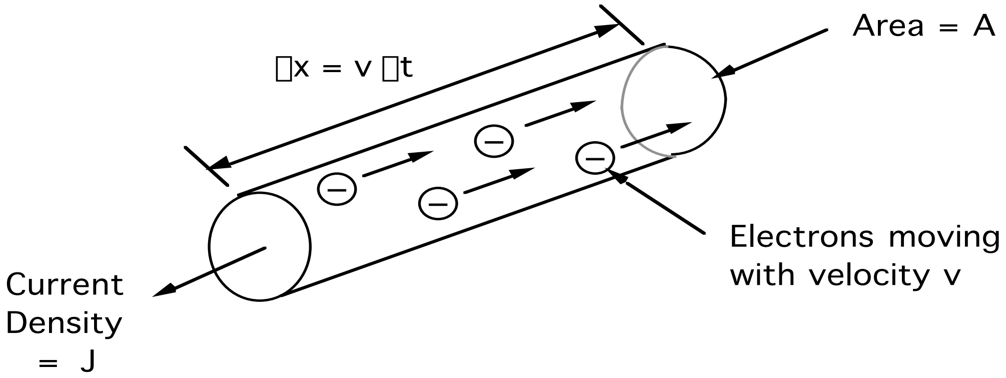
Review of Basic Semiconductor Physics

Current Flow and Conductivity

- Charge in volume $A\Delta x = \Delta Q$

  $= q\,n\,A\,\Delta x = q\,n\,A\,v\Delta t$
- Current density $J = (\Delta Q/\Delta t)A^{-1}$
  $= q\,n\,v$

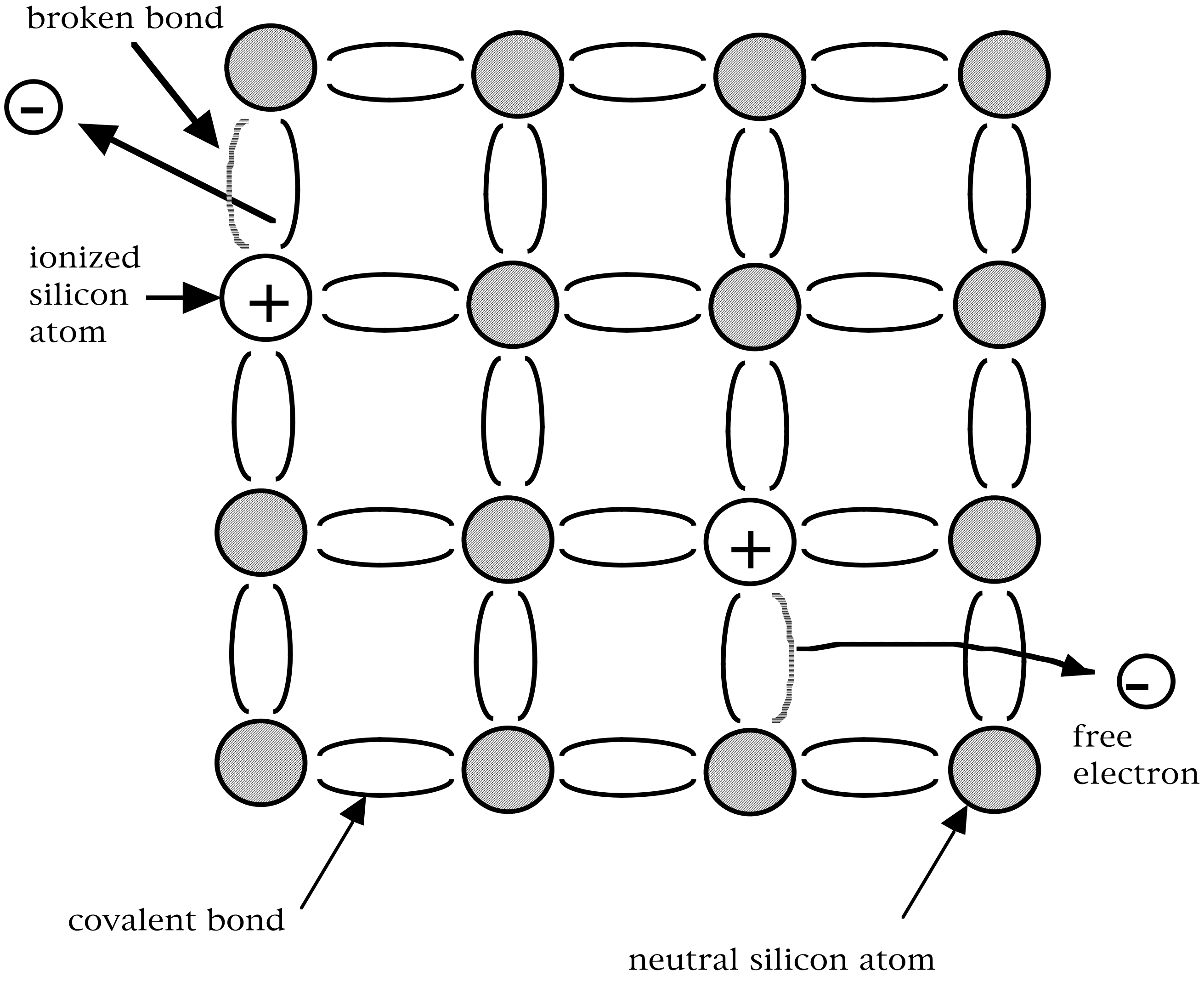


- Metals - gold, platinum, silver, copper, etc.
  - $n = 10^{23}\ \text{cm}^{-3}$; $\sigma = 10^{7}$ mhos-cm
- Insulators - silicon dioxide, silicon nitride, aluminum oxide
  - $n < 10^{3}\ \text{cm}^{-3}$; $\sigma < 10^{-10}$ mhos-cm
- Semiconductors - silicon, gallium arsenide, diamond, etc.
  - $10^{8} < n < 10^{19}\ \text{cm}^{-3}$; $10^{-10} < \sigma < 10^{4}$ mhos-cm

Thermal Ionization

- Si atoms have thermal vibrations about equilibrium point.

