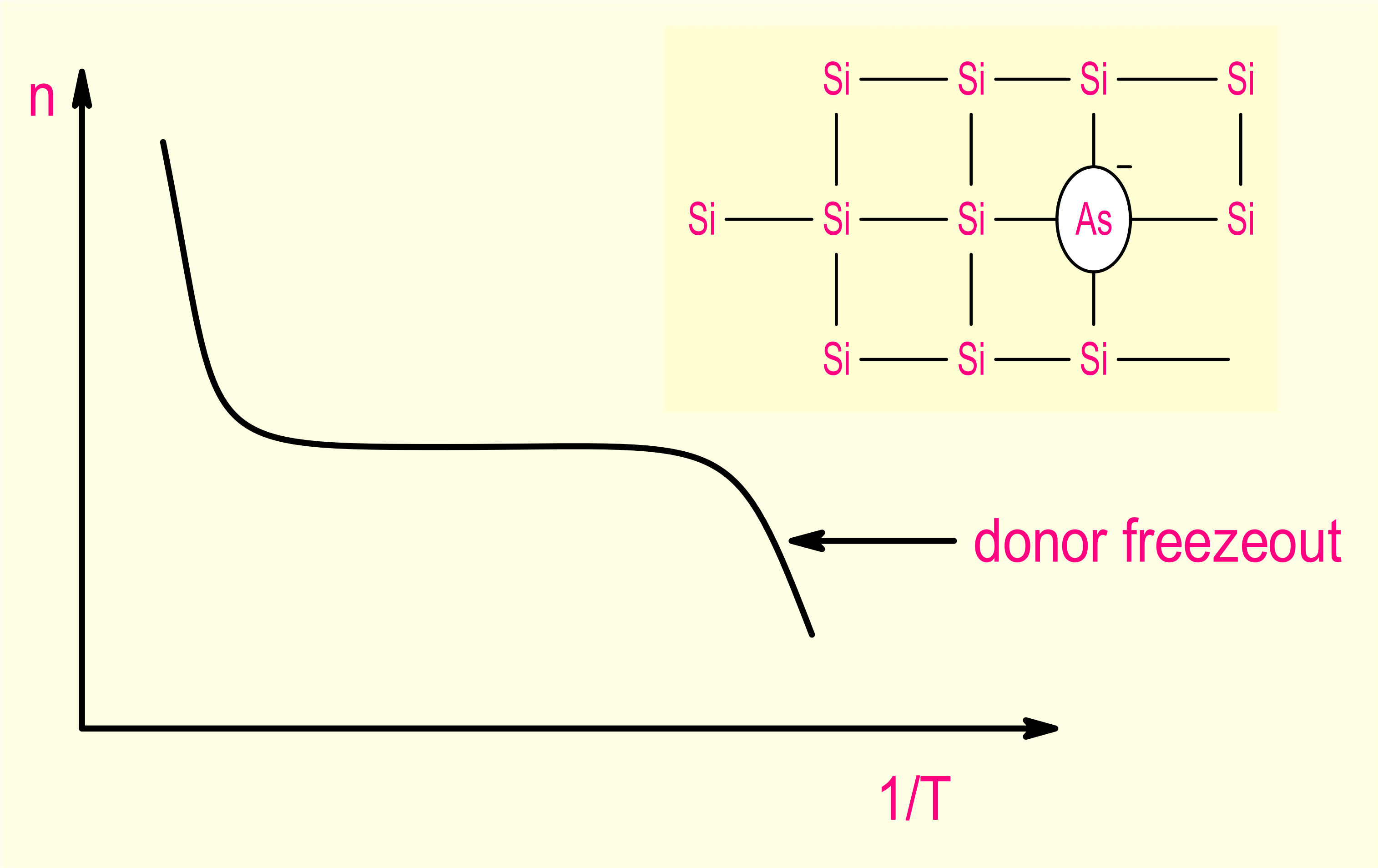


Negatively charged acceptor atoms

$$p >> n$$

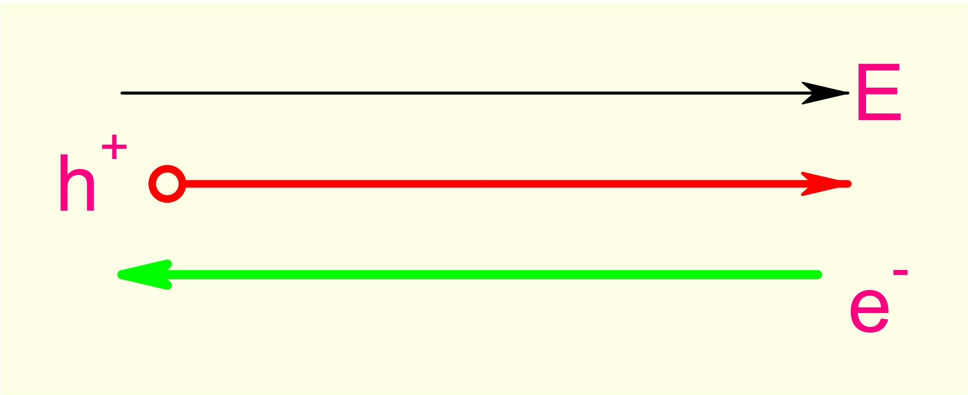
G-Number

Number of carriers is dependent on temperature !

