Lecture 5
PN Junction

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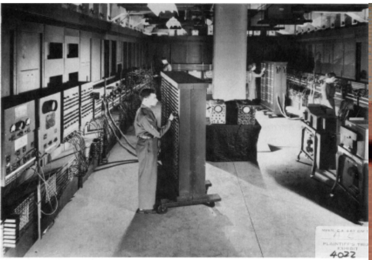
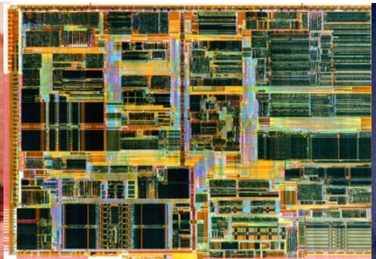
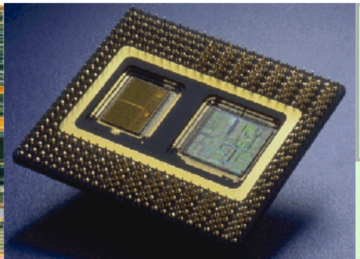
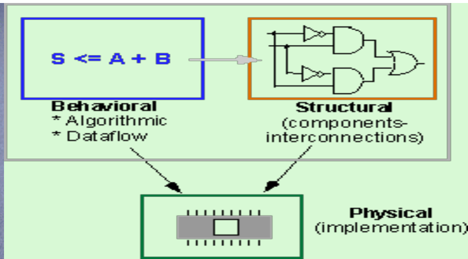
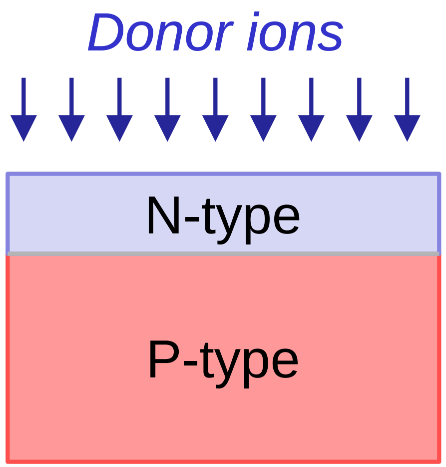


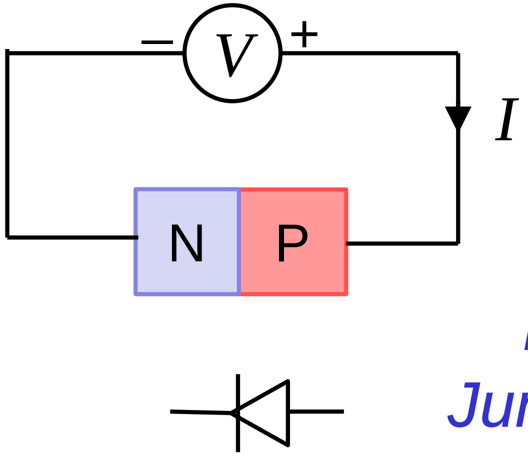




Nature of PN Junction

- We have considered properties of N and P-type semiconductors in isolation
- What happens when we have a transition in a single crystal from one type to the other ?

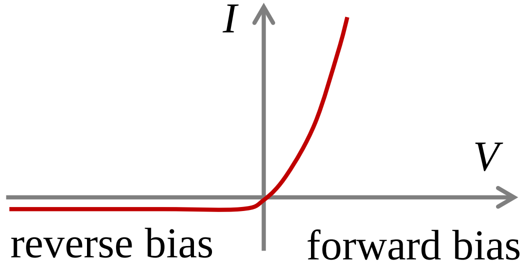
Fabrication





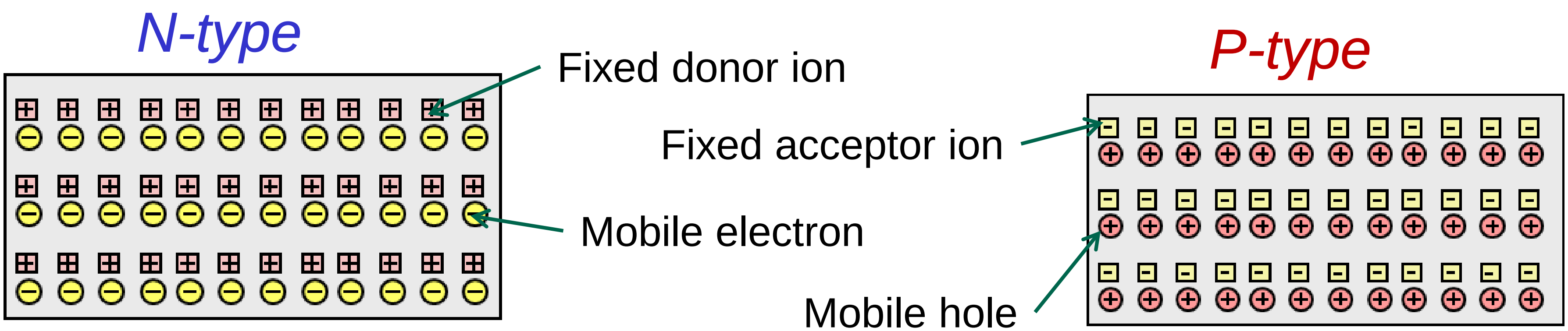
PN Junction Diode

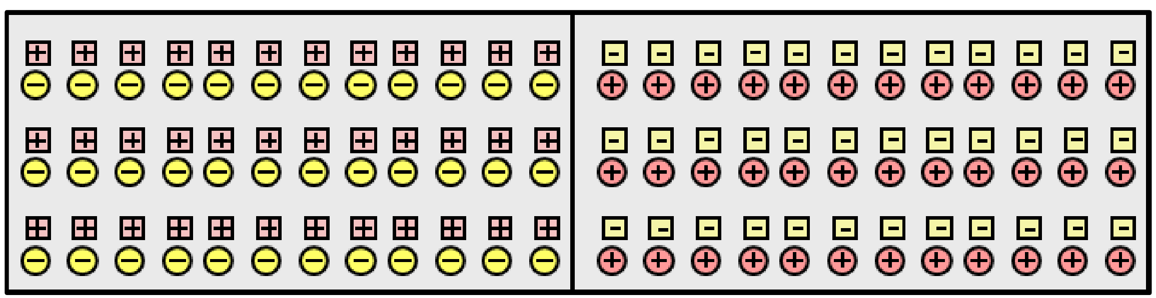
- PN junction present in perhaps every semiconductor device

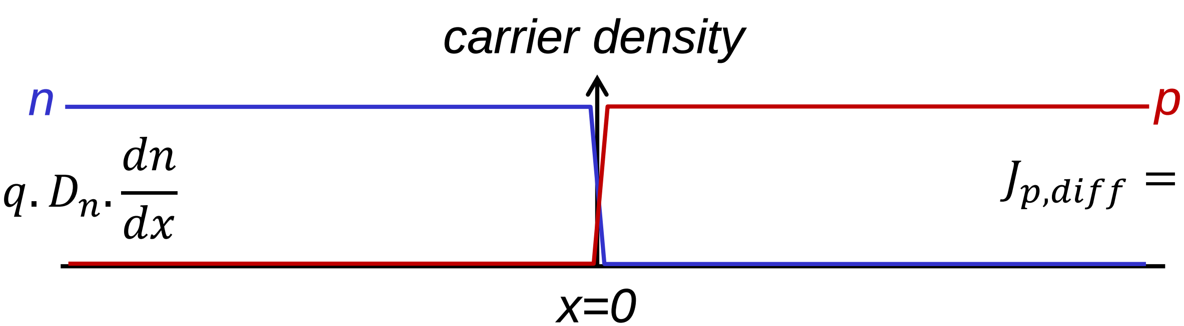


Abrupt PN Junction

- Suppose we bring N & P crystals together:





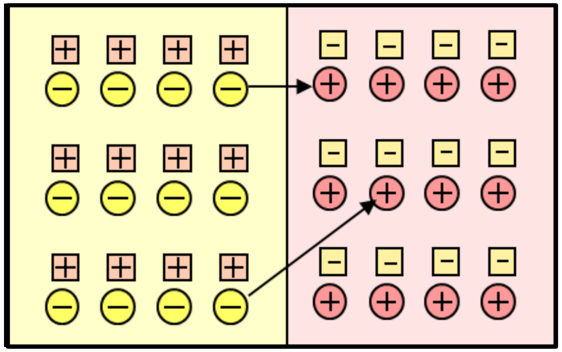


$$J_{n,diff} = q.D_n.\frac{dn}{dx}$$

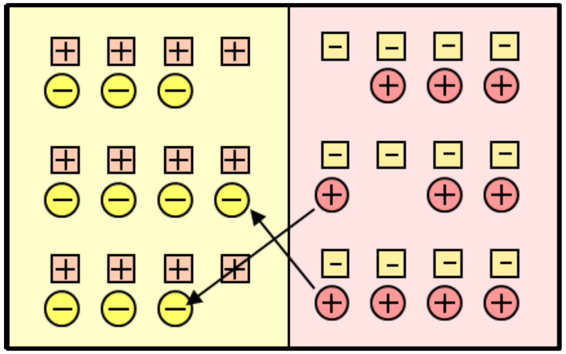
$$J_{p,diff} = -q.D_p.\frac{dp}{dx}$$

Carrier Diffusion

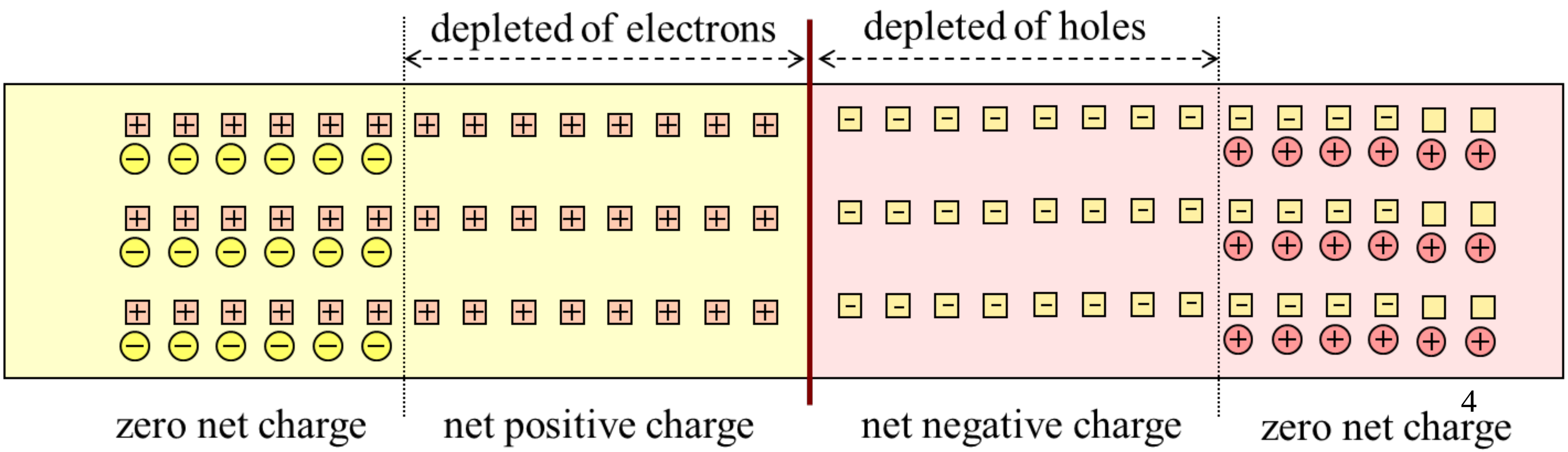
Electrons diffuse to right and recombine with holes



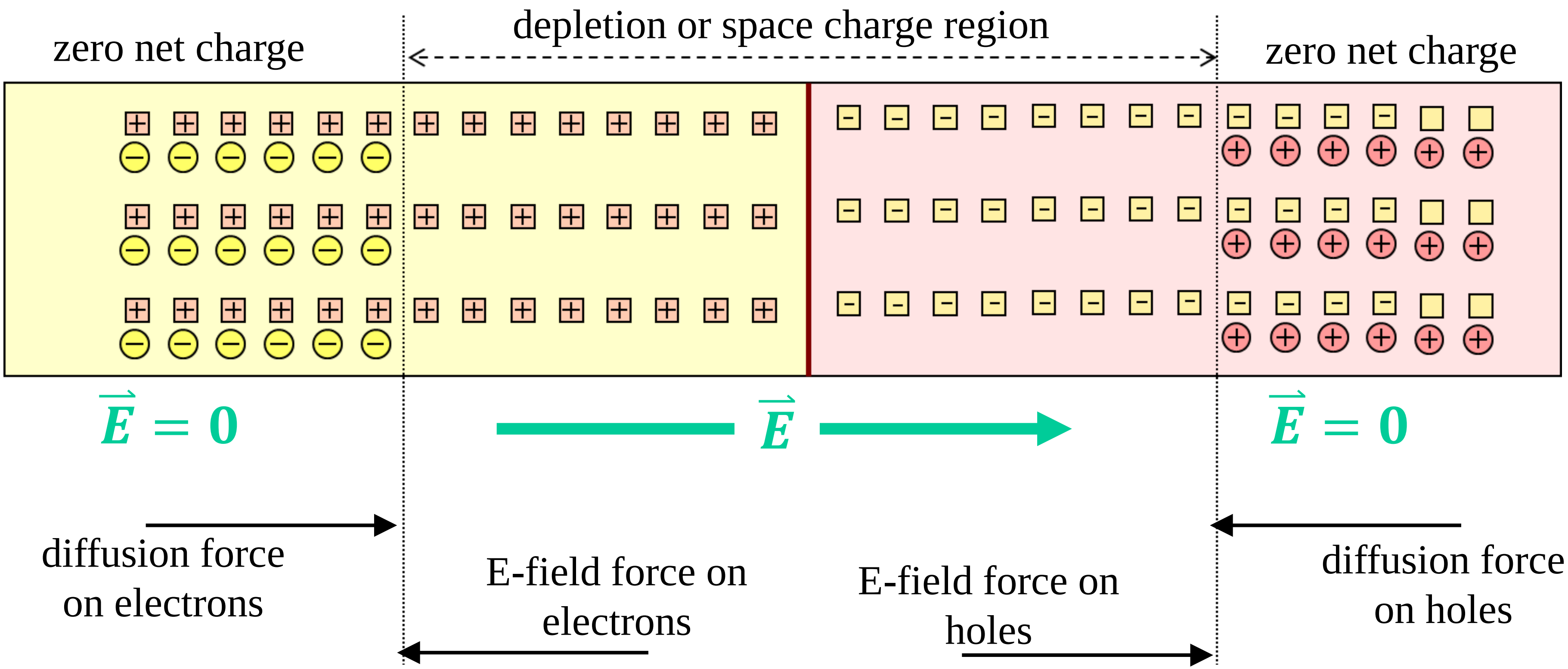
Holes diffuse to left and recombine with electrons



Leaving charged region of ionized donors:



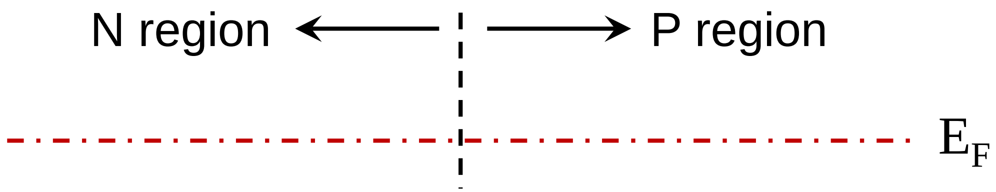
Electric Field in Depletion Region



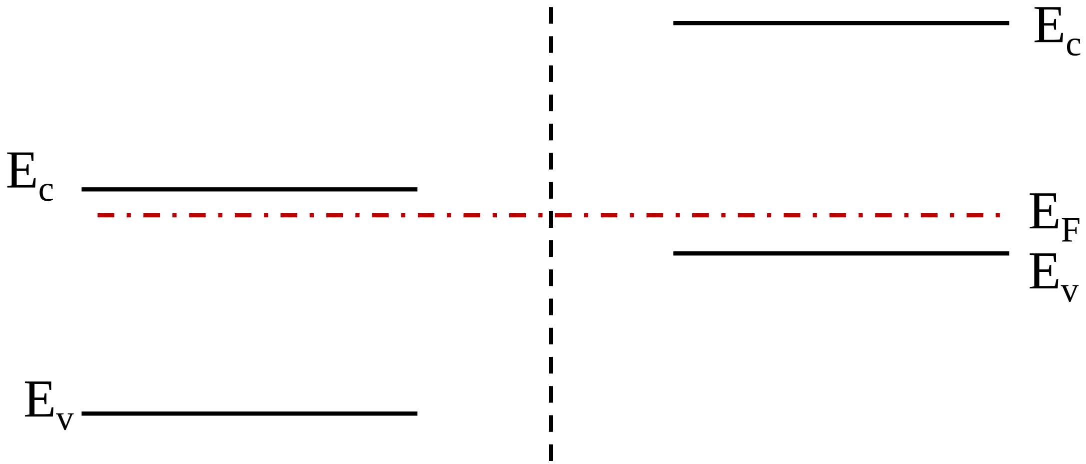
- Net positive and negative charges induce electric field
- Electric field pulls carriers in opposite direction to diffusion
- In thermal equilibrium, carriers diffuse until electric field exactly balances diffusion force

Energy Band Diagram – Zero Bias

- Under zero external bias, junction is in thermal equilibrium
  - one Fermi level throughout device

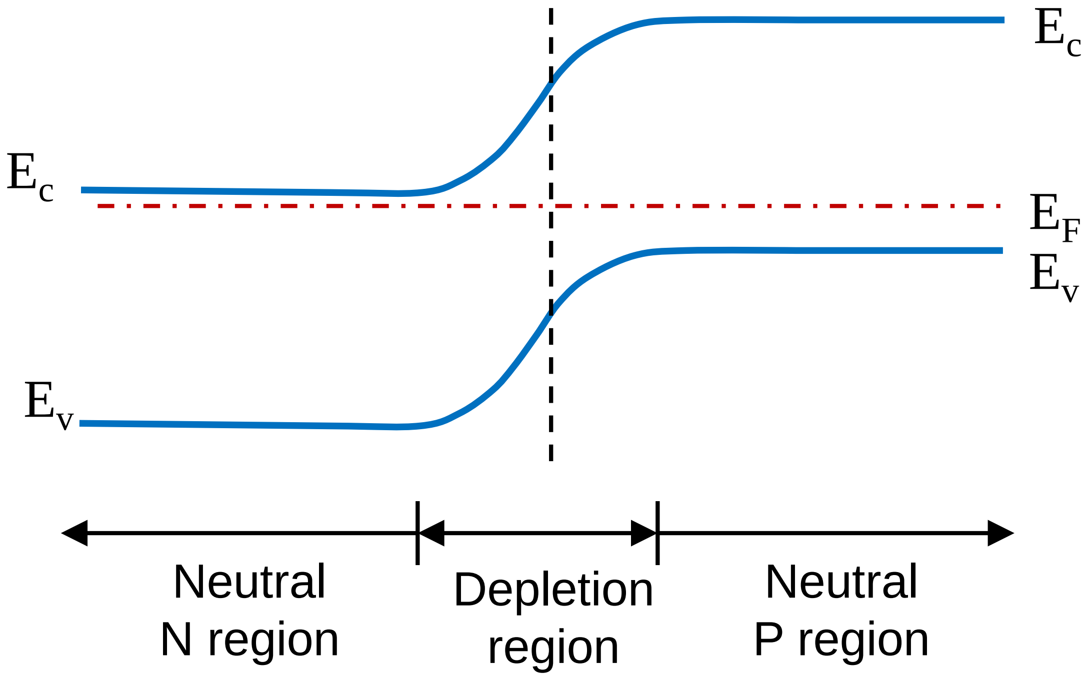


- Far from the junction, we have N-type (with E_c close to E_F) and P-type (with E_V close to E_F)