- Small percentage of Si atoms have large enough vibrational energy to break covalent bond and liberate an electron.



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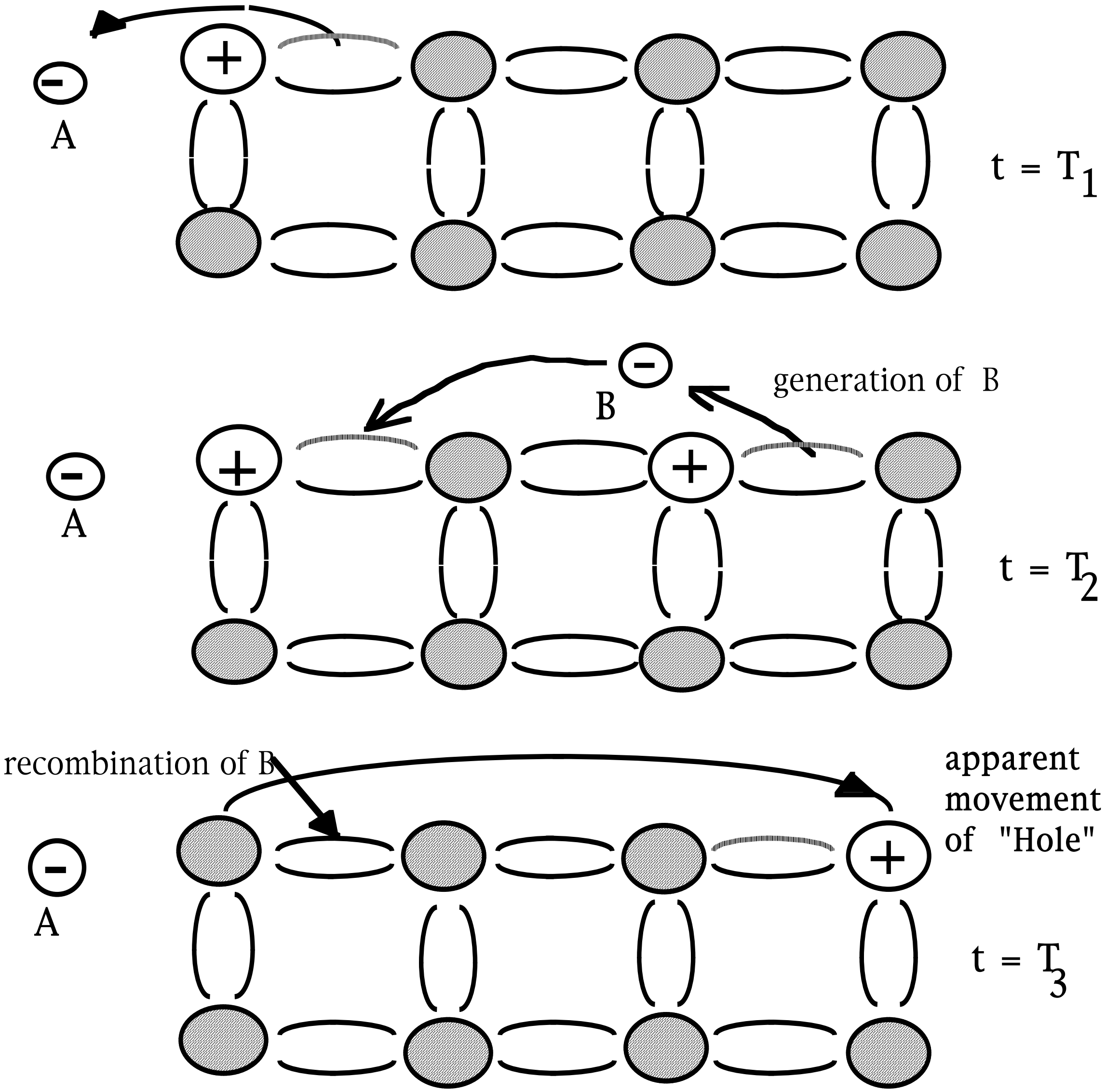
Electrons and Holes

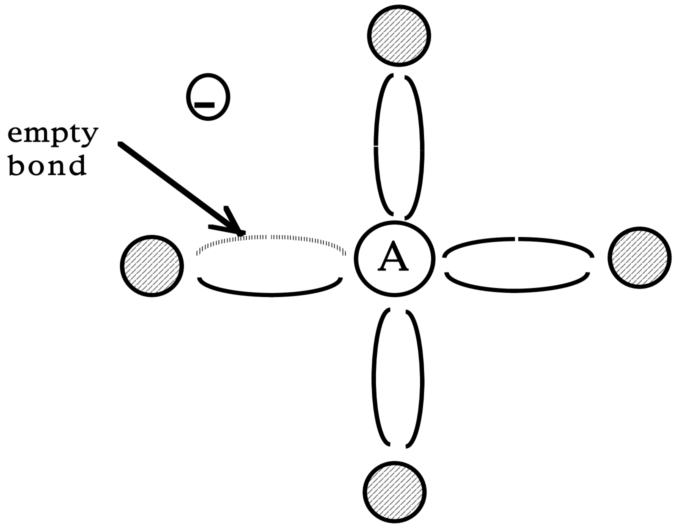
- $T_3 > T_2 > T_1$
- Density of free electrons = n : Density of free holes = p
  - p = n = $n_i(T)$ = intrinsic carrier density.
- $n_i^2(T) = C \exp(-qE_g/(kT))$ = 10^{20} cm^{-6} at 300 °K
  - T = temp in °K
  - k = 1.4×10^{-23} joules/ °K
  - E_g = energy gap = 1.1 eV in silicon
  - q = 1.6×10^{-19} coulombs