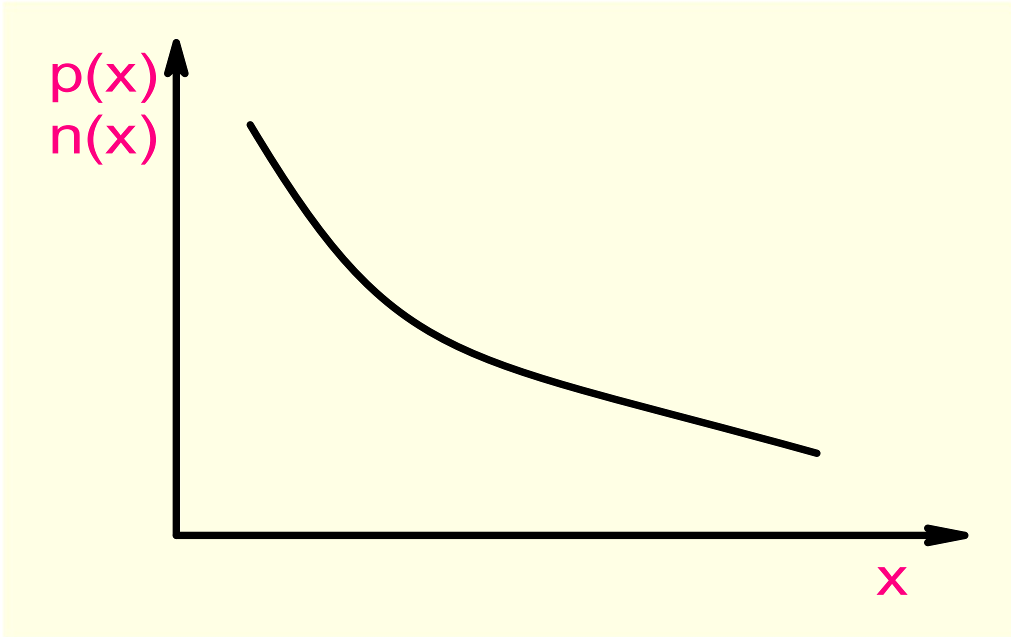


Current flow

Drift current due to Electric field

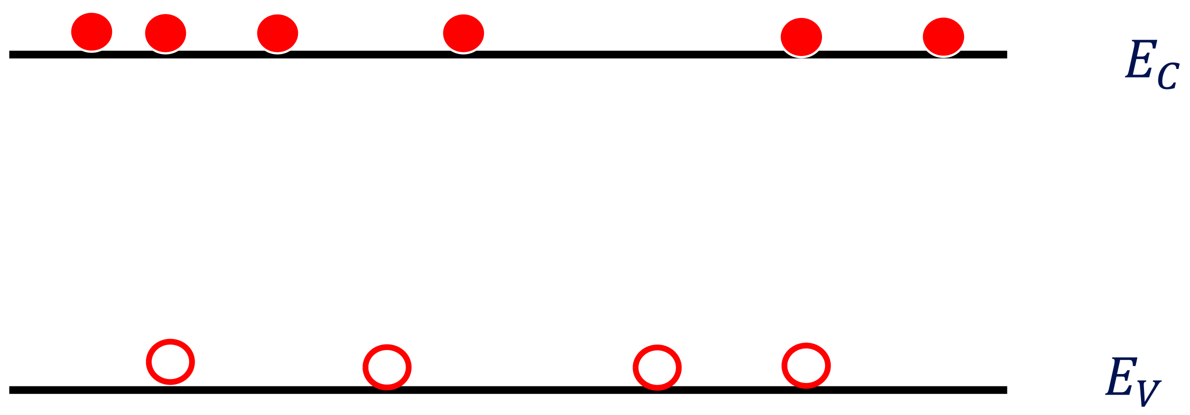


Diffusion to concentration gradient



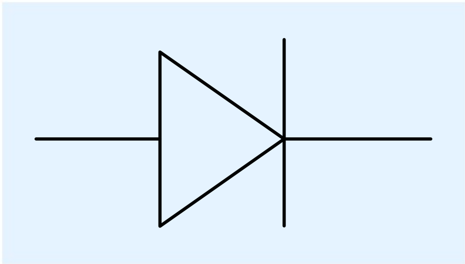
G-Number

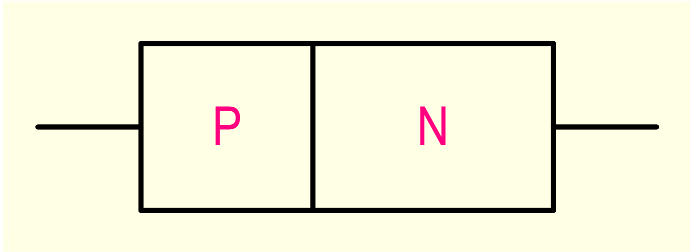
RecombinationGeneration

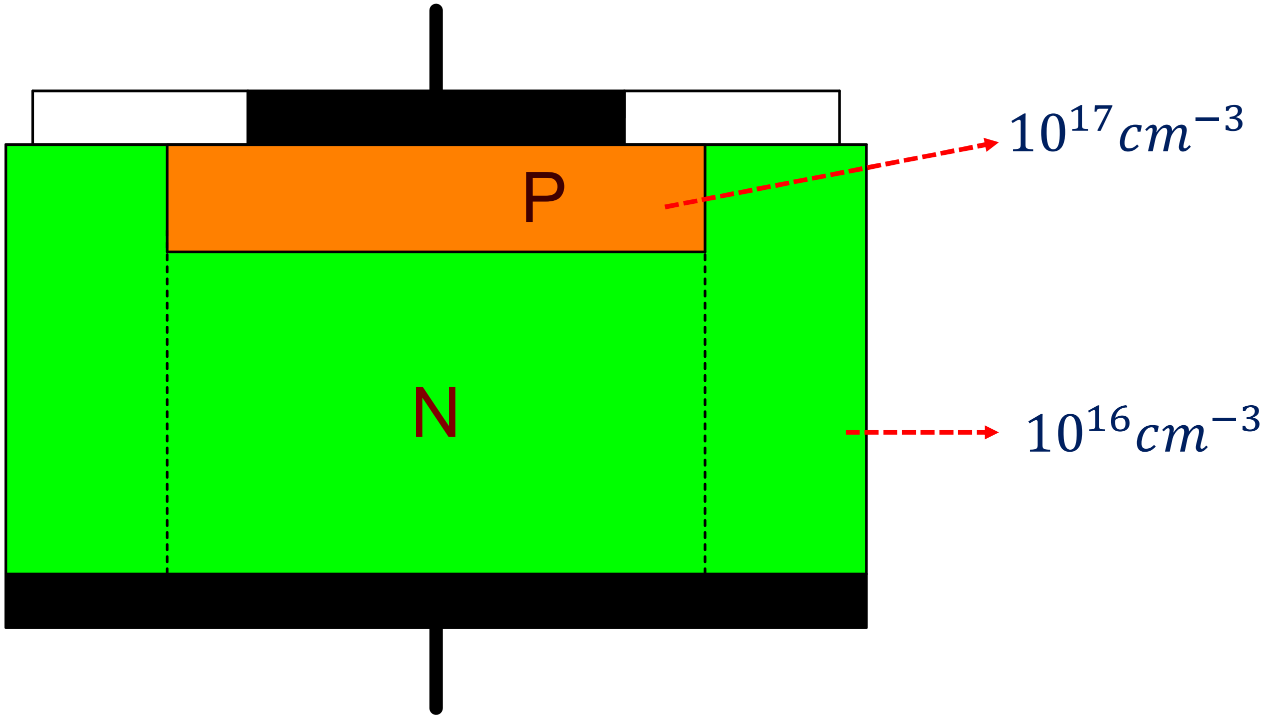


PN Junction Diode

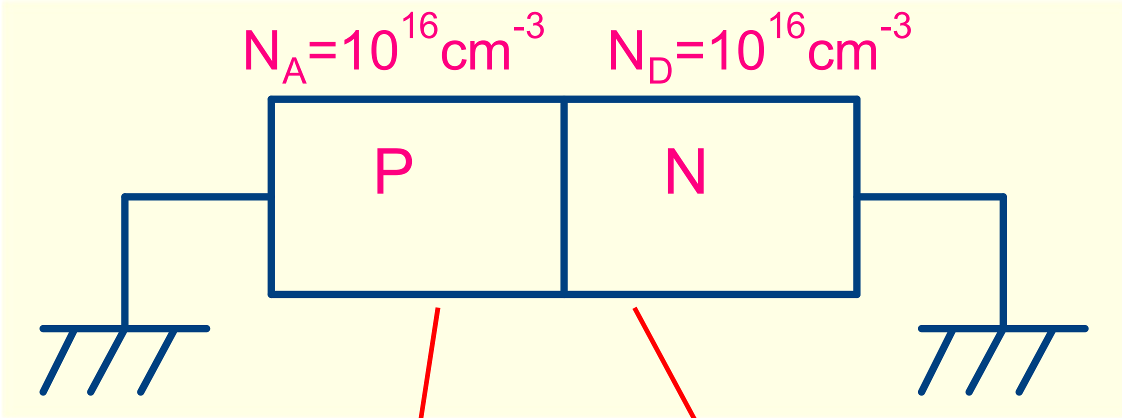
PN Junction Diode

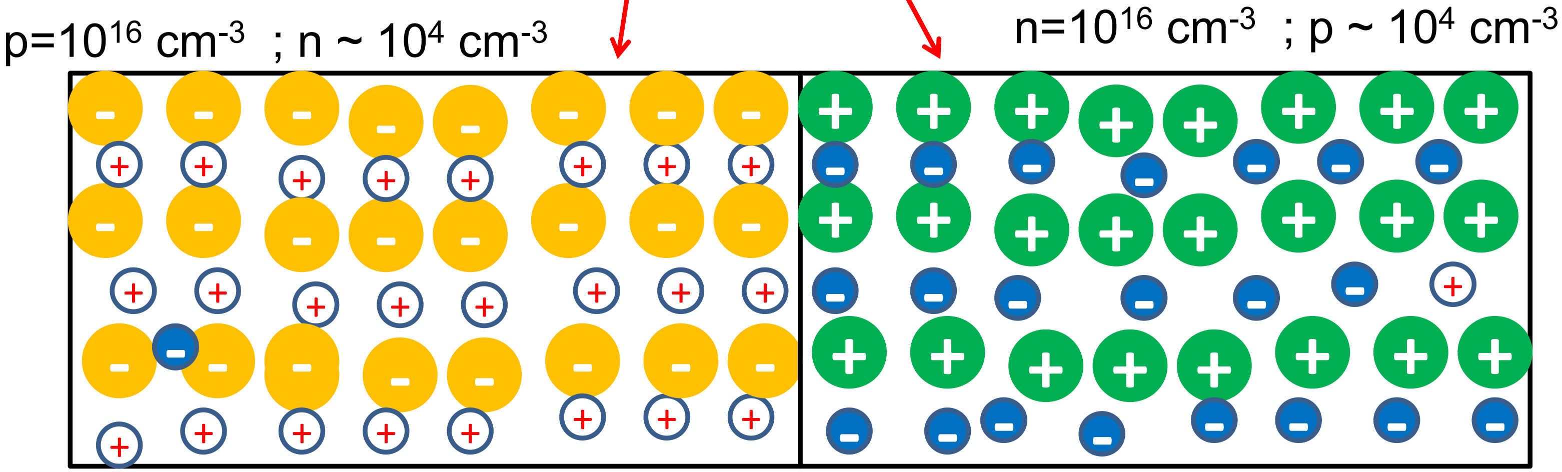






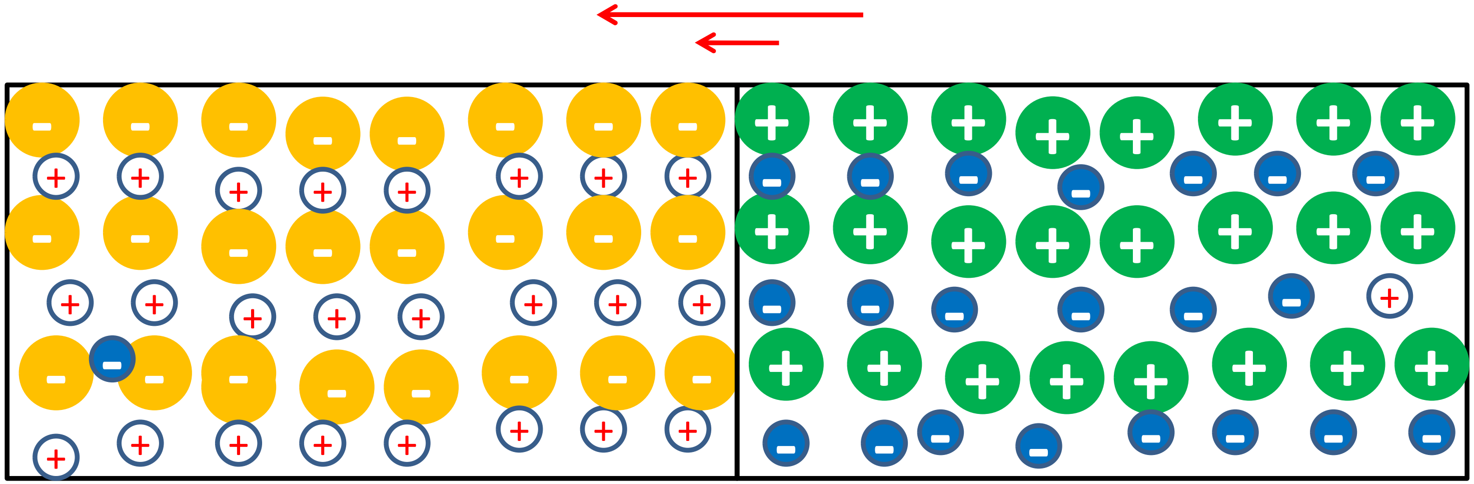
Basic Operation





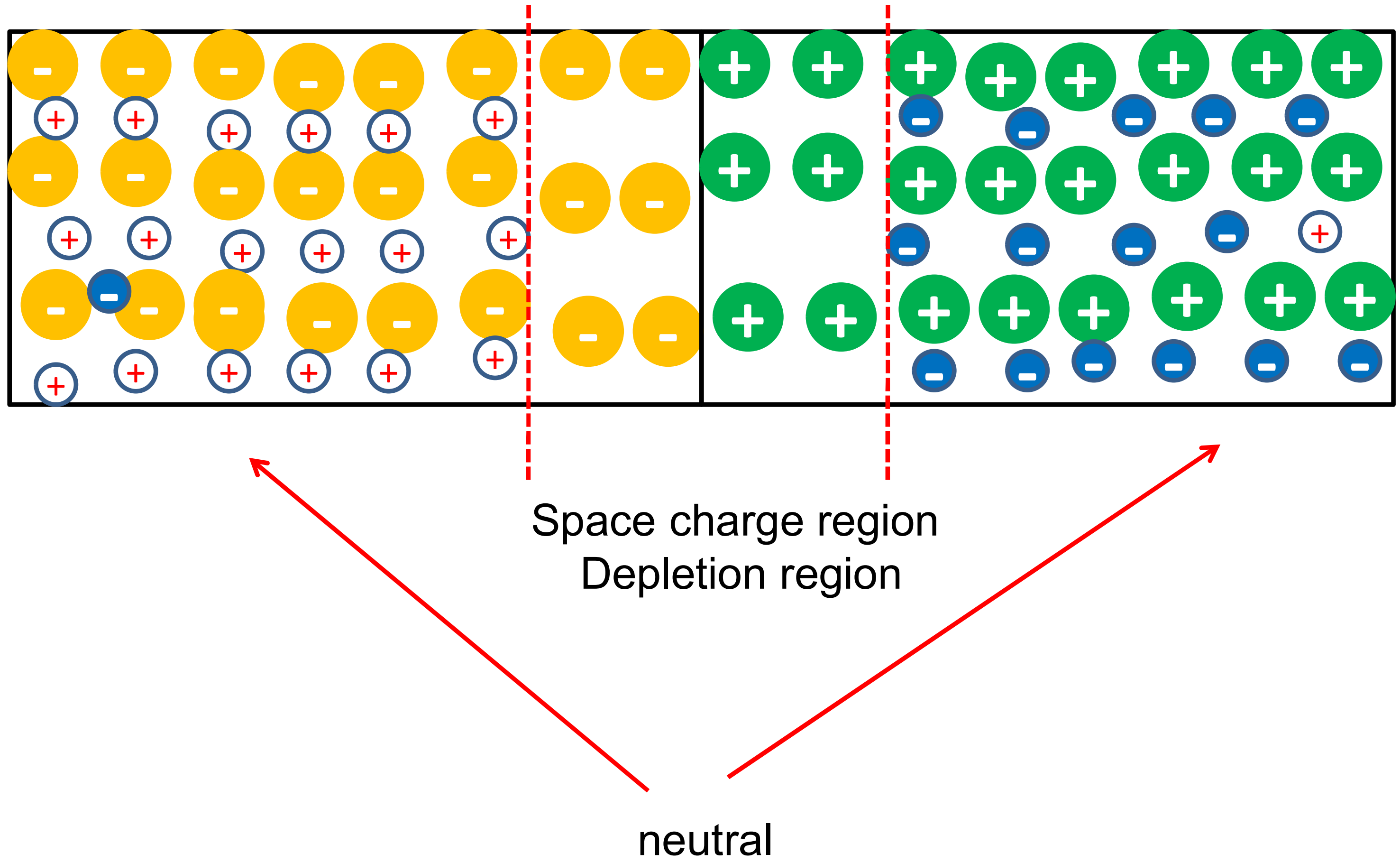
Holes will tend to diffuse from p →n and electrons from n→p