Energy Band Diagram – Depletion Region

- Within depletion region, assume (for now) that conduction & valence energies joined by a smooth curve

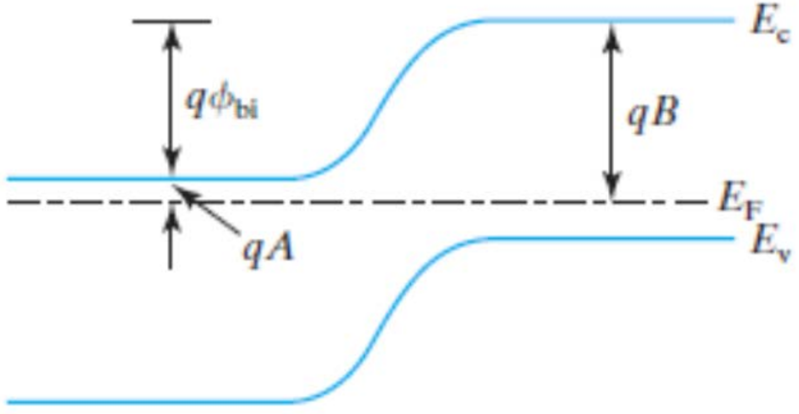


- In depletion region, E_F is far from both E_c and E_v

$$n \approx 0 \text{ and } p \approx 0 \text{ in depletion layer}$$

Built-In Potential

- E_c and E_v are not flat – indicates a potential difference
- This voltage differential ϕ_{bi} is called built-in potential
  - exists at interface of any two dissimilar metals



- In N-region:

$$n = N_d = N_c . e^{-qA/kT}$$

$$A = \frac{kT}{q} . ln\left(\frac{N_c}{N_d}\right)$$

- In P-region:

$$n = \frac{{n_i}^2}{N_a} = N_c . e^{-qB/kT}$$

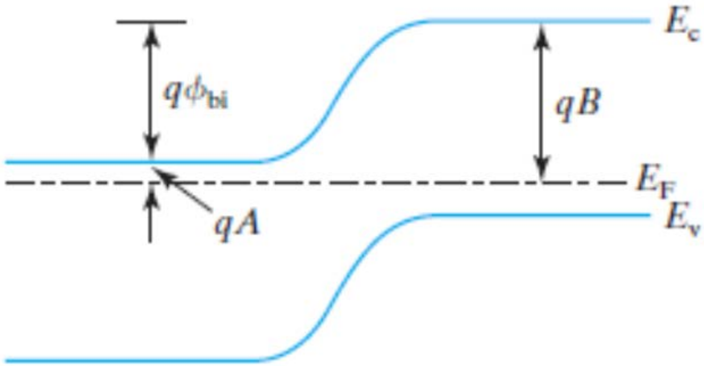
$$B = \frac{kT}{q} . ln\left(\frac{N_c . N_a}{{n_i}^2}\right)$$

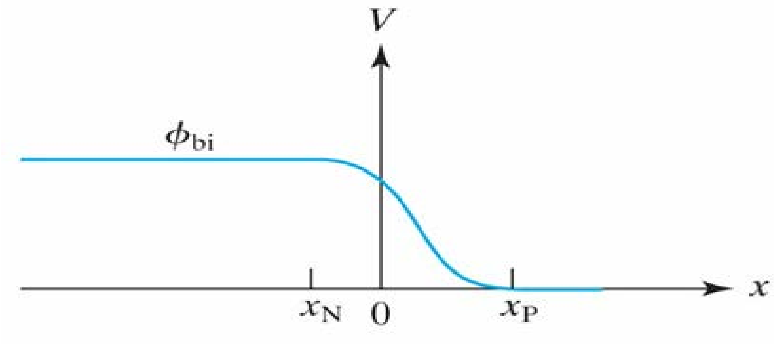
Calculating Built-In Potential

$$\varnothing_{bi} = B - A$$

$$= \frac{kT}{q} . \left[ln\left(\frac{N_c . N_a}{{n_i}^2}\right) - \ln\left(\frac{N_c}{N_d}\right)\right]$$

$$\varnothing_{bi} = \frac{kT}{q} . ln\left(\frac{N_d . N_a}{{n_i}^2}\right)$$

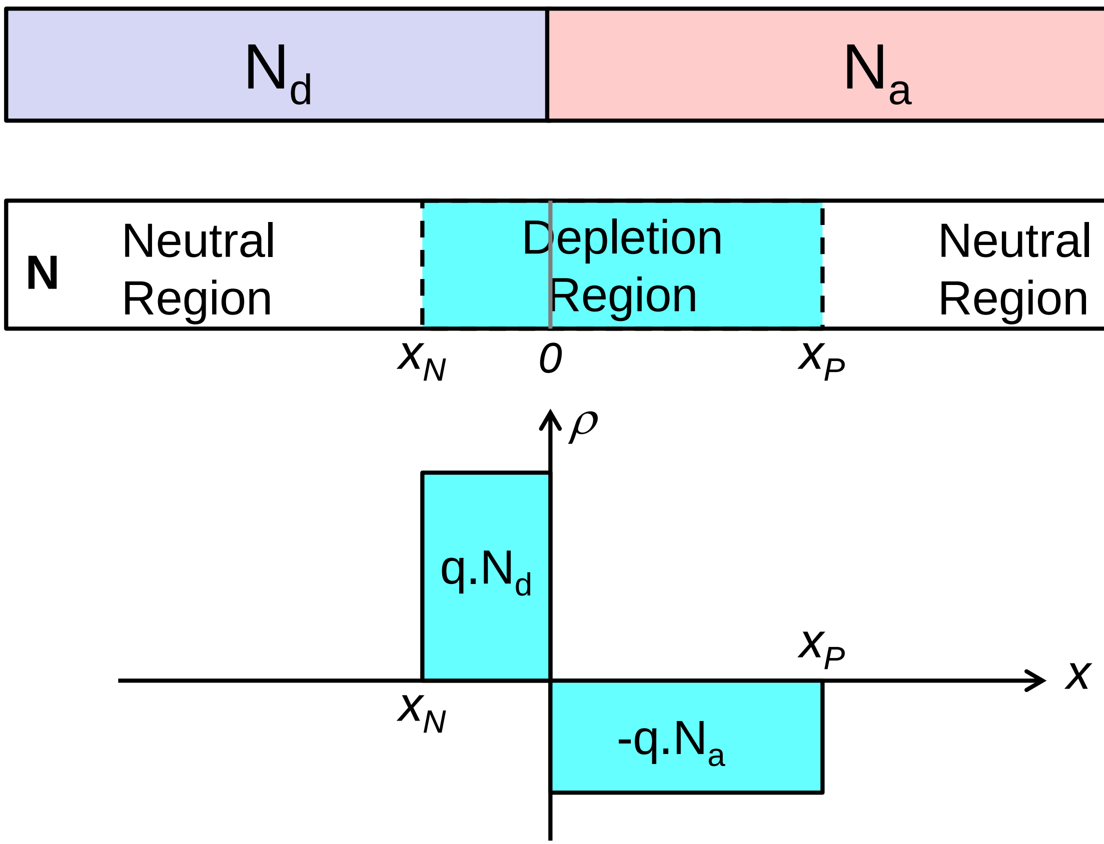




- Typically $\varnothing_{bi} \approx 0.7V - 0.9V$ in silicon
- Can we measure this with a voltmeter ?
- Why does this not generate drift current?

Depletion Layer Model

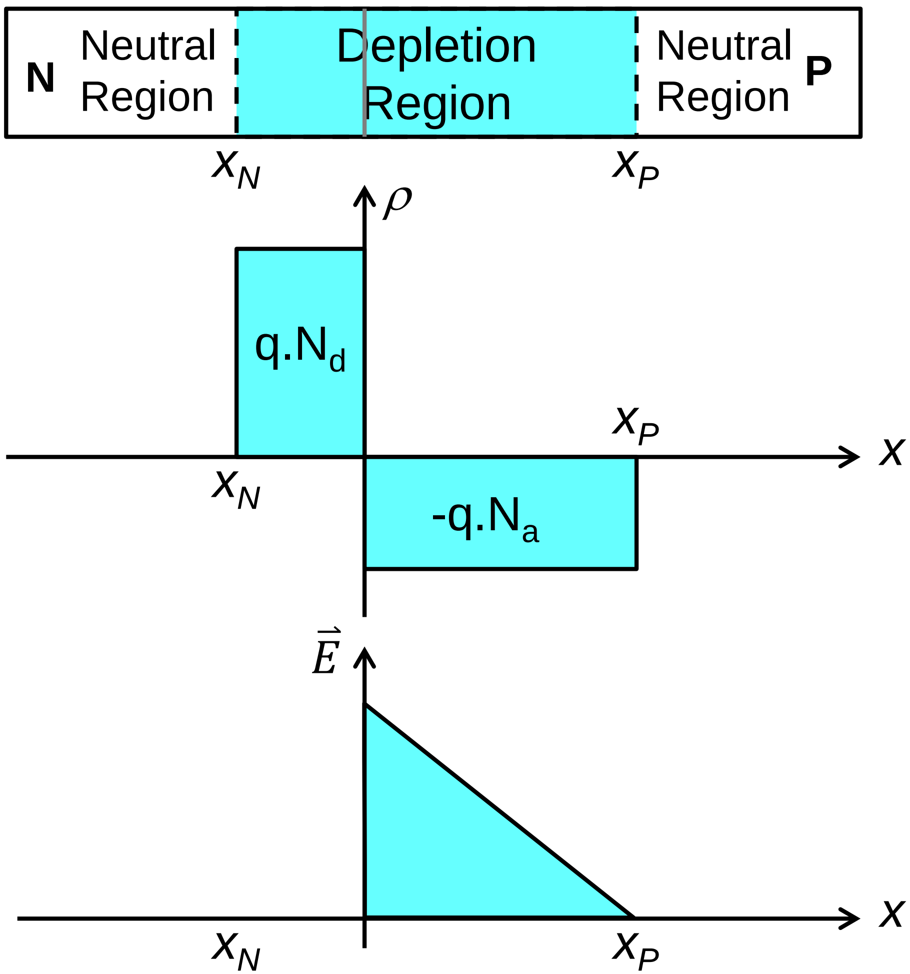
- Divide step PN junction into three regions
- Assume that $p = n = 0$ in depletion region
  - charge density ρ equals dopant ion density in depletion region
  - charge density $\rho = 0$ in neutral regions