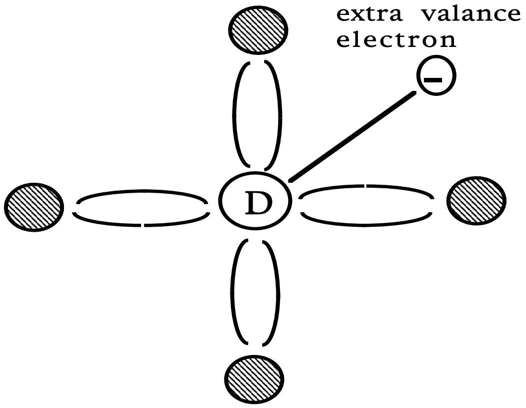
Doped Semiconductors

- Extrinsic (doped) semiconductors:$p = p_o \neq n = n_o \neq n_i$
- Carrier density estimates:
    - Law of mass action $n_o p_o = n_i^2(T)$
    - Charge neutrality $N_a + n_o = N_d + p_o$

- P-type silicon with $N_a >> n_i$: $p_o \approx N_a$, $n_o \approx n_i^2 / N_a$



- N-type silicon with $N_d >> n_i$: $n_o \approx N_d$, $p_o \approx n_i^2 / N_d$



Nonequilibrium and Recombination

- Thermal Equilibrium - Carrier generation = Carrier recombination
  - $n = n_o$ and $p = p_o$

- Nonequilibrium - $n > n_o$ and $p > p_o$
  - $n = n_o + \Delta n$ and $p = n_o + \Delta n$; Δn = excess carrier density
  - Excess holes and excess electrons created in equal numbers by breaking of covalent bonds
  - Generation mechanisms -light (photoelectric effect), injection, impact ionization

- Recombination - removal of excess holes and electrons
  - Mechanisms - free electron captured by empty covalent bond (hole) or trapped by impurity or crystal imperfection
  - Rate equation: $d(\Delta n)/dt = -\Delta n/\tau$
  - Solution $\Delta n = \Delta n(0)\, e^{-t/\tau}$

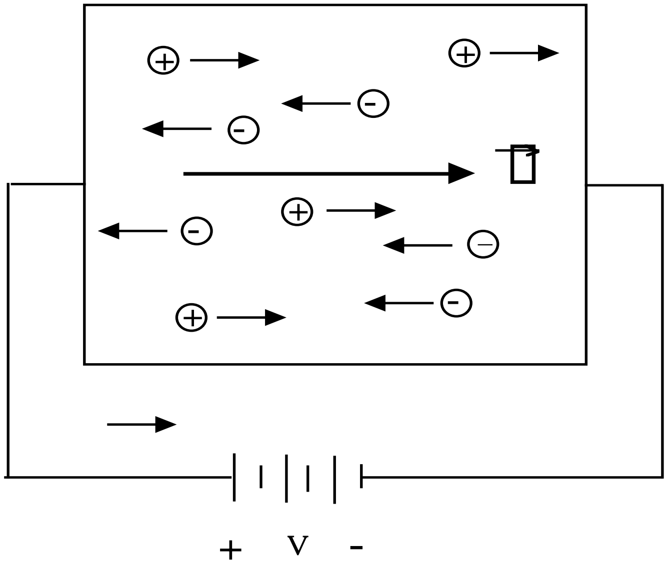
Carrier Lifetimes

- τ = excess carrier lifetime
  - Usually assumed to be constant. Changes in two important situations.
  - τ increases with temperature T
  - τ decreases at large excess carrier densities ; $\tau = \tau_o/[1 + (\delta n/n_b)^2]$

- Control of carrier lifetime values.
  - Switching time-on state loss tradeoff mandates good lifetime control.
  - Control via use of impurities such as gold - lifetime killers.
  - Control via electron irradiation - more uniform and better control.

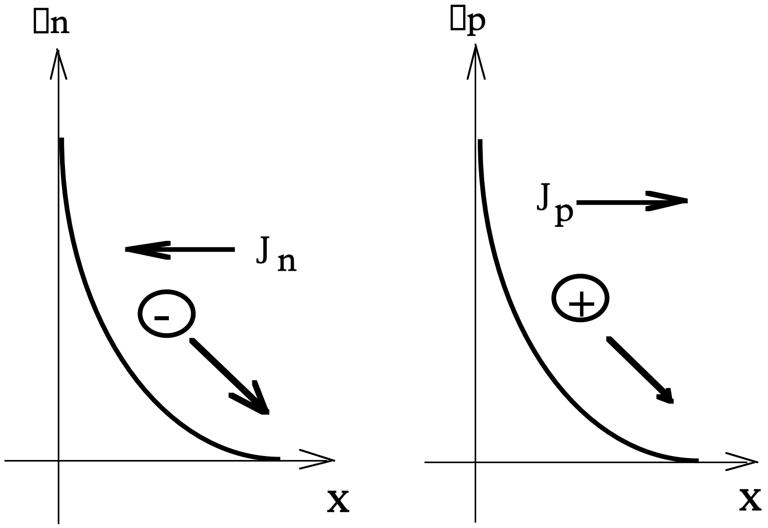
Current Flow

Drift



- $J_{drift} = q\,\mu_n\,n\,E + q\,p\,\mu_p\,E$
- $\mu_n = 1500\ cm^2/V\text{-}sec$ for silicon at room temp. and $N_d < 10^{15}\ cm^{-3}$
- $\mu_p = 500\ cm^2/V\text{-}sec$ for silicon at room temp. and $N_a < 10^{15}\ cm^{-3}$