Electric field opposes flow of carriers



Eventually equilibrium is reached and there is no net flow of carriers across the junction

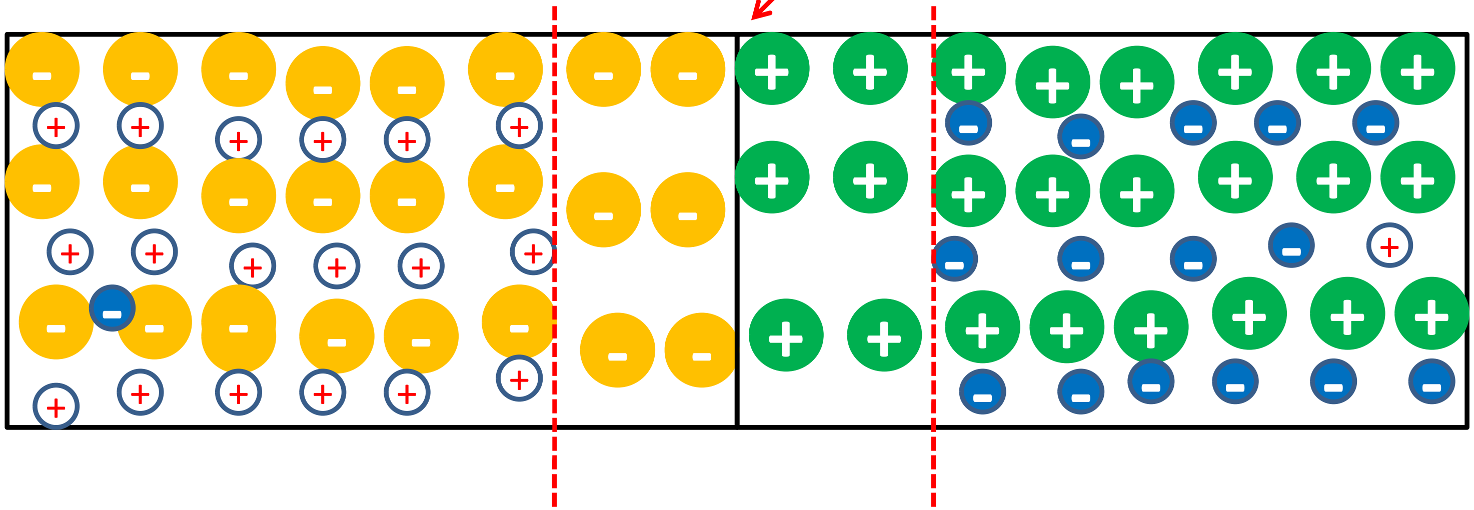
PN Junction Under Equilibrium



Although small, depletion region has some carriers

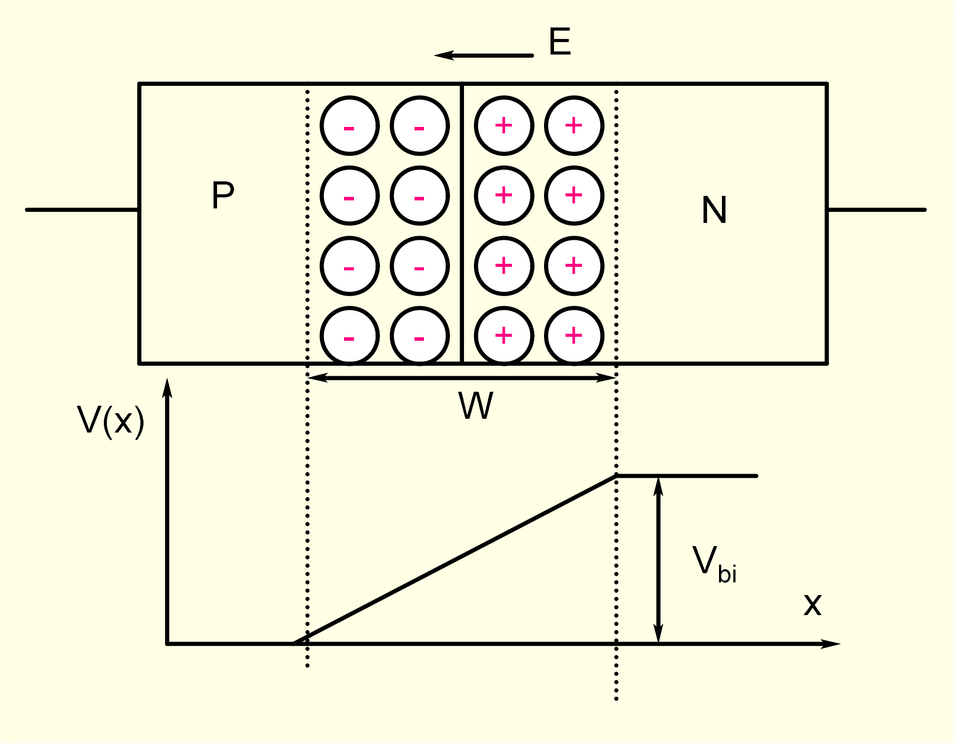
$n = 10^{16}$ cm^{-3} ; $p \sim 10^{4}$ cm^{-3}

$p = 10^{16}$ cm^{-3} ; $n \sim 10^{4}$ cm^{-3}



Space charge region
Depletion region

Built-in Potential V_{bi}



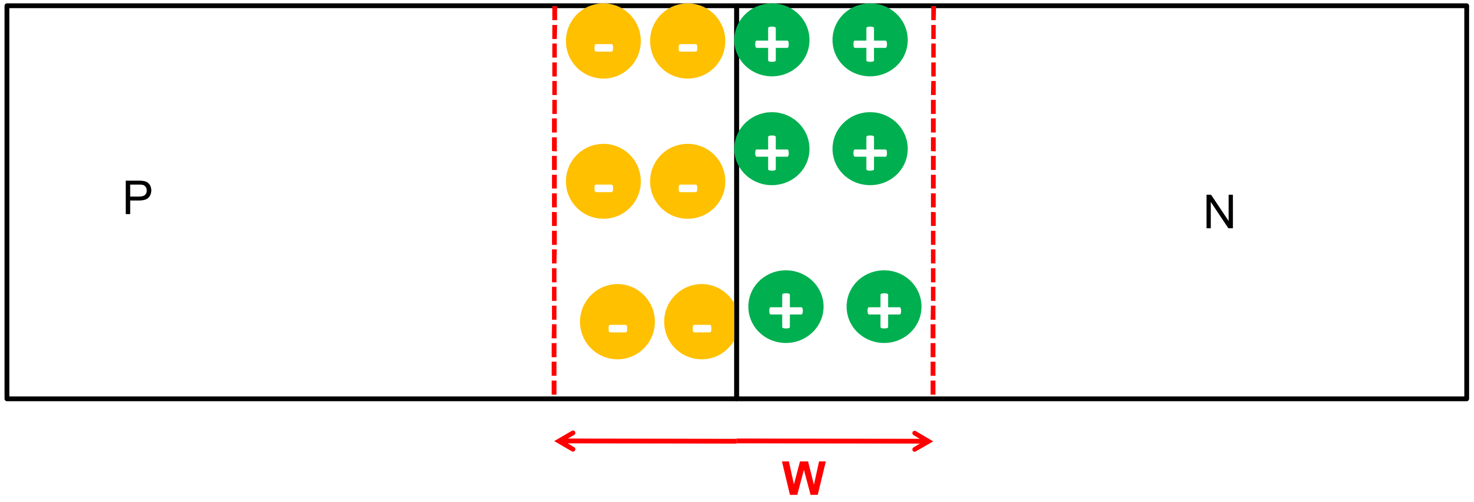
$$V_{bi} = \frac{kT}{q} \ln\left[\frac{N_A N_D}{n_i^2}\right]$$

$N_A = N_D = 10^{16}\ cm^{-3}$,   T = 300°K

$V_{bi} = 0.86$ V

Anytime you put two different materials into contact, a potential develops between them.

Depletion region



$$W = \sqrt{\frac{2\varepsilon_s}{q} \times \left(\frac{1}{N_A} + \frac{1}{N_D}\right) \times V_{bi}}$$

$$\varepsilon_s = 11.7 \times 8.85 \times 10^{-14}\, F/cm;\; q = 1.6 \times 10^{-19}\, C$$

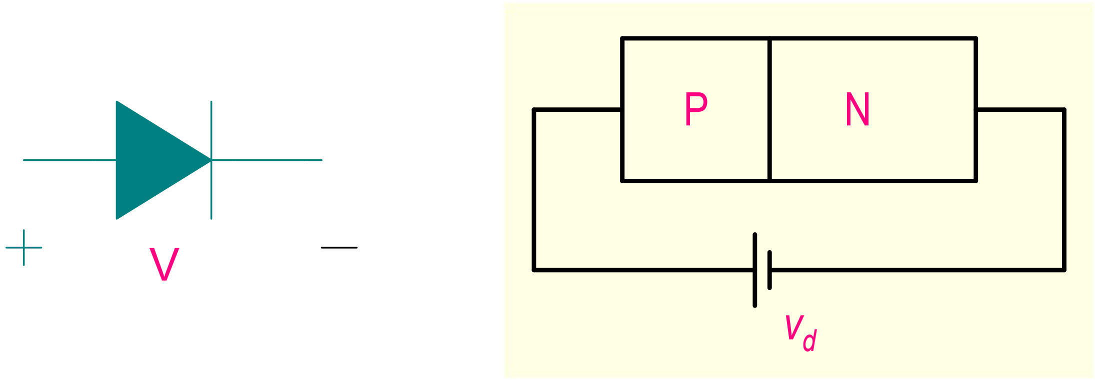
$N_A = N_D = 10^{16}\ cm^{-3}$, T = 300°K