Poisson's Equation

- Poisson's Equation:

$$\frac{d^2V}{dx} = -\frac{d\vec{E}}{dx} = -\frac{\rho}{\varepsilon_s}$$



- On P side of depletion region:

$$\rho = -q.N_a \quad \Rightarrow \quad \frac{d\vec{E}}{dx} = -\frac{q.N_a}{\varepsilon_s}$$

$$\vec{E}(x) = -\frac{q.N_a}{\varepsilon_s}.x + const.$$

- Setting $\vec{E}(x_P) = 0$, gives

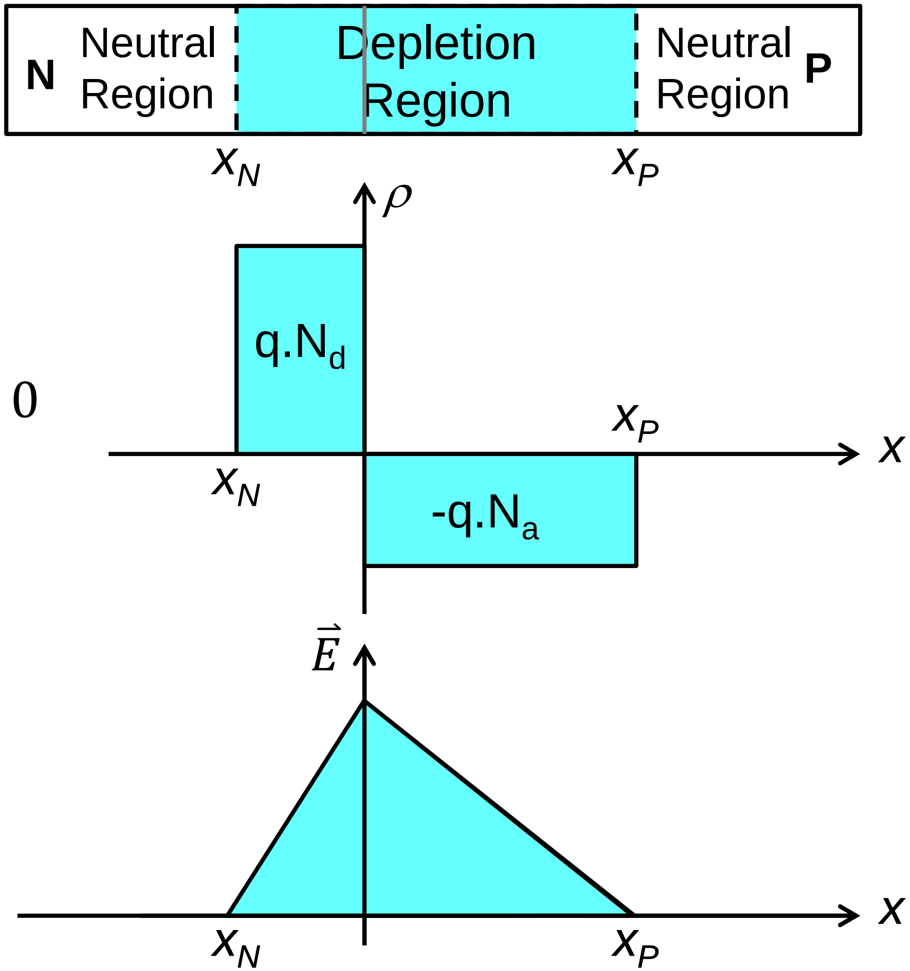
$$\vec{E}(x) = \frac{q.N_a}{\varepsilon_s}.(x_P - x) \qquad 0 \le x \le x_P$$

Electric Field

- Similarly, on N side of depletion region:

$$\rho = q.N_d \quad \Rightarrow \quad \frac{d\vec{E}}{dx} = \frac{q.N_d}{\varepsilon_s}$$

$$\vec{E}(x) = \frac{q.N_d}{\varepsilon_s}.(x - x_N) \qquad x_N \leq x \leq 0$$



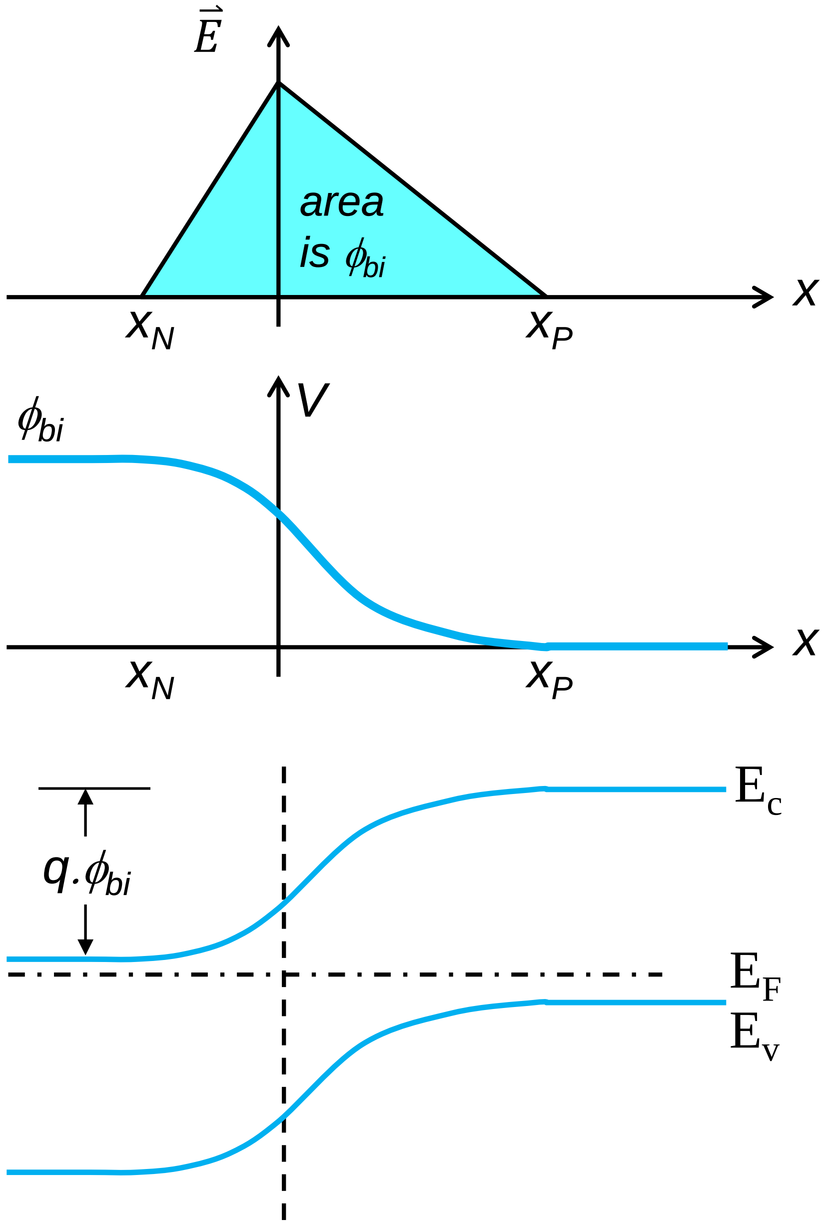
- Equating P side and N side fields at x=0:

$$N_a.|x_P| = N_d.|x_N|$$

- Depletion region extends further into more lightly doped side

- A highly asymmetrical junction (N^+P or P^+N) is called one-sided junction

Potential in the Depletion Region



- On P-side: using $\vec{E} = -dV/dx$ and integrating expressions for electric field and arbitrarily setting $V(x_P) = 0$

$$V(x) = \frac{q.N_a}{2\varepsilon_s}(x_P - x)^2 \qquad 0 \le x \le x_P$$

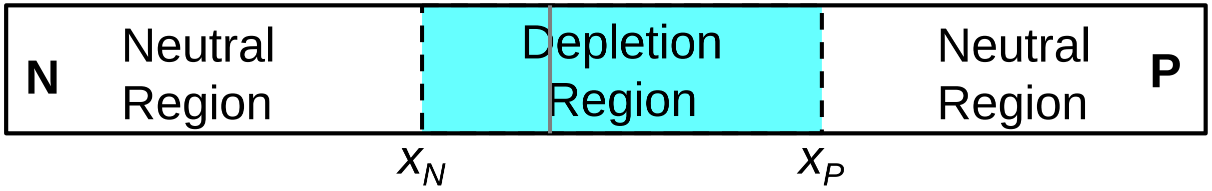
- Similarly, on N-side, and setting $V(x_N) = \emptyset_{bi}$

$$V(x) = \emptyset_{bi} - \frac{q.N_d}{2\varepsilon_s}(x - x_N)^2$$

$$for\ x_N \le x \le 0$$

- Can now quantitatively draw energy band diagram

Depletion Layer Width



- Equating N and P side potentials at x=0, gives:

$$x_P - x_N = W_{dep} = \sqrt{\frac{2\varepsilon_s.\phi_{bi}}{q}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)}$$