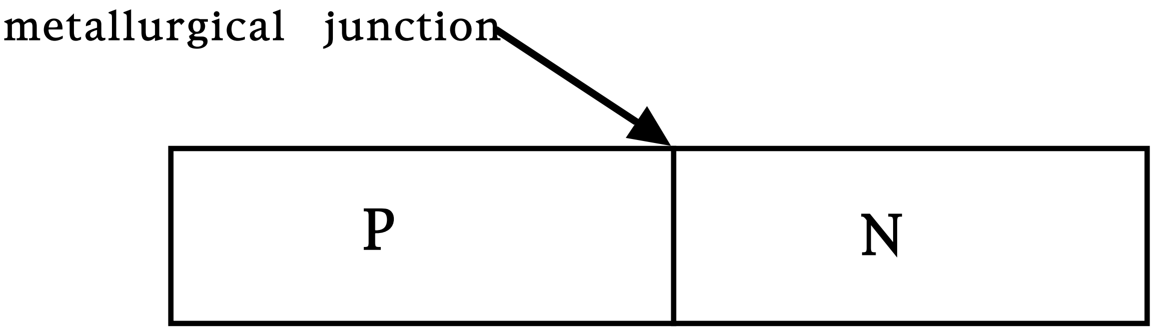
Diffusion

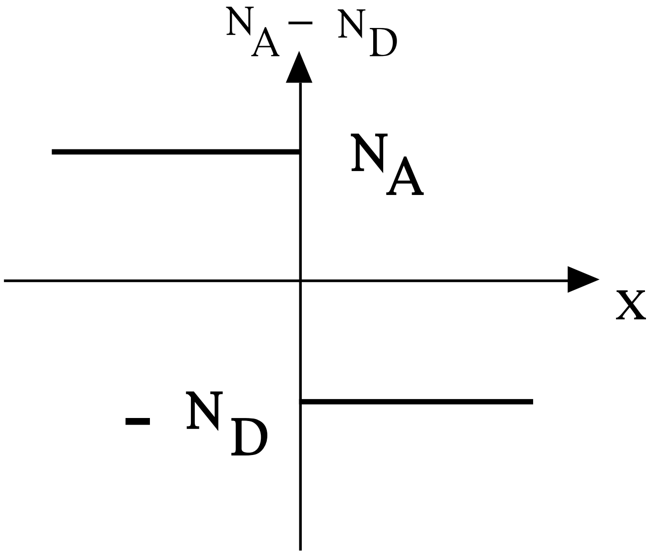


- $J_{diff} = J_n + J_p = q\,D_n dn/dx - q\,D_p\,dp/dx$
- $D_n/\mu_n = D_p/\mu_p = kT/q$; Einstein relation
- D = diffusion constant, μ = carrier mobility

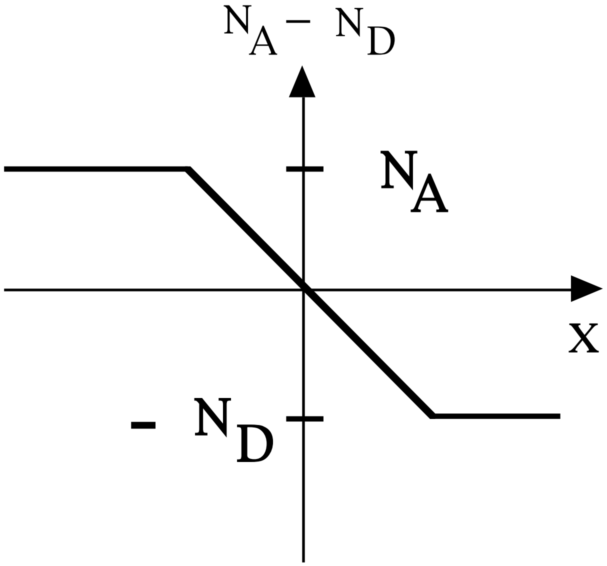
- Total current density $J = J_{drift} + J_{diff}$