$V_{bi} = 0.86$ V

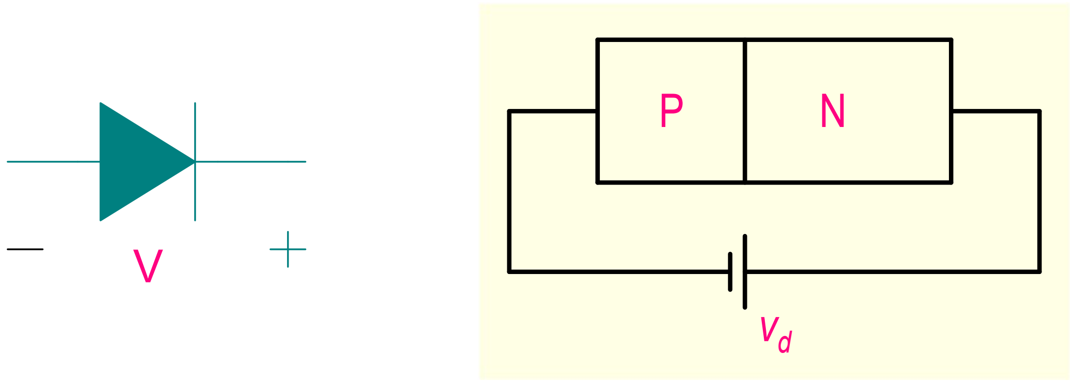
$$W = 4300\, A^o$$

$$1A^o = 10^{-8}\, cm$$

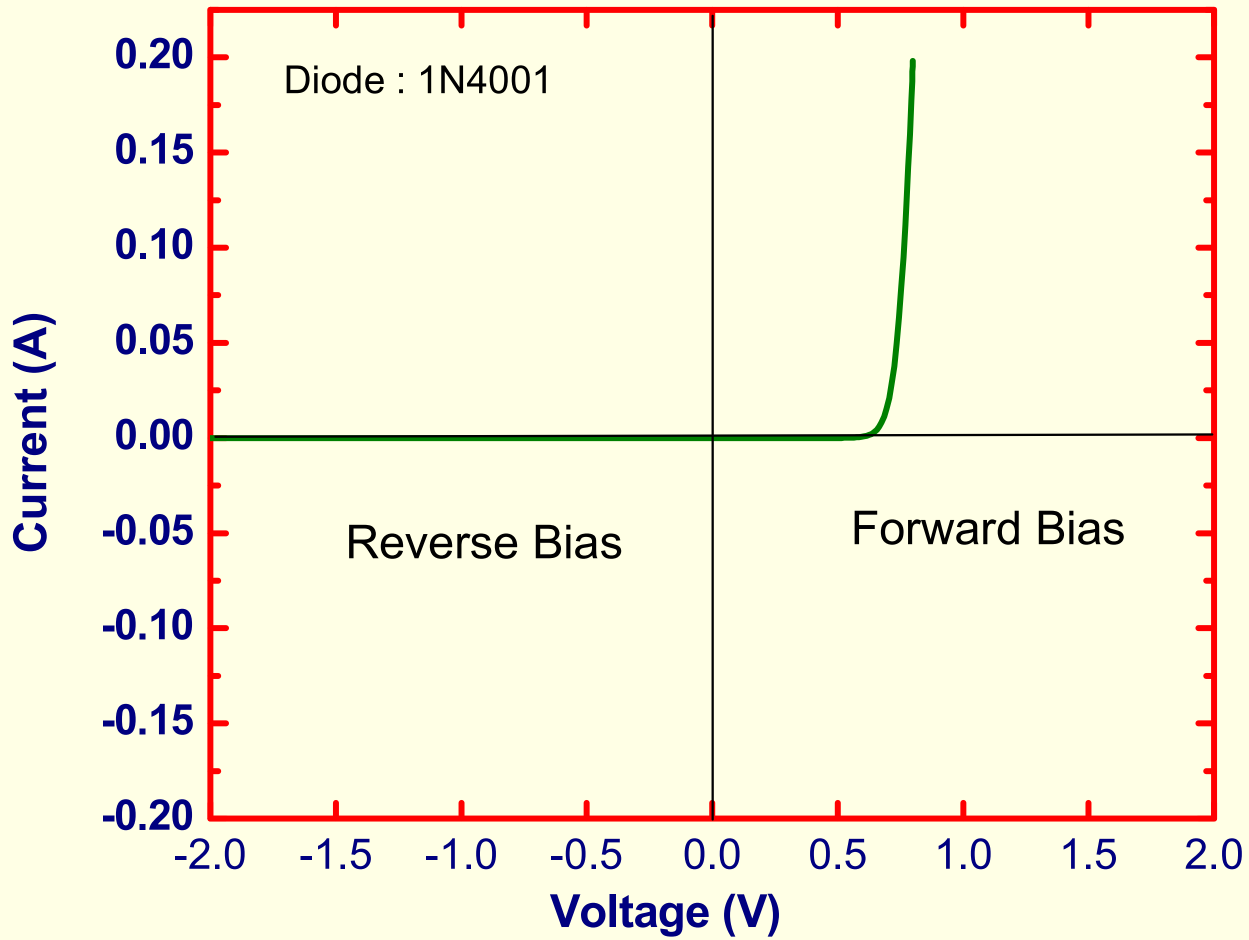
Forward and Reverse Bias



Forward Bias: P is biased at a higher voltage compared to N

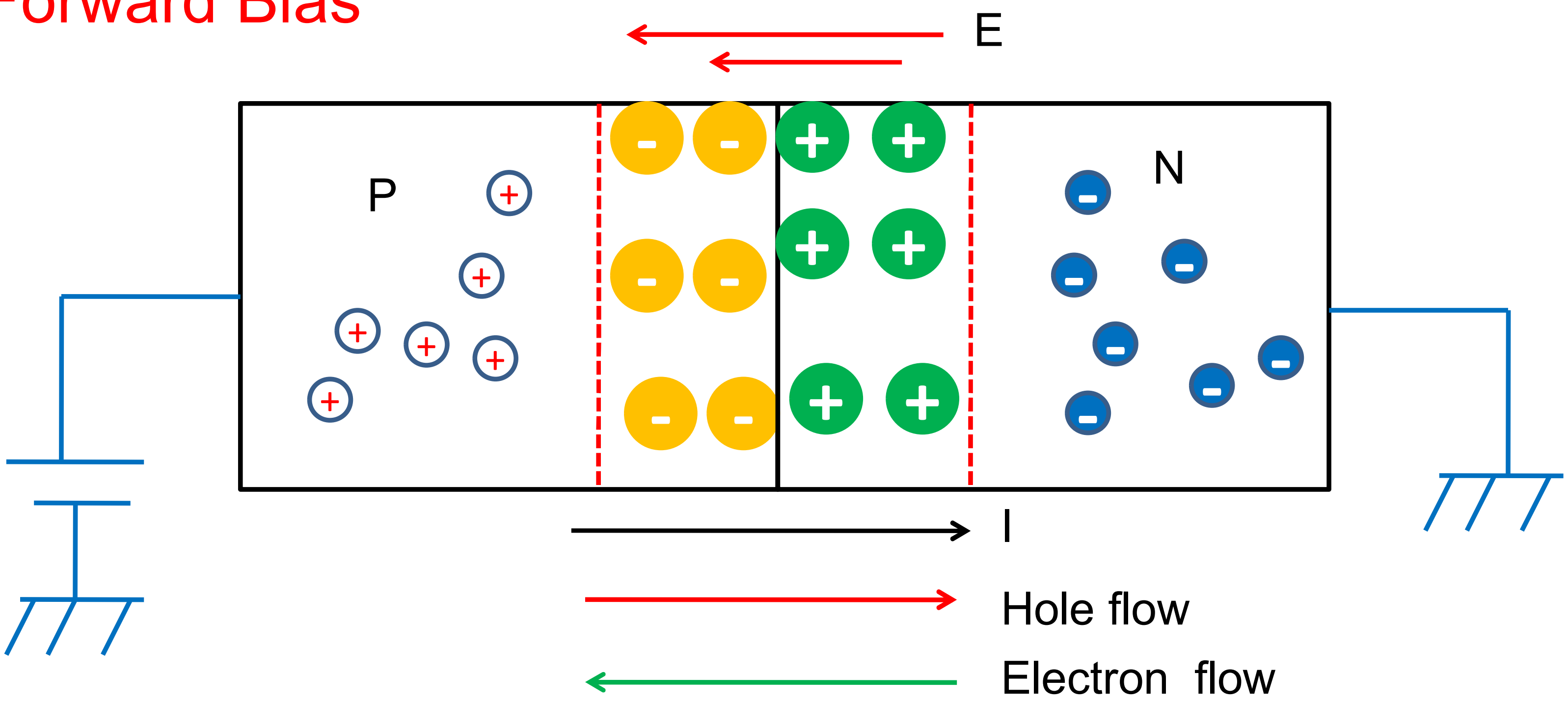


Reverse Bias: N is biased at a higher voltage compared to P

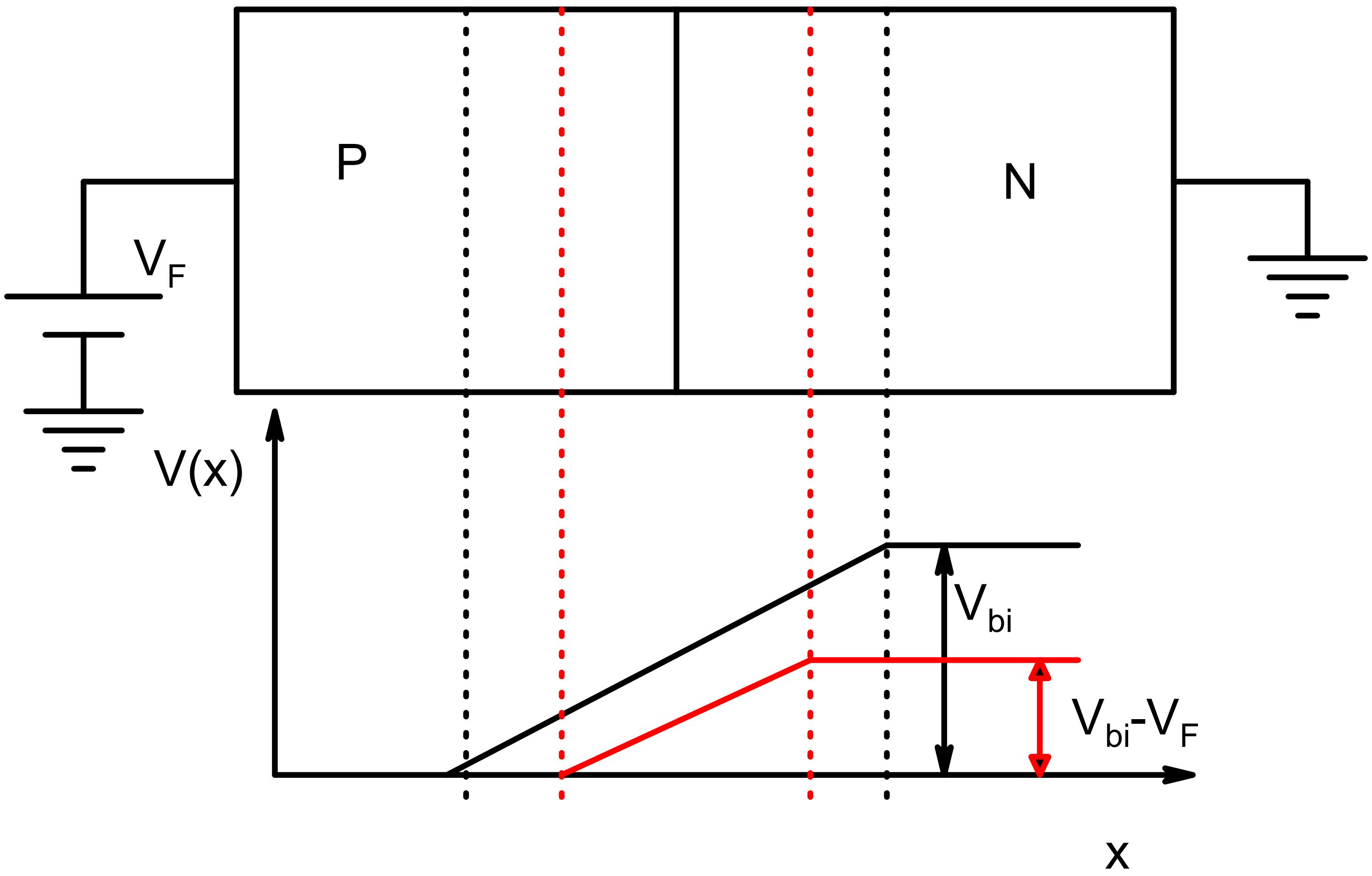


The p-n junction conducts significant current in the forward-bias region.