- If $N_a \gg N_d$, as in a P⁺N junction

$$W_{dep} \approx \sqrt{\frac{2\varepsilon_s.\phi_{bi}}{q.N_d}} \approx |x_N|$$

- Similarly, if $N_d \gg N_a$ as in N⁺P junction:

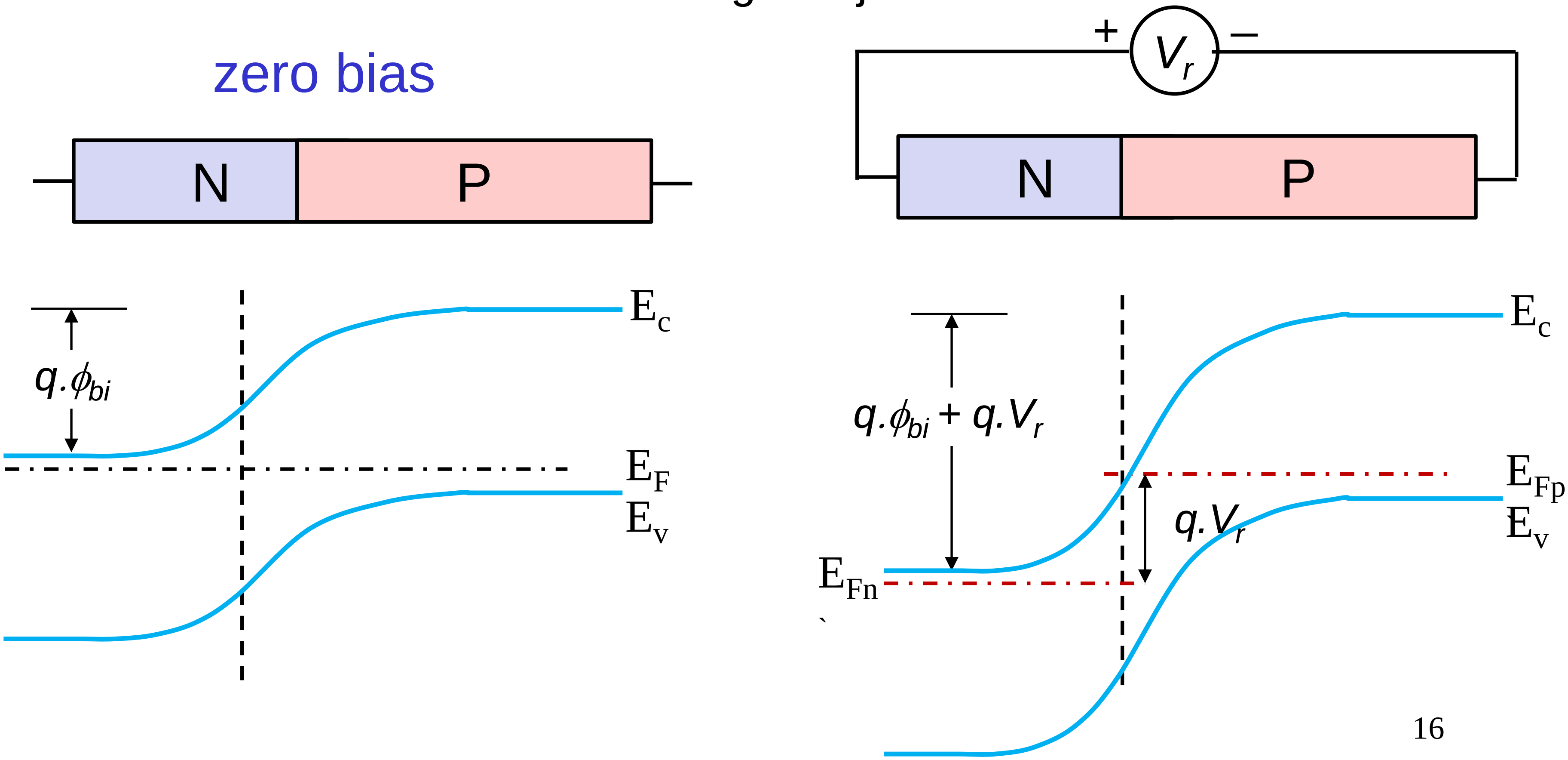
$$W_{dep} \approx \sqrt{\frac{2\varepsilon_s.\phi_{bi}}{q.N_a}} \approx |x_P|$$

Example: PN Junction

- A P^+N junction has $N_a = 10^{19} cm^{-3}$ and $N_d = 10^{16} cm^{-3}$. What is (a) the built-in potential, (b) W_{dep}, (c) x_N and (d) x_P ?

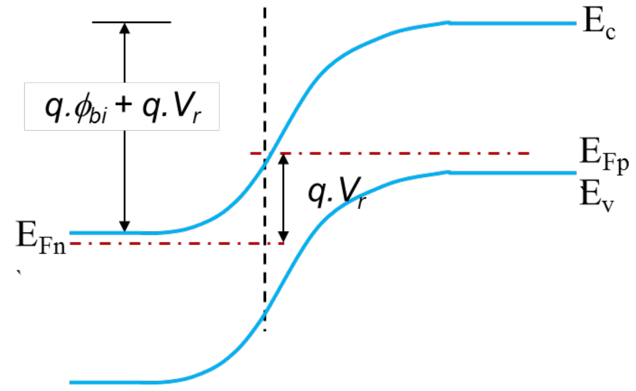
Reverse Biased PN Junction

- When a positive voltage is applied to N region relative to P region, the PN junction is said to be reverse biased
- No longer in thermal equilibrium
  - Fermi level not constant throughout junction



Reverse Biased Depletion Width

- Potential barrier to flow of majority carriers has increased from $\emptyset_{bi}$ to $(\emptyset_{bi}+V_r)$

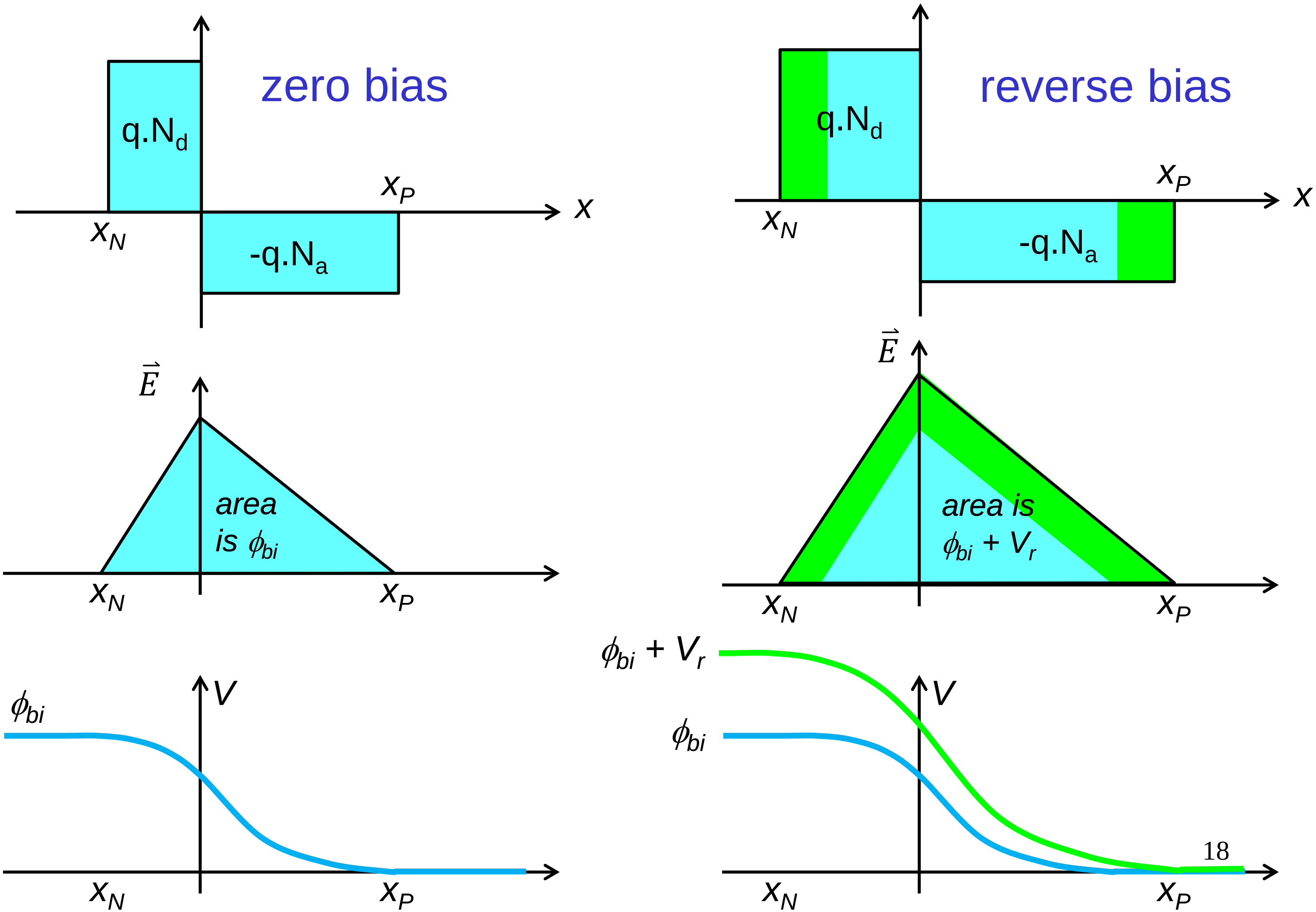


- Reverse biased current is very small
  - Due to minority carriers in N an P sections
  - *Since current is small:*
- IR drop in neutral regions is negligible
  - All reverse bias appears across depletion region
- Analysis using Poisson's equation (at thermal equilibrium) is still valid if the $\emptyset_{bi}$ term is replaced with $(\emptyset_{bi}+V_r)$

$$W_{dep} = \sqrt{\frac{2\varepsilon_s(\emptyset_{bi} + V_r)}{q.N}} = \sqrt{\frac{2\varepsilon_s \times potential\ barrier}{q.N}}$$