PN Junction





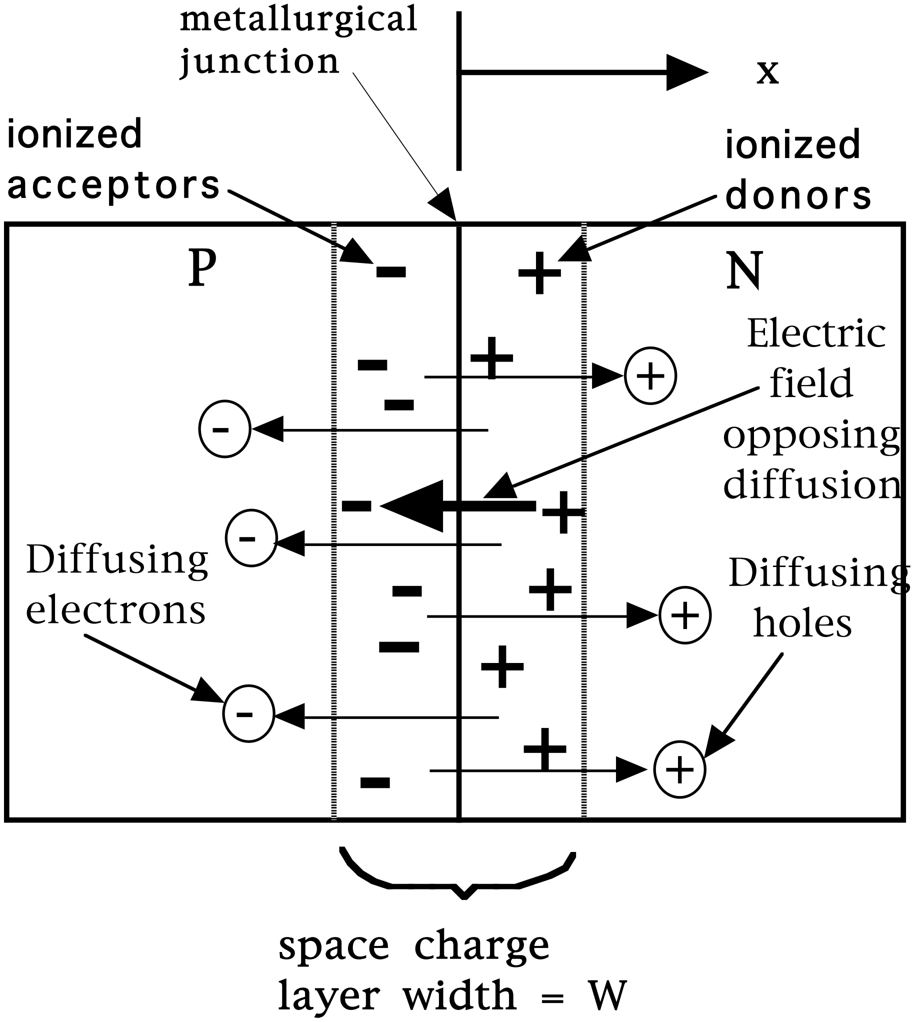
Step (abrupt) junction



Linearly graded junction

Formation of Space Charge Layer

- Diffusing electrons and holes leave the region near metallurgical junction depleted of free carriers (depletion region).
- Exposed ionized impurities form space charge layer.
- Electric field due to space charge opposes diffusion.



Quantitative Description of Space Charge Region

- Assume step junction.

$$\frac{d^2\square}{dx^2} = -\frac{\square}{\square}$$

$$\square = -qN_a \;;\; x < 0$$

$$\square = qN_d \;;\; x > 0$$

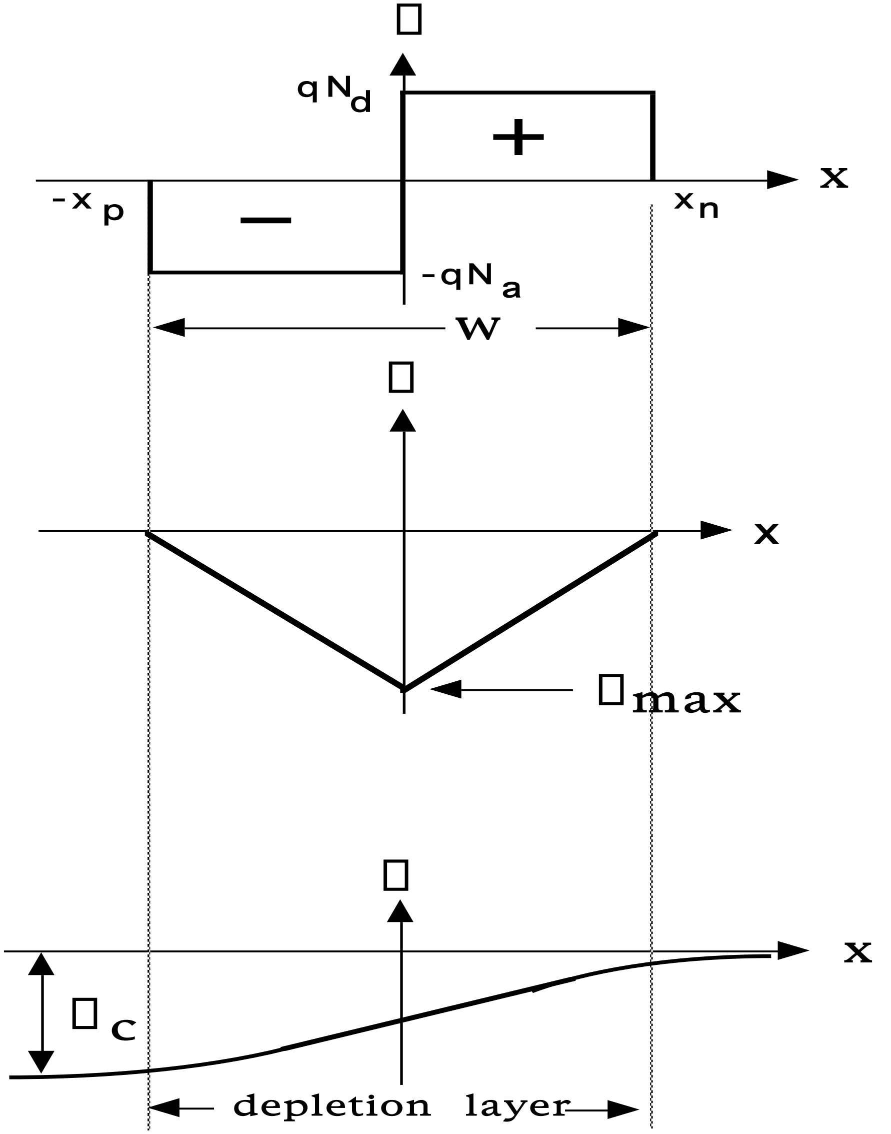
$$\frac{d\square}{dx} = -E(x)$$

$$E(x) = \frac{qN_a(x+x_p)}{\square} ;\; -x_p < x < 0$$

$$E(x) = \frac{qN_d(x-x_n)}{\square} ;\; 0 < x < x_n$$

$$\square_c = - \square_{-x_p}^{x_n} E(x)dx$$

$$\square_c = -\frac{qN_a x_p{}^2 \square + \square qN_d x_n{}^2}{2\square}$$



Contact (Built-in, Junction) Potential

- In thermal equilibrium $J_n = q\,\mu_n\, n\,\frac{d\Phi}{dx} + q\,D_n\,\frac{dn}{dx} = 0$