Forward Bias

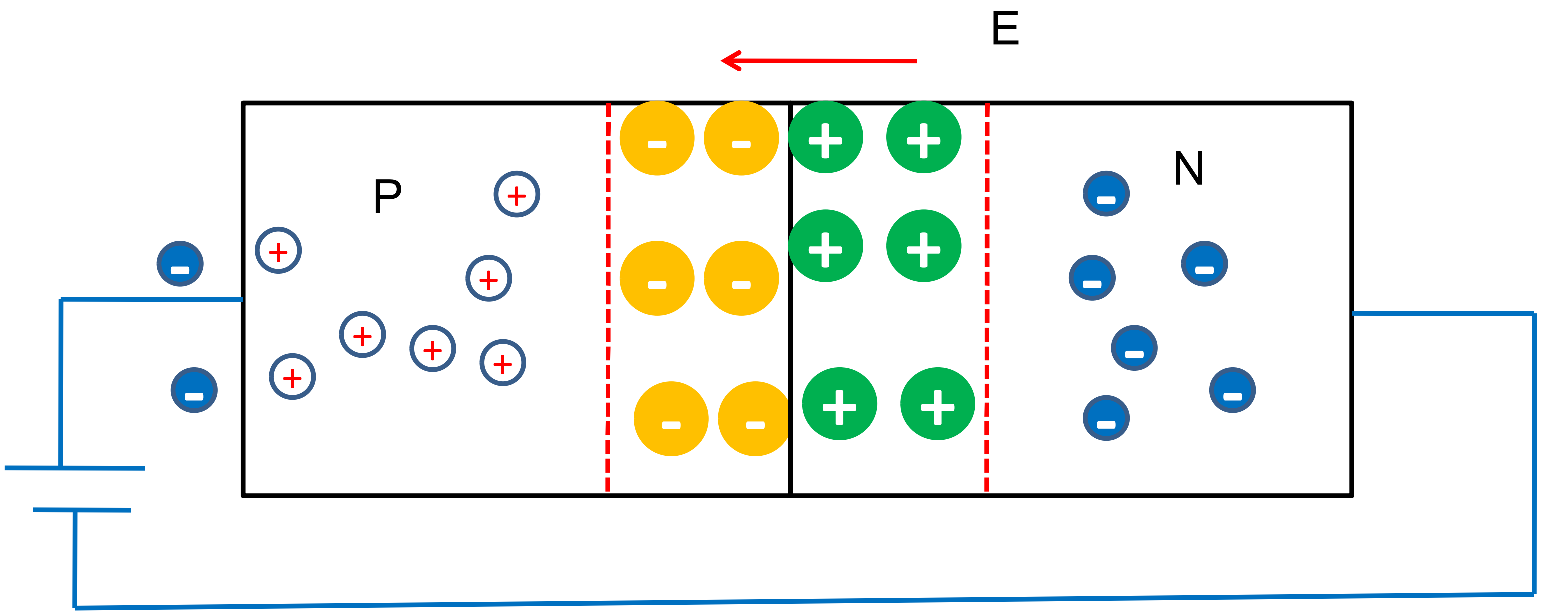


Application of forward bias lowers the built-in potential and allows holes and electrons to cross the junction and result in current flow



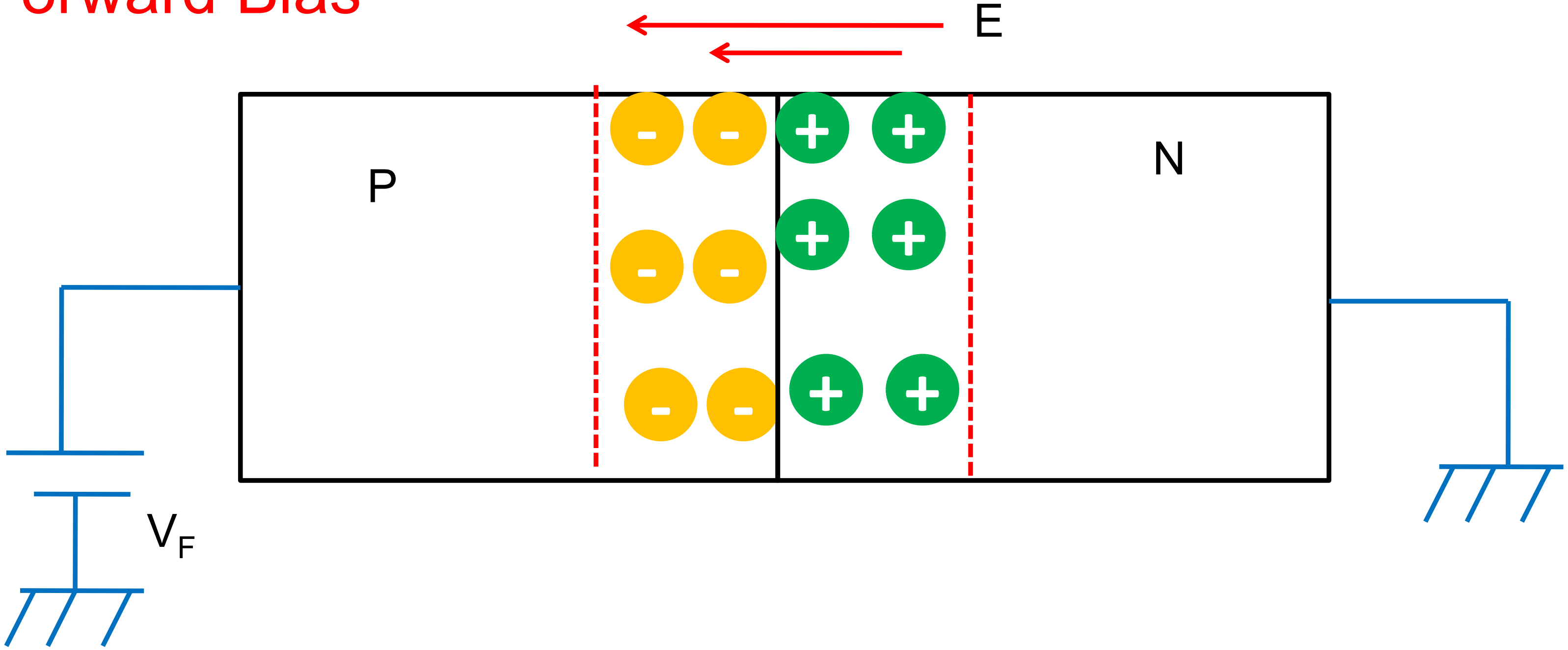
P
N
V_F
V(x)
V_{bi}
V_{bi}-V_F
x

Mechanism of Current flow



Current flows through carrier **injection** and **recombination**

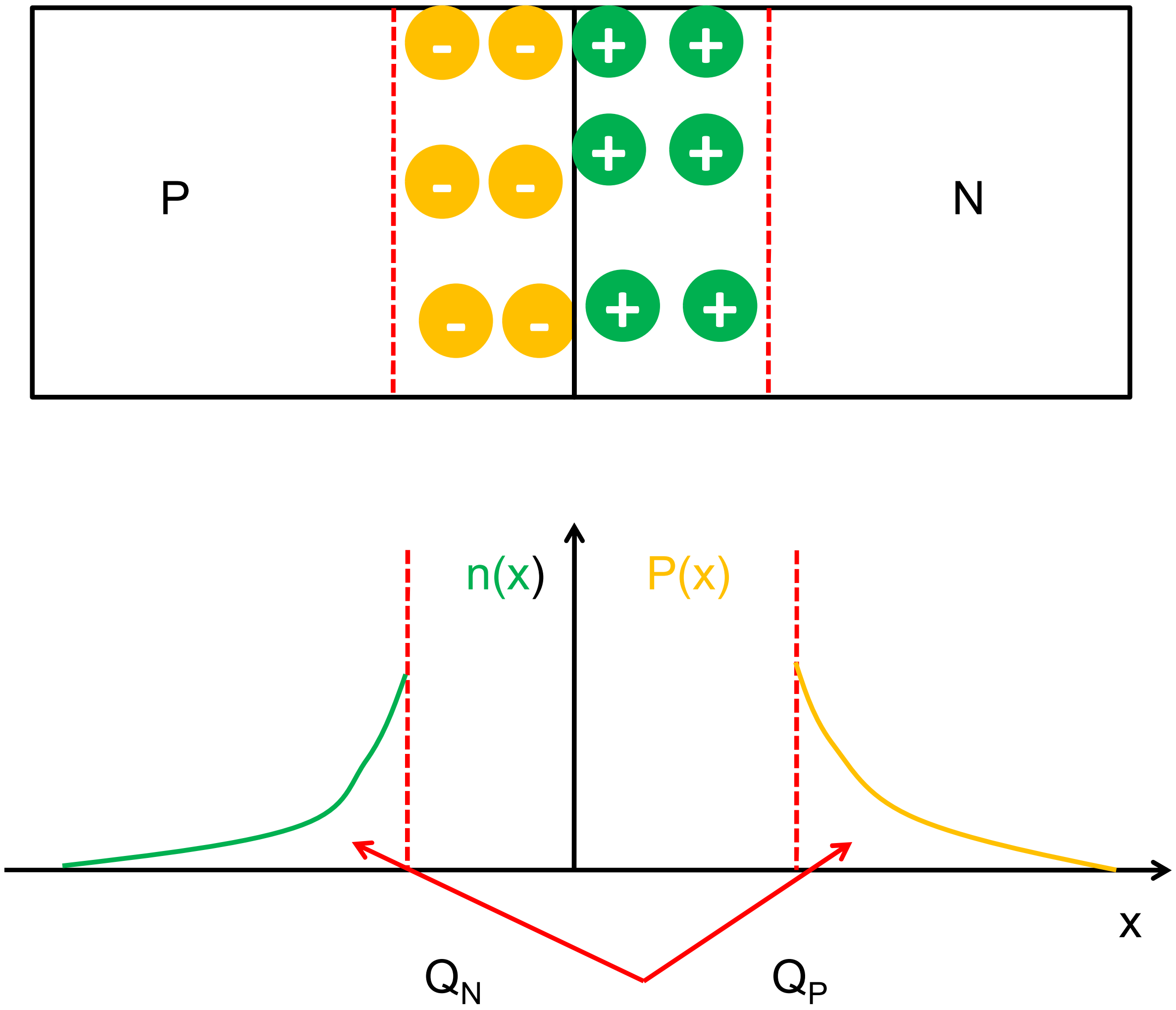
Forward Bias



Application of forward bias reduces depletion width.