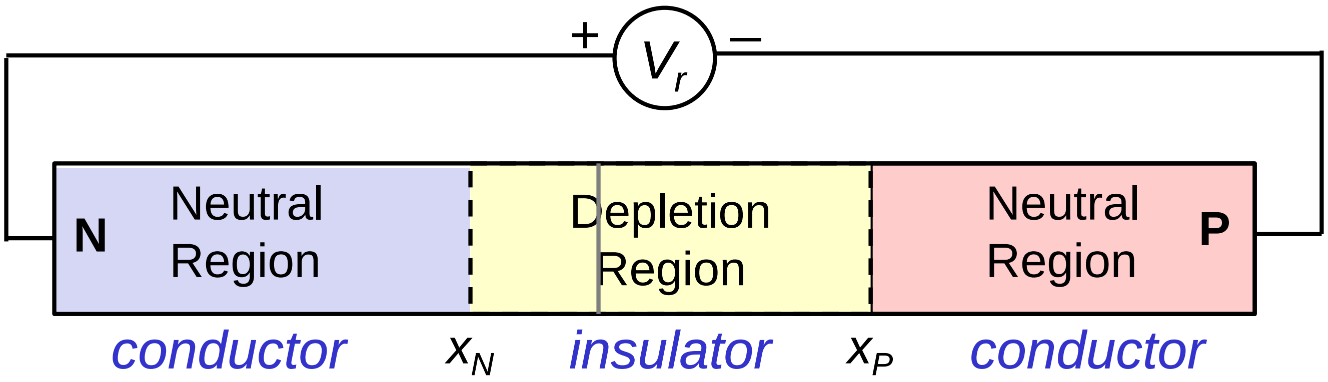
$$where\ \frac{1}{N} = \frac{1}{N_d} + \frac{1}{N_a} \approx \frac{1}{lighter\ dopant\ density}$$

Reverse Biased Field & Potential

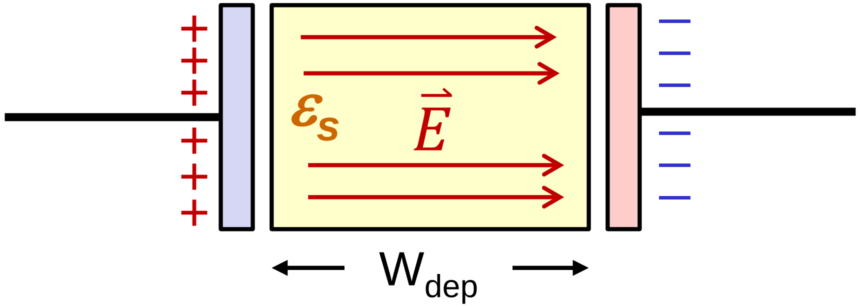


Capacitance Model

- Two neutral regions separated by depletion region can be viewed as two conductors separated by an insulator



- PN Junction can be modeled as parallel plate capacitor



$$C_{dep} = \frac{\varepsilon_s . A}{W_{dep}}$$

Capacitance Values

$$C_{dep} = \frac{\varepsilon_s . A}{W_{dep}}$$

- Substituting for W_{dep} gives:

$$C_{dep} = A.\sqrt{\frac{q.N.\varepsilon_s}{2(\emptyset_{bi} + V_r)}}$$

remember:

$$\frac{1}{N} = \frac{1}{N_A} + \frac{1}{N_D}$$

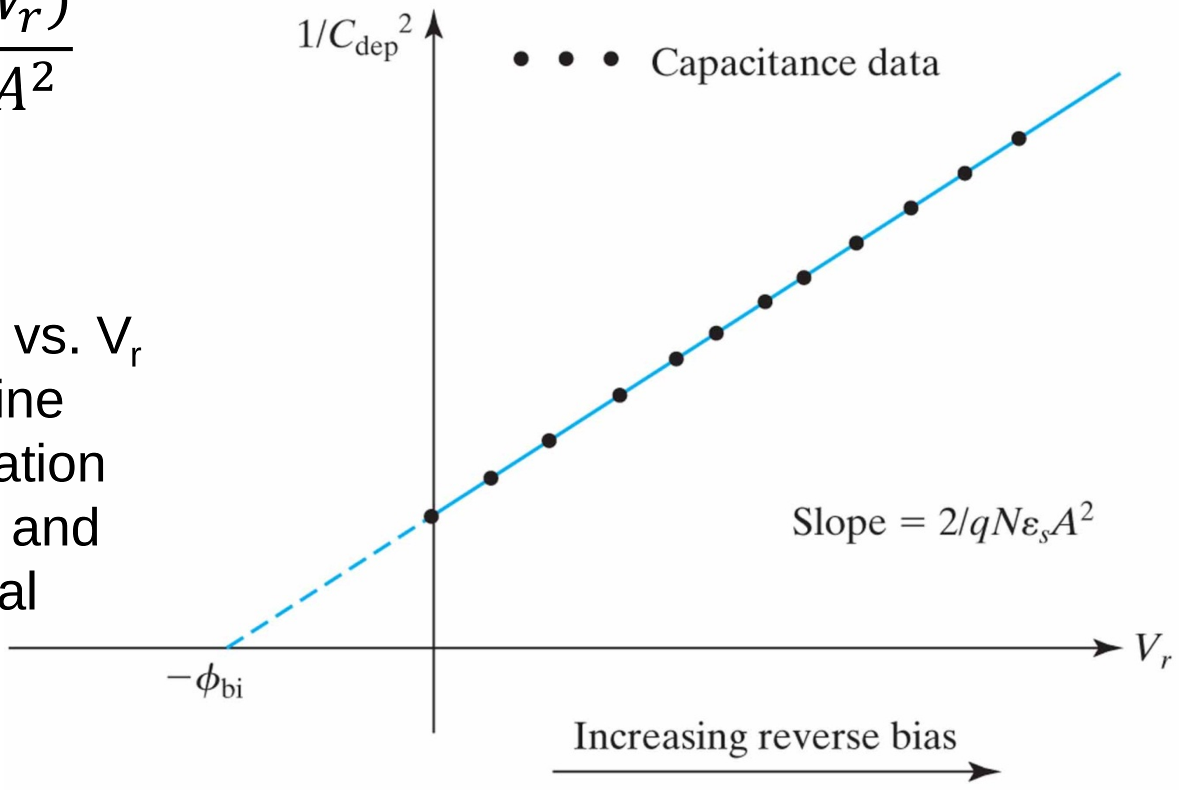
- C_{dep} increases with doping concentration in more lightly doped side
- C_{dep} decreases as applied reverse bias increases
- C_{dep} is important as PN junctions are present in most semiconductor devices

Capacitance-Voltage Characteristic

- rewriting capacitance expression:

$$\frac{1}{{C_{dep}}^2} = \frac{2(\phi_{bi} + V_r)}{q.N.\varepsilon_s.A^2}$$

- Measured capacitance vs. V_r can be used to determine lighter doped concentration in a one-sided junction and also the built-in potential