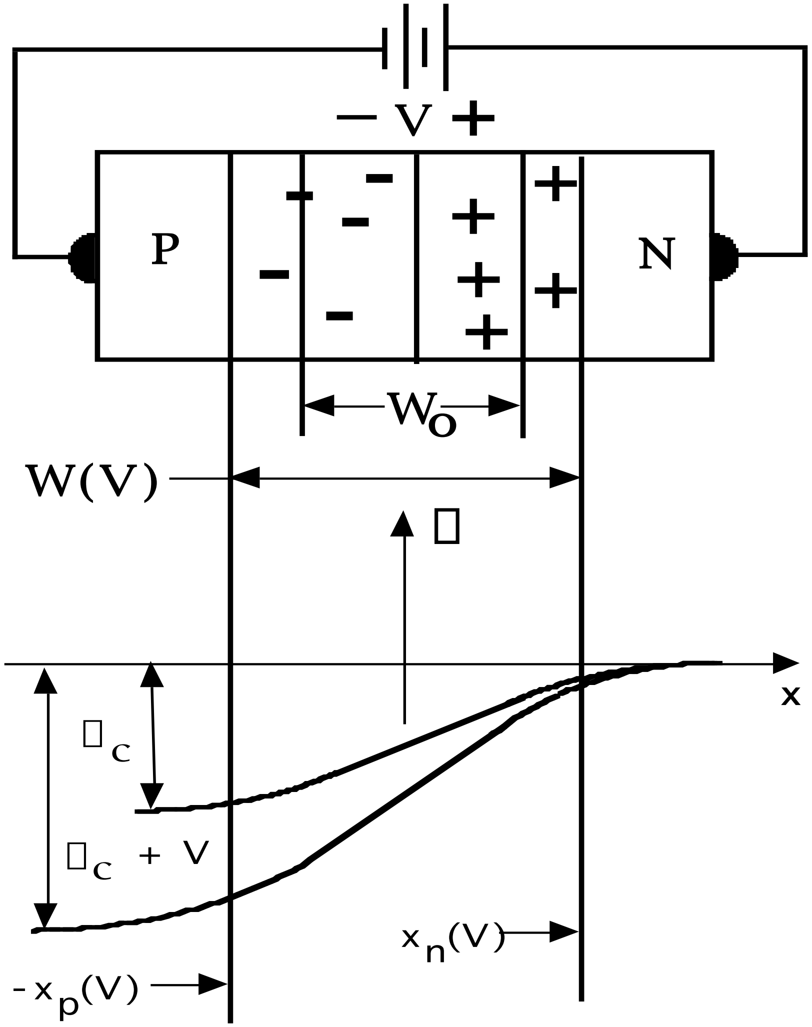
- Separate variables and integrate ; $\displaystyle\int_{\Phi(x_p)}^{\Phi(x_n)} d\Phi = -\frac{D_n}{\mu_n}\int_{n(x_p)}^{n(x_n)} \frac{dn}{n}$

- $\Phi(x_n) - \Phi(x_p) = \Phi_c = \frac{kT}{q}\,\ln\left(\frac{N_a N_d}{n_i^2}\right)$; Φ_c = contact potential

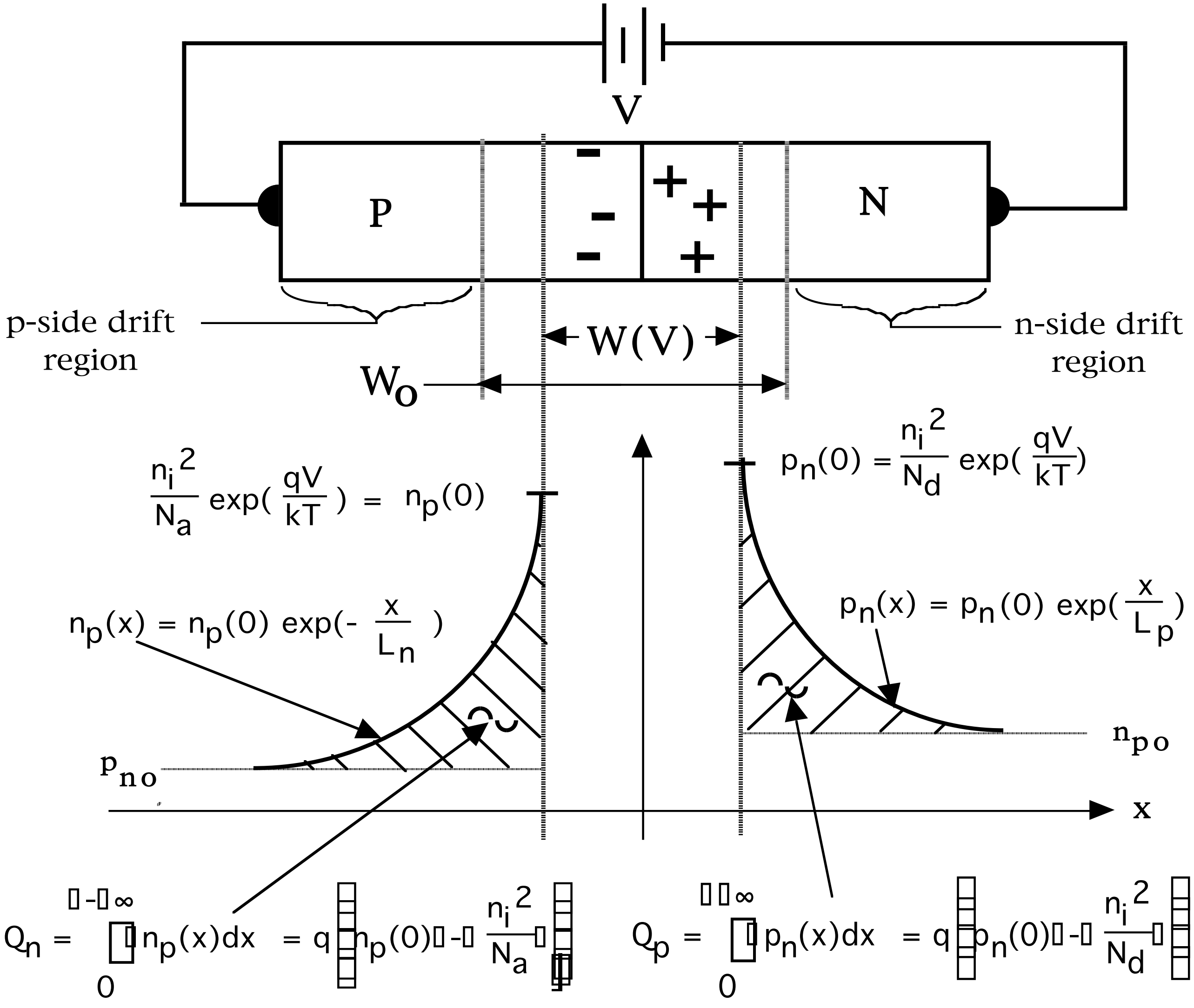
- Example
  - Room temperature kT/q = 0.025 eV
  - $N_a = N_d = 10^{16}\ \text{cm}^{-3}$; $n_i^2 = 10^{20}\ \text{cm}^{-6}$
  - $F_c = 0.72$ eV