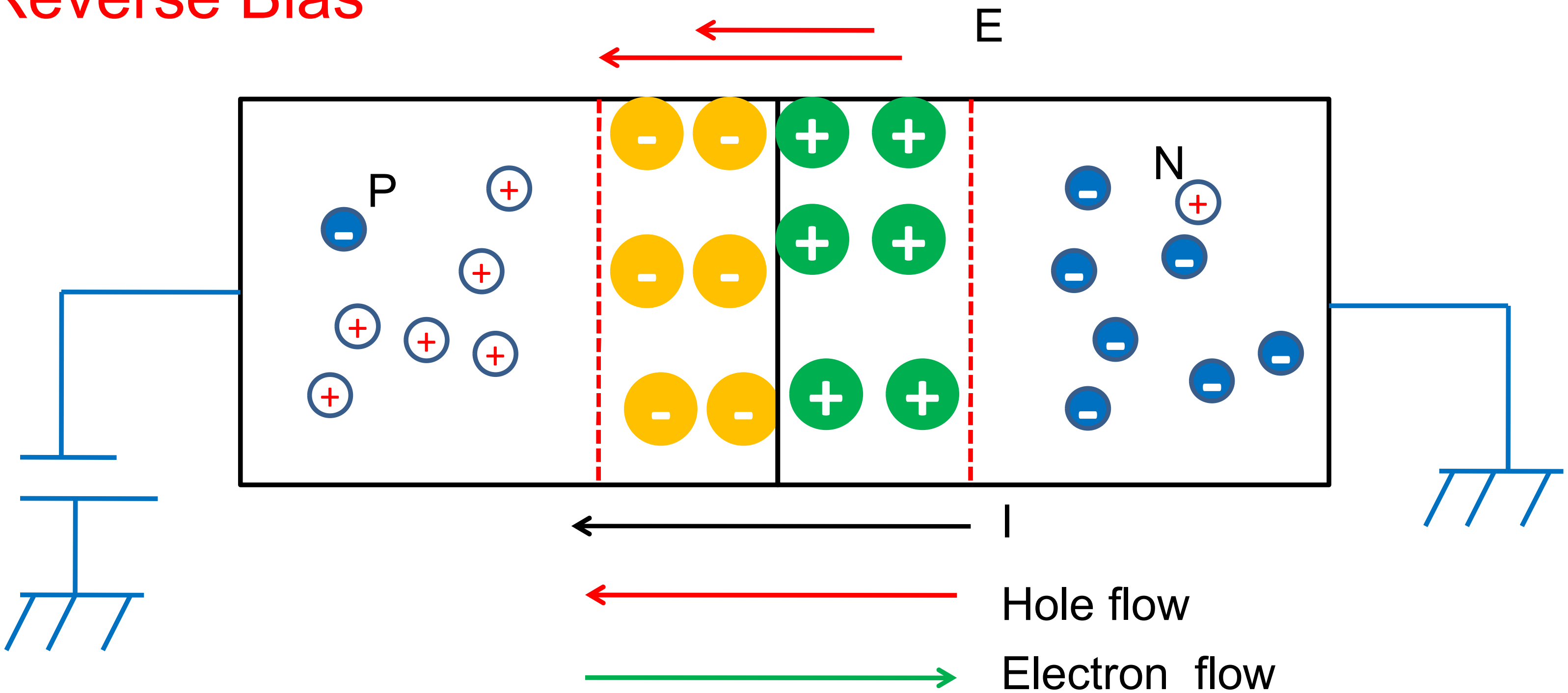
Change in depletion charge with voltage gives rise to junction capacitance (also called depletion capacitance) C_J

Excess carriers in P and N regions



Diffusion capacitance

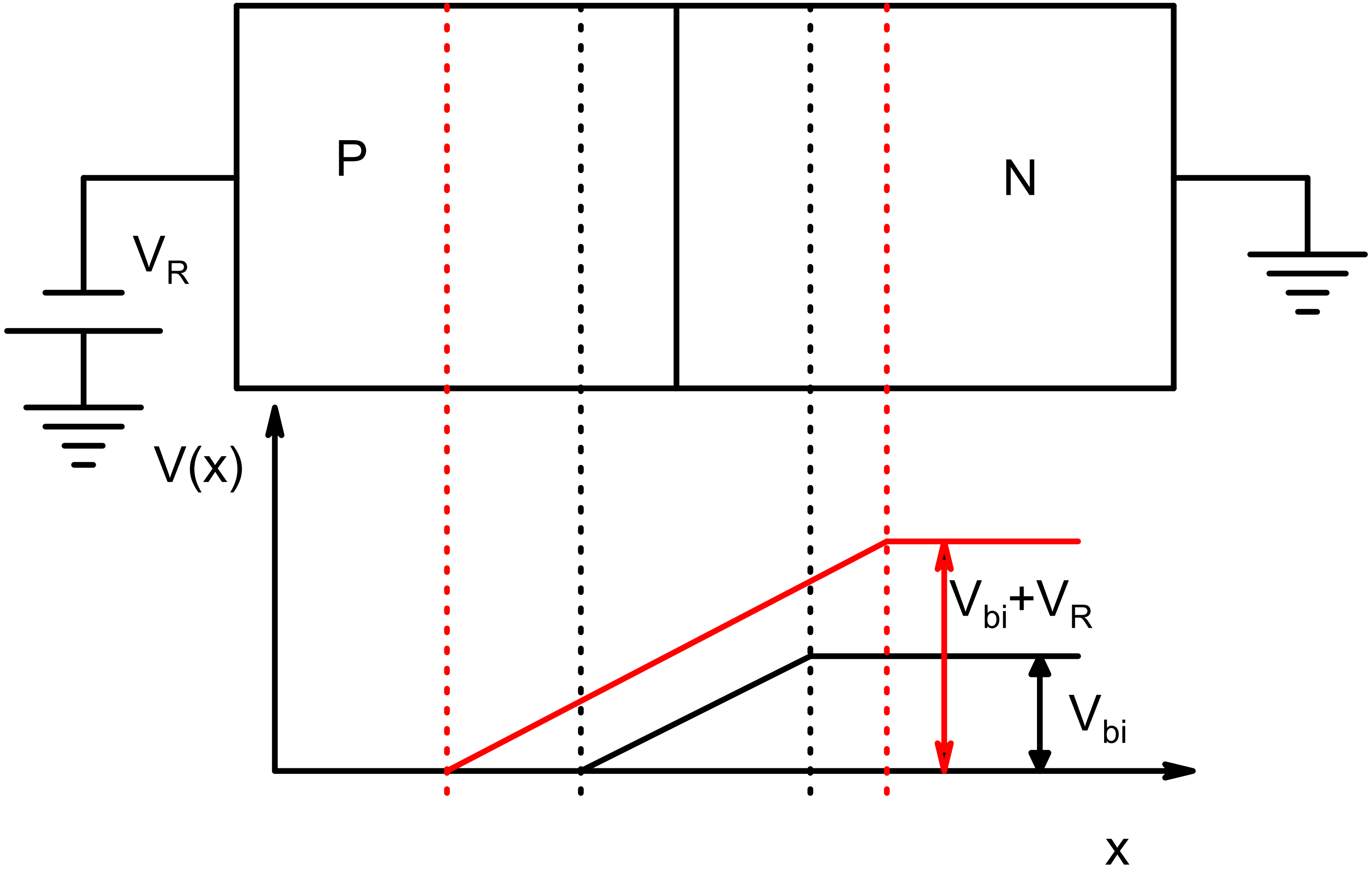
Reverse Bias



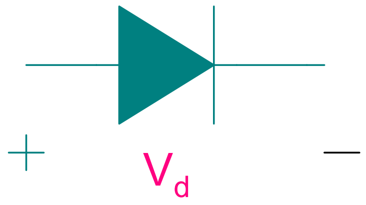
Because of very few electrons in p-type and holes in N-type current is very small !