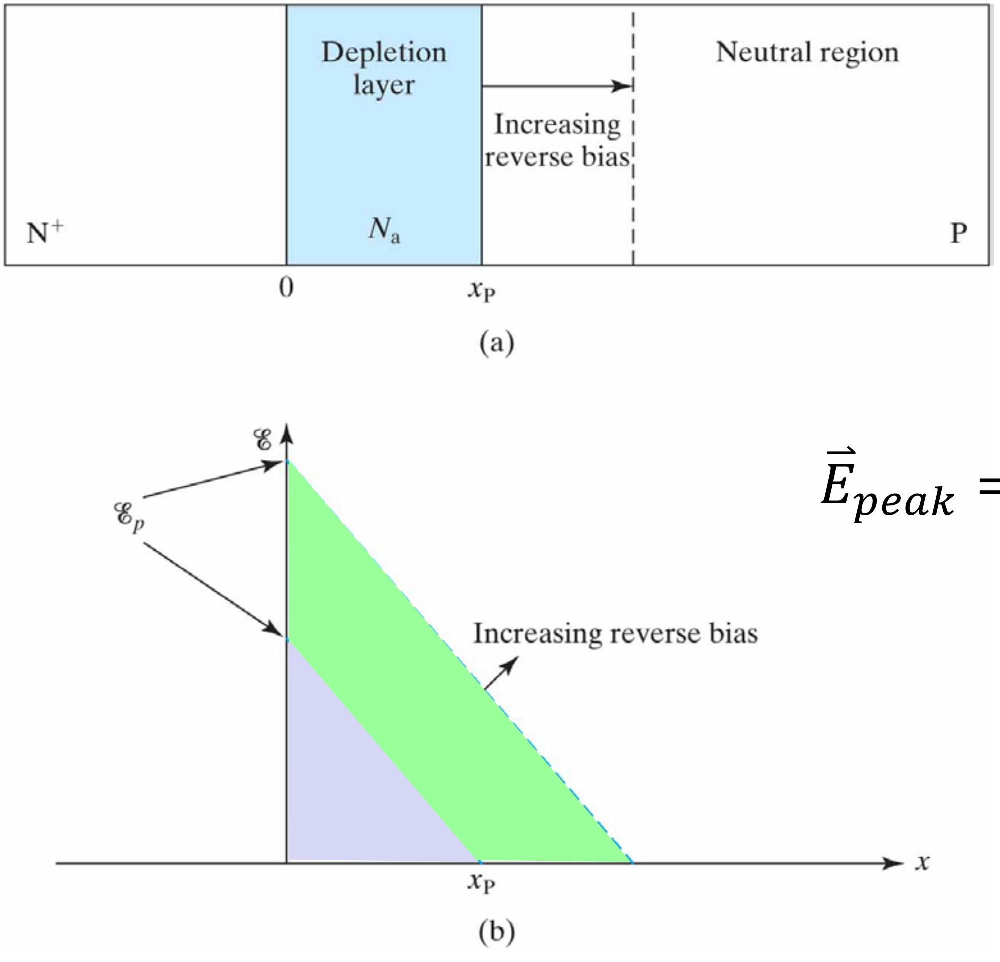


Example: C-V data

- The measured slope of the $1/C^2\ vs. V_r$ plot for a PN diode is $2 \times 10^{31}\ F^{-2}V^{-1}$ and the intercept is at $-0.84\ V$. The area of the PN junction is $1\ \mu m^2$. Find the lighter doping concentration N_l and the heavier doping concentration N_h . (*Accuracy?)*

Peak Electric Field

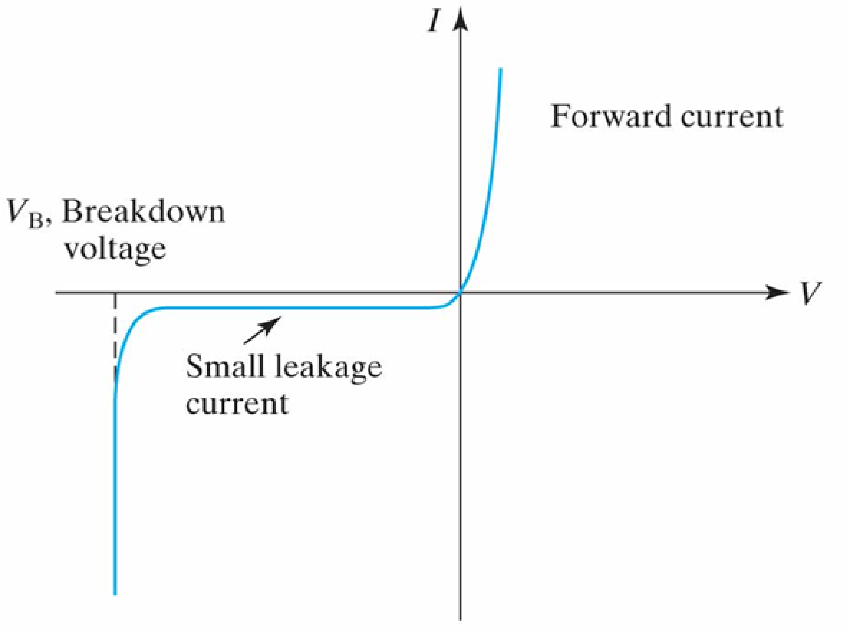
- Under moderate bias reverse current negligibly small
- As reverse bias is increased, peak electric field increases:



$$\vec{E}_{peak} = \vec{E}(0) = \left[\frac{2q.N}{\varepsilon_s}(\emptyset_{bi} + V_r)\right]^{1/2}$$

Junction Breakdown

- When electric field reaches critical value $\vec{E}_{crit}$ junction will break down and conduct large current

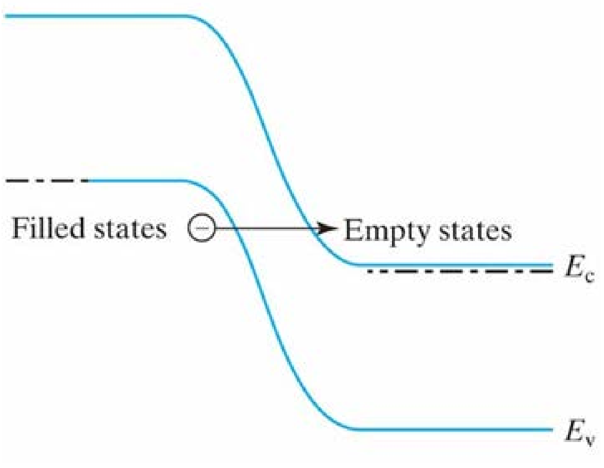


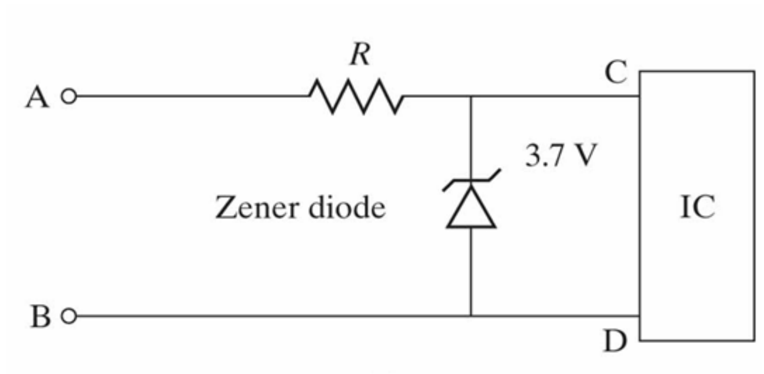
$$V_B = \frac{\varepsilon_s . \vec{E}_{crit}^{\;2}}{2q.N} - \emptyset_{bi}$$

- Two types of breakdown:
  - Tunneling (or Zener) breakdown in heavily doped junctions
  - Avalanche breakdown in moderately doped junctions

Tunneling (Zener) Breakdown

- When heavily doped junction is reverse biased, only a small distance separates electrons in P-side valence band from empty states in N-side conduction band:

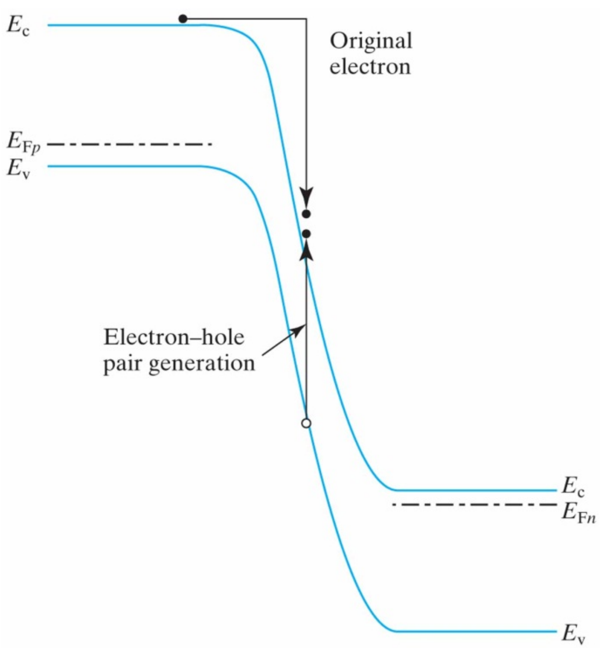




- Electrons can "tunnel" across junction
  - $\vec{E}_{crit} \approx 10^6\ volts/cm$
  - Breakdown is not destructive as long as current is controlled
  - Zener diodes operate in this mode with well controlled V_B