Reverse-Biased Step Junction

- Starting equations
  - $W(V) = x_n(V) + x_p(V)$
  - $V + \square_c = -\dfrac{qN_a x_p^2 \square + \square qN_d x_n^2}{2\square}$
  - Charge neutrality $qN_a x_p = qN_d x_n$
- Solve equations simultaneously
  - $W(V) = W_o\sqrt{1+V/\square_c}$
  - $W_o = \sqrt{\dfrac{2\square\square_c(N_a+N_d)}{qN_aN_d}}$
  - $E_{max} = \dfrac{2\square_c}{W_o}\sqrt{1\square+\square V/\square_c}$



Forward-Biased PN Junction



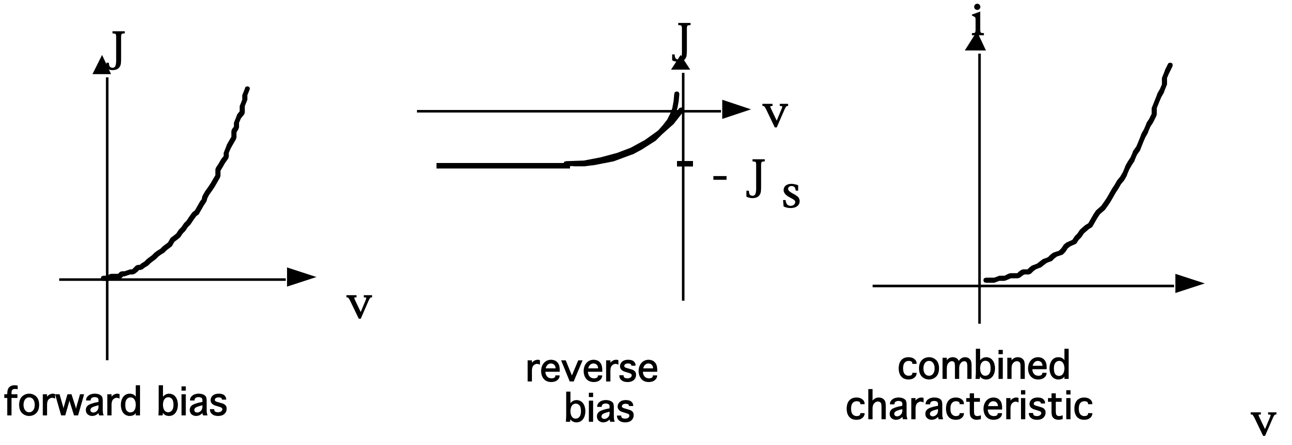
- Forward bias favors diffusion over drift.
- Excess minority carrier injection into both p and n drift regions.
- Minority carrier diffusion lengths.
  - $L_n = [D_n \tau_n]^{0.5}$
  - $L_p = [D_p \tau_p]^{0.5}$

Ideal PN Junction I-V Characteristics

- Excess carriers in drift regions recombined and thus more must be constantly injected if the distributions np(x) and pn(x) are to be maintained.
- Constant injection of electrons and holes results in a current density J given by

$$J = \frac{Q_n}{\tau_n} + \frac{Q_p}{\tau_p} = q\, n_i^2 \left[\frac{L_n}{N_a \tau_n} + \frac{L_p}{N_d \tau_p} \right] \left[\exp\left(\frac{qV}{kT}\right) - 1 \right]$$

$$J = J_s \left[\exp\left(\frac{qV}{kT}\right) - 1 \right] \; ; \; J_s = q\, n_i^2 \left[\frac{L_n}{N_a \tau_n} + \frac{L_p}{N_d \tau_p} \right]$$