Application of reverse bias increases the built-in potential

Reverse Bias



Diode : I-V Characteristics



$$I = I_S \times \{\exp(\frac{V_D}{nV_T}) - 1\}$$

I_S : Reverse Saturation Current

$V_T = kT/q \cong 26mV$ at T = 300K

n is called ideality factor and is equal to 1 for ideal diodes

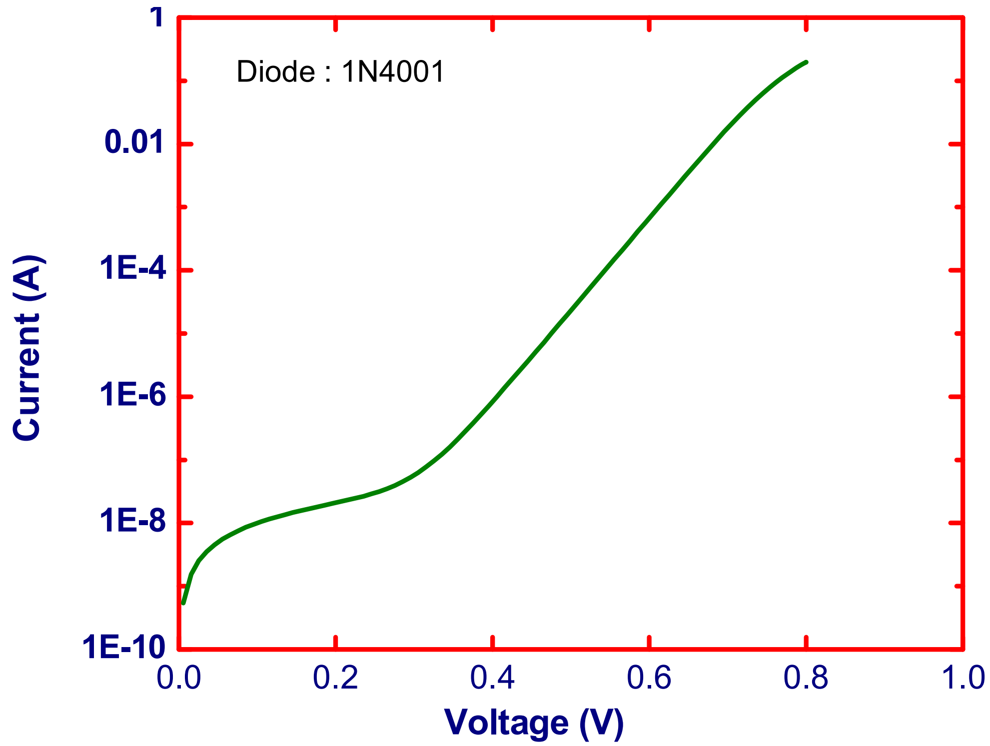
Forward Bias

$$I = I_S \times \{\exp(\frac{v_d}{V_T}) - 1\}$$

$$v_d >> V_T = 26\,mV$$

$$I \cong I_S \times \exp(\frac{v_d}{V_T})$$

$$\ln(I) = \ln(I_S) + \frac{v_d}{V_T}$$

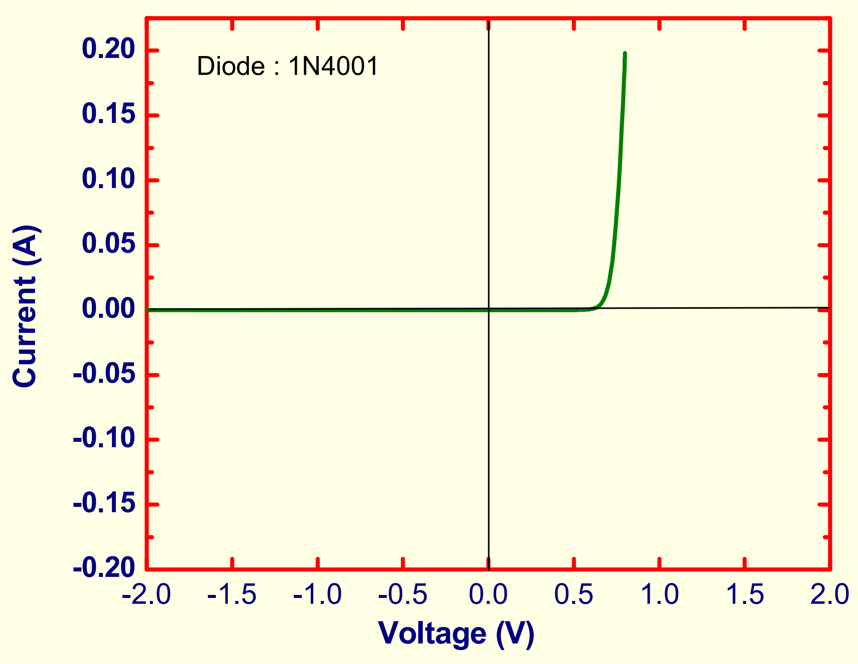


Reverse Bias

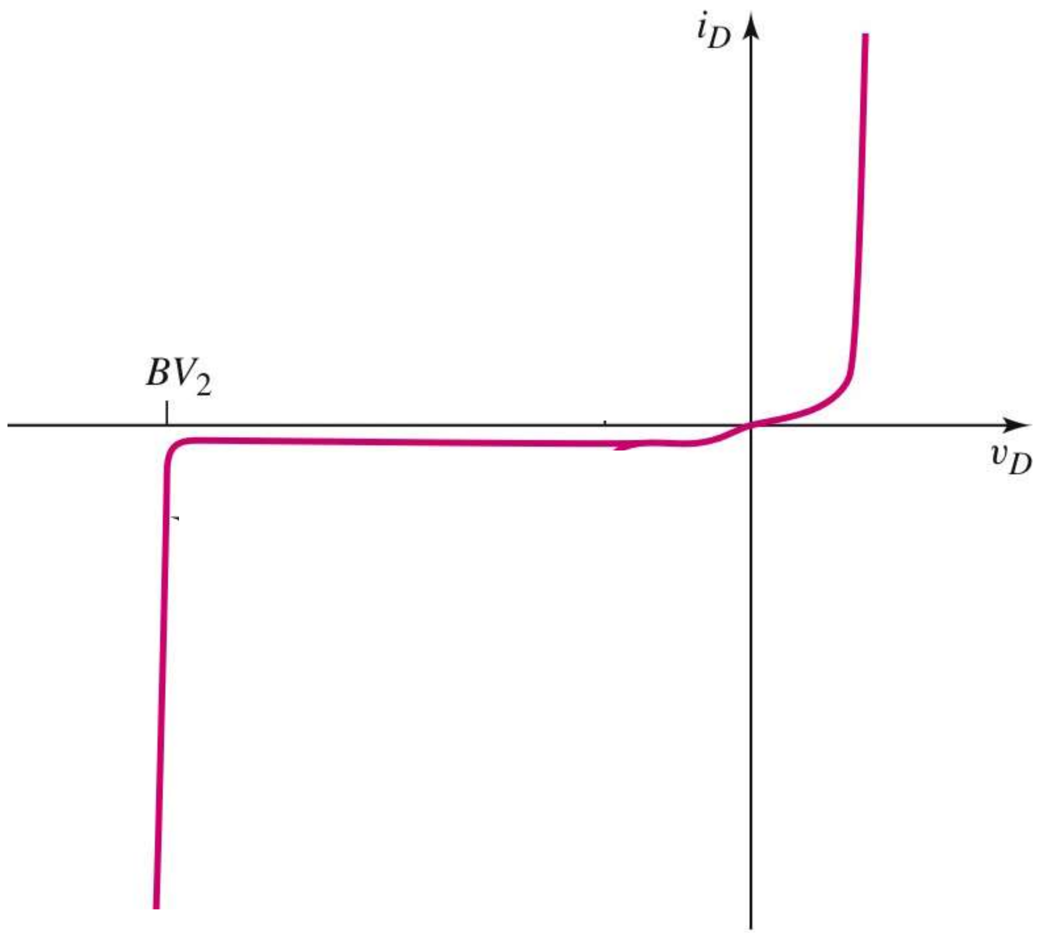
$$I = I_S \times \{\exp(\frac{v_d}{V_T}) - 1\}$$

$$v_d = -v_R$$

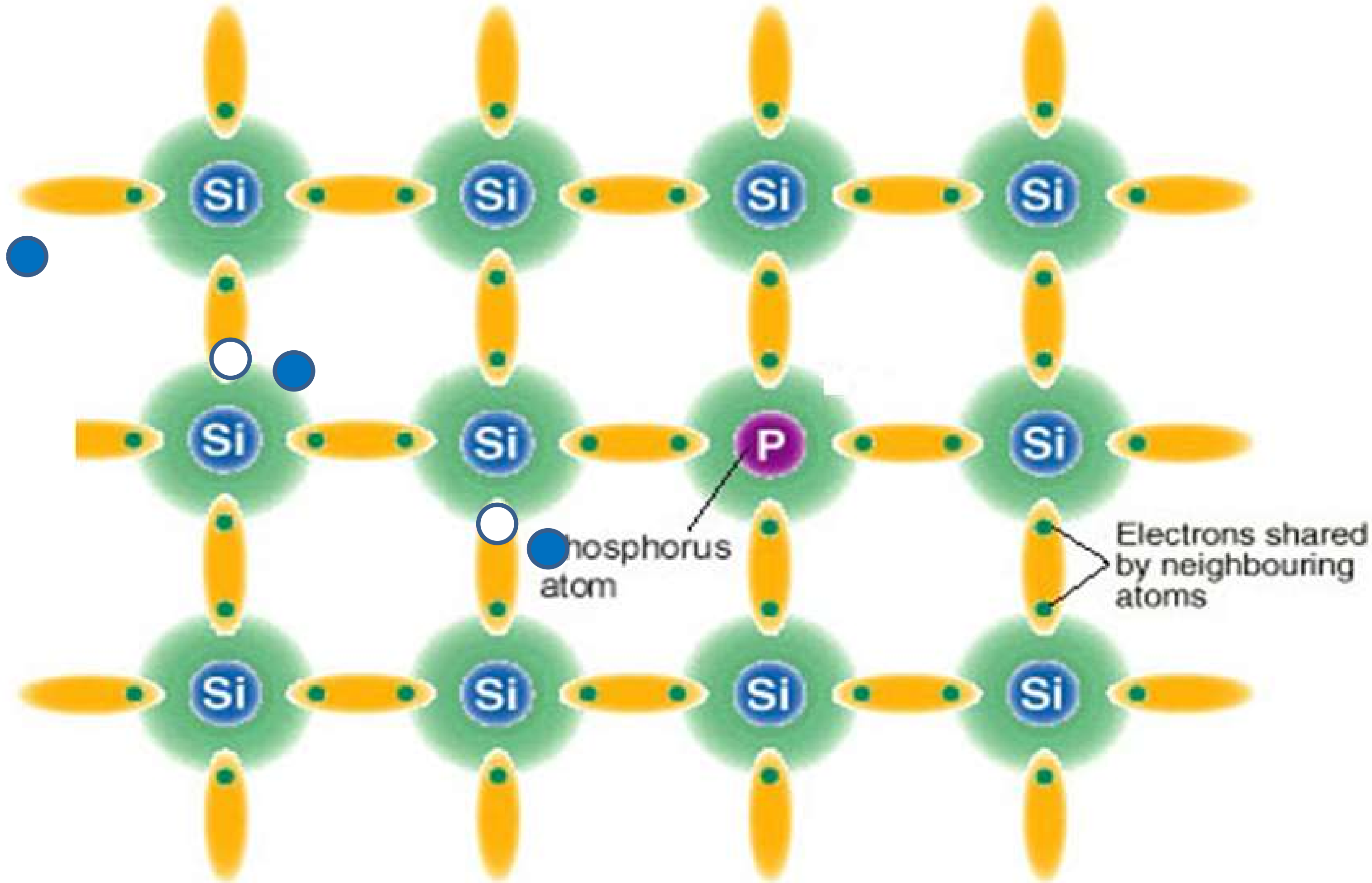
$$I = I_S \times \{\exp(-\frac{v_R}{V_T}) - 1\} \cong -I_S$$