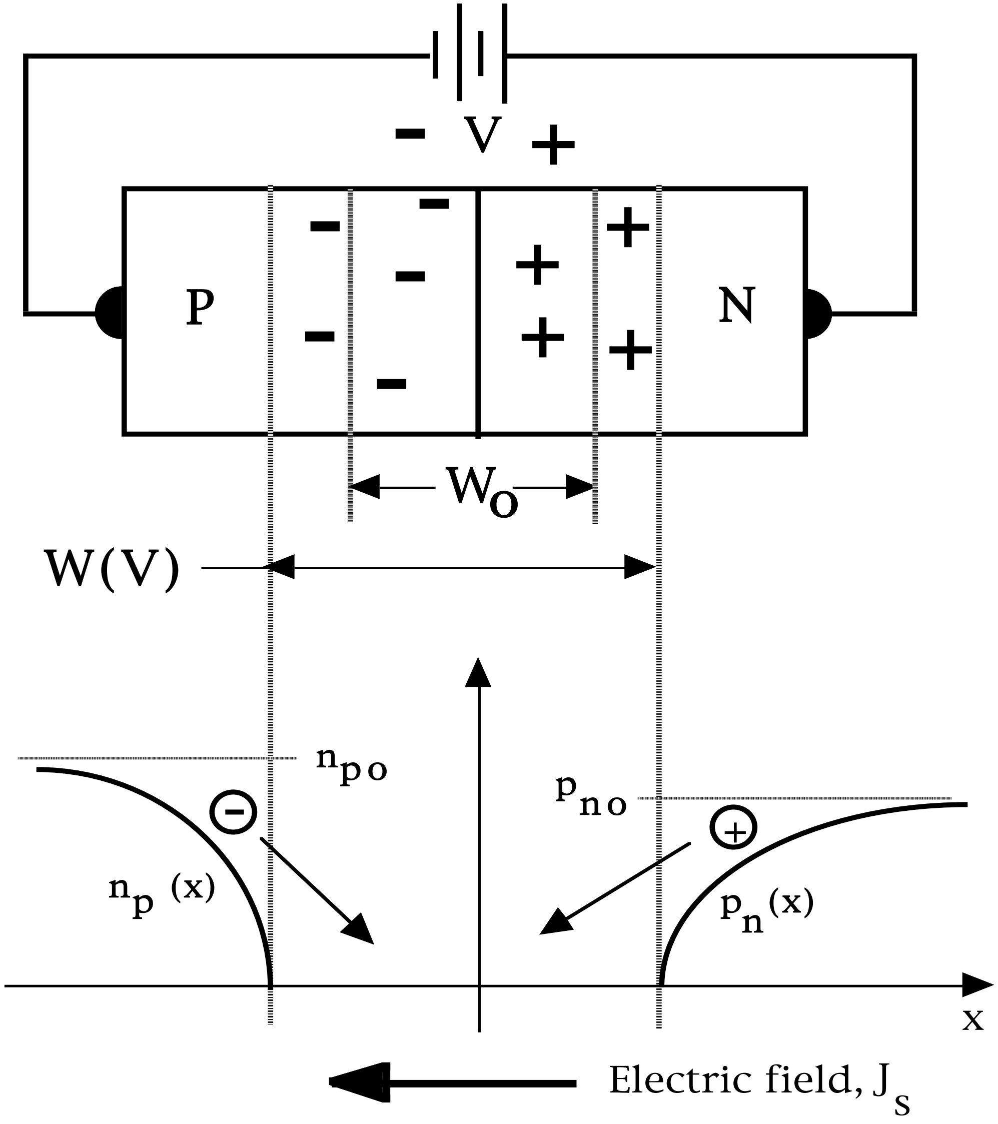


forward bias

reverse bias

combined characteristic

Reverse Saturation Current



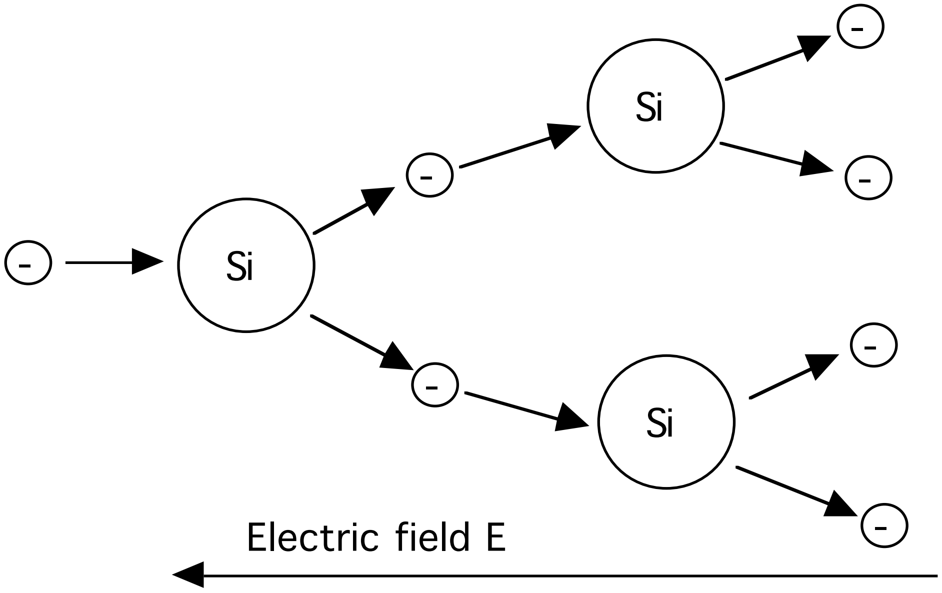
- Carrier density gradient immediately adjacent to depletion region causes reverse saturation current to flow via diffusion.

- J_s independent of reverse voltage V because carrier density gradient unaffected by applied voltage.

- J_s extremely temperature sensitivity because of dependence on n_i^2(T.)

Impact Ionization

- $E \geq E_{BD}$; free electron can acquire sufficient from the field between lattice collisions ($t_c \approx 10^{-12}$ sec) to break covalent bond.
- Energy = $0.5mv^2 = q\,E_g$; $v = q\,E_{BD}t_c$



- Solving for E_{BD} gives

$$E_{BD} = \sqrt{\frac{2 \cdot E_g \cdot m}{q \cdot t_c^2}}$$

- Numerical evaluation
  - m = 10^{-27} grams, E_g = 1.1 eV, $t_c = 10^{-12}$ sec.
  - $E_{BD} = \sqrt{\frac{(2)\cdot(1.1)\cdot(10^{27})}{(1.6\text{x}10^{-19})\cdot(10^{-24})}} = 3\text{x}10^5$ V/cm
    - Experimental estimates are 2-3.5x10^5 V/cm