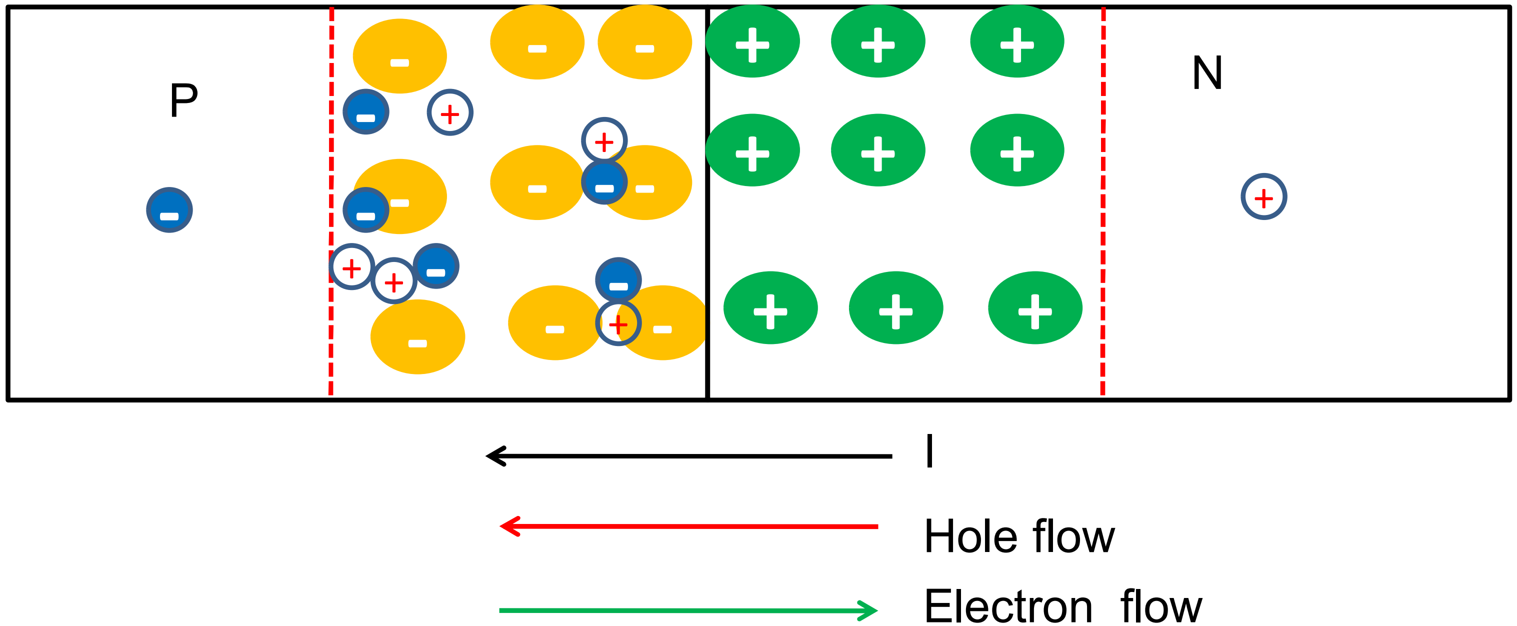
Breakdown



Impact Ionization



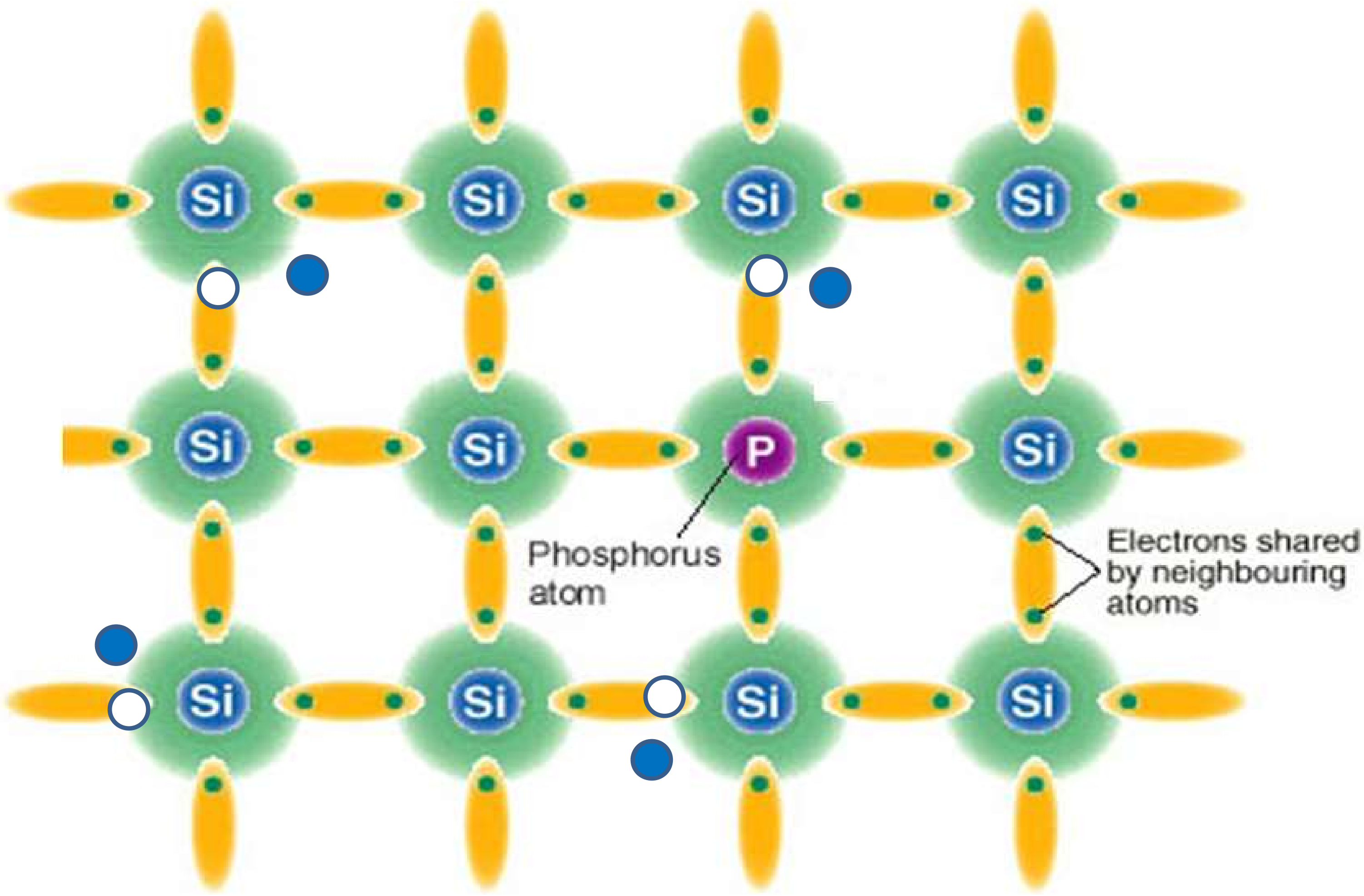
Breakdown Mechanism: Avalanche



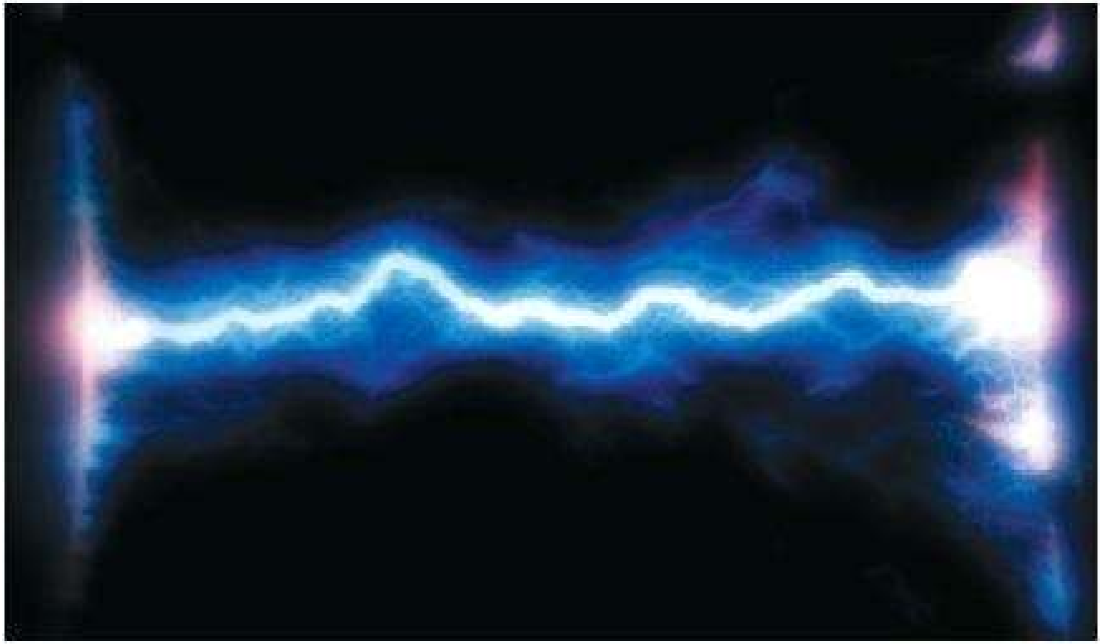
A multiplication of carriers takes place due to impact ionization in the depletion region, as a result of which large current begins to flow.

Avalanche

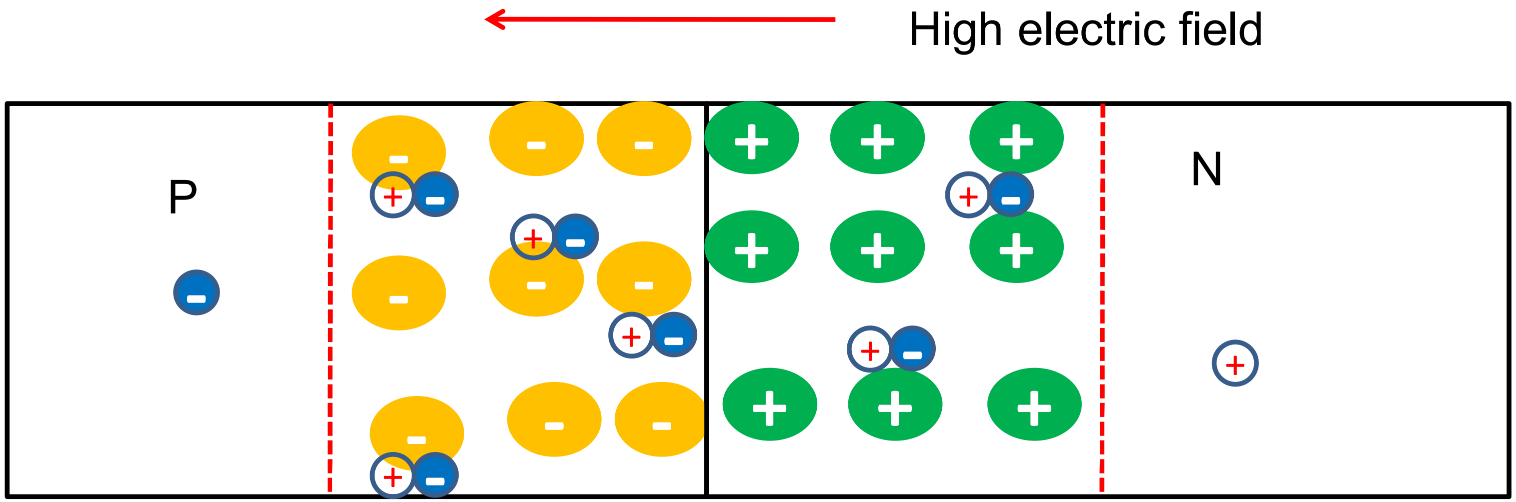
Ionization can also occur due to electric field



Electric Arc



Breakdown: Zener Heavily doped junctions



Electric field "**breaks the bond**" creating electron and hole pairs. These carriers move to give rise to large current.

Most of the common pn junction diodes breakdown due to avalanche mechanism. Even diodes which are called zener diodes have avalanche breakdown