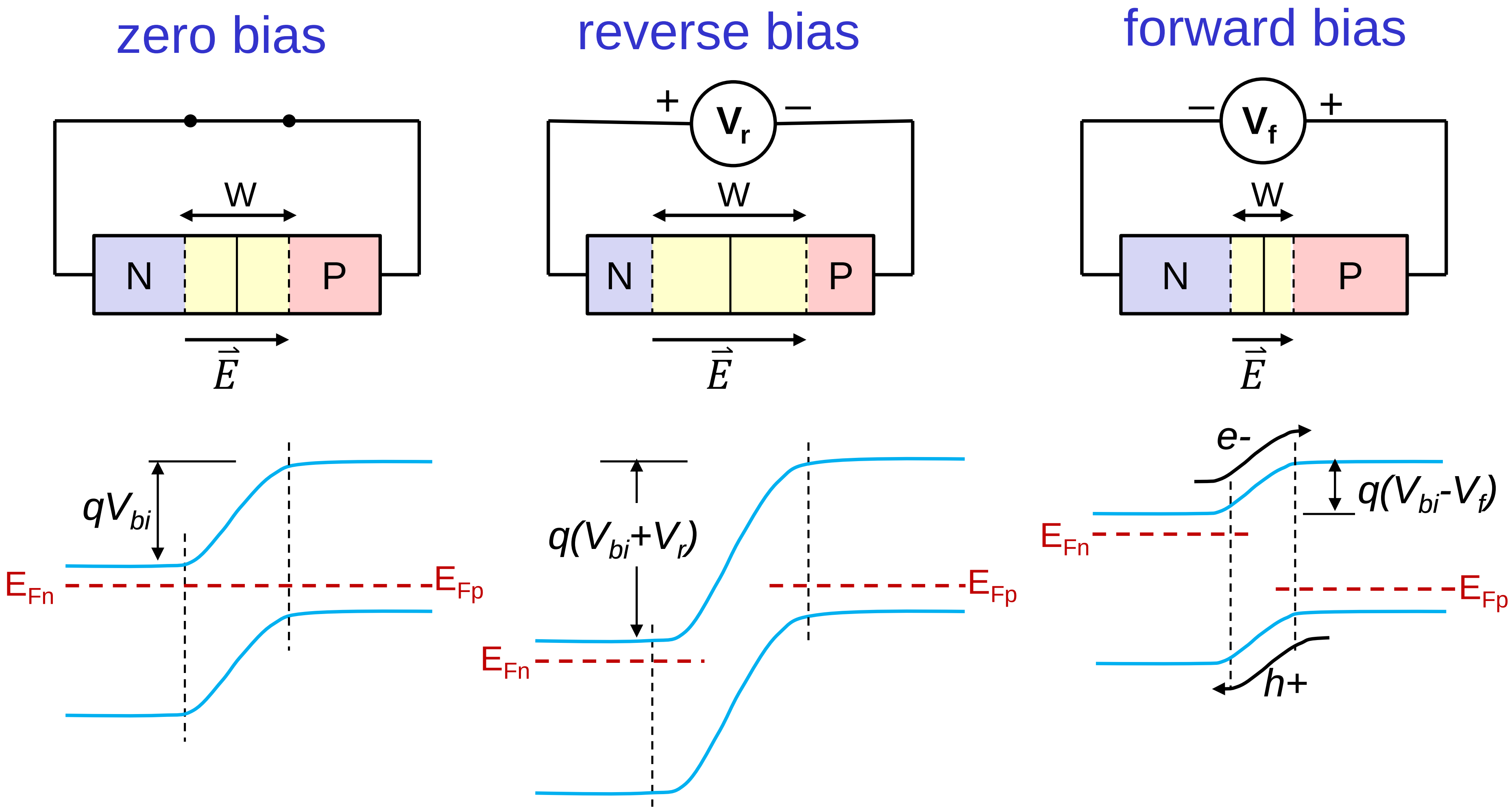
Avalanche Breakdown

- In moderately doped junctions, high electric fields cause minority carriers to accelerate across depletion region
- They may gain enough kinetic energy to raise an electron from the valence band to conduction band (impact ionization)
  - creates an extra electron-hole pair which will also be accelerated
- Extra carriers collide with lattice and create still more carriers
  - avalanche effect



- $\vec{E}_{crit} \approx 5 \times 10^5 \ V/cm$ at $N = 10^{17} cm^{-3}$
- $V_B \approx 15V$ at $N = 10^{17} cm^{-3}$

Forward Biased Junction

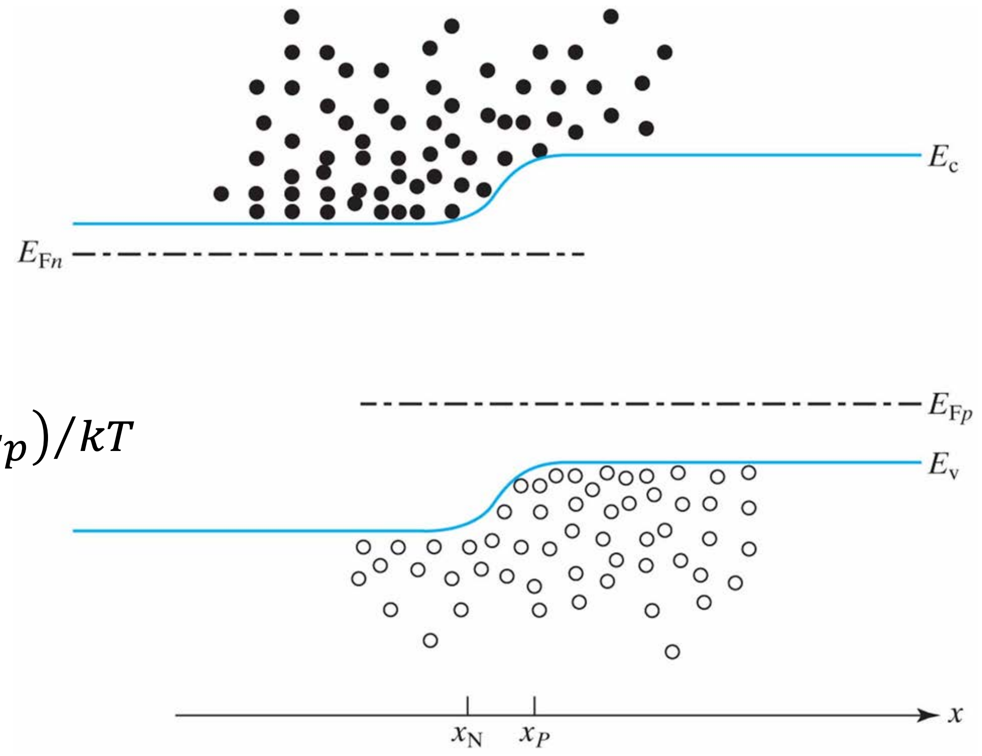


- Reduced electric field allows electrons to diffuse from N to P
  - and holes to diffuse from P to N
  - known as minority carrier injection

Minority Carrier Injection

- Forward bias of V reduces barrier height from $\emptyset_{bi}$ to $\emptyset_{bi} - V$
- Upsets balance between drift and diffusion
- Electrons are injected into P-side, holes into N-side

- Assuming E_{Fn} remains constant through to x_P, at edge of neutral P region:



$$n(x_P) = N_c . e^{-(E_c - E_{Fn})/kT}$$

$$= N_c . e^{-(E_c - E_{Fp})/kT} . e^{(E_{Fn} - E_{Fp})/kT}$$

$$= n_{P0} . e^{(E_{Fn} - E_{Fp})/kT}$$

$$= n_{P0} . e^{qV/kT}$$

Quasi-Equilibrium Boundary Condition

- Minority carrier density in neutral region at the edge of depletion region is raised by $e^{qV/kT}$

$$n(x_P) = n_{P0}.\, e^{qV/kT} = \frac{{n_i}^2}{N_a} e^{qV/kT}$$

$$p(x_N) = p_{N0}.\, e^{qV/kT} = \frac{{n_i}^2}{N_d} e^{qV/kT}$$

- Rewriting in terms of excess minority carriers:

$$n'(x_P) \equiv n(x_P) - n_{P0} = n_{P0}.\, (e^{qV/kT} - 1)$$

$$p'(x_N) \equiv p(x_N) - p_{N0} = p_{N0}.\, (e^{qV/kT} - 1)$$

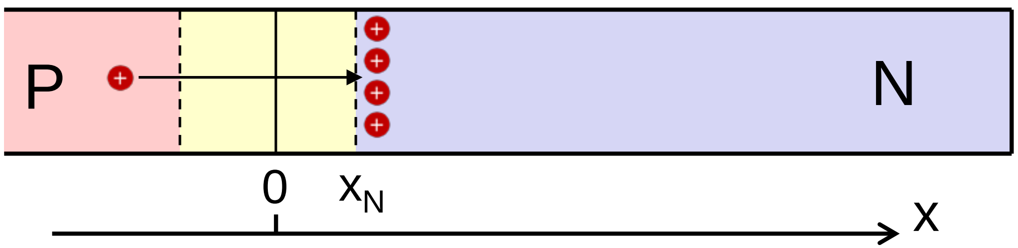
- In Si at 300°K, a forward bias of 0.6V raises minority carrier density by a factor of 10^{10} !

Example: Carrier Injection

- A P^+N junction has $N_a = 10^{18} cm^{-3}$ and $N_d = 10^{16} cm^{-3}$.

a) What are the minority carrier densities at the depletion region edges at zero bias?
b) What are the minority carrier densities at the depletion region edges with a forward bias of *0.6V* ?
c) What are the excess minority carrier densities at the depletion region edges with a forward bias of *0.6V* ?
d) What are the majority carrier densities at the depletion region edges with a forward bias of *0.6V* ?
e) What are the minority carrier densities at the depletion region edges with a negative bias of *1.8V* ?

Carrier Transport in Neutral Region



- Consider transport of minority holes in neutral N region

- Apply diffusion equation (Lecture 4) under the conditions:
  - steady state
  - constant doping (in neutral region)
  - negligible electric field

$$\frac{d^2p'}{dx^2} = \frac{p'}{D_p.\tau_p} = \frac{p'}{{L_p}^2} \qquad \text{where} \quad L_p \equiv \sqrt{D_p.\tau_p}$$

  - L_p is the minority carrier diffusion length

Minority Carrier Diffusion Length

- Similarly, in the P neutral region:

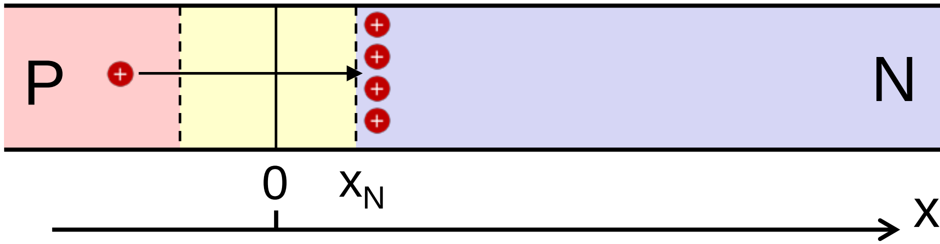
$$\frac{d^2n'}{dx^2} = \frac{n'}{{L_n}^2} \quad \text{where} \quad L_n \equiv \sqrt{D_n.\tau_n}$$

- Minority carrier diffusion length is a measure of how far an injected minority carrier will travel before recombination

- Varies from few μm to hundreds of μm depending on τ

- Note that these equations are only valid for minority carriers
  - Cannot neglect drift in neutral region for majority carriers

Excess Carriers in Forward Biased Junction



- We solve $$\frac{d^2p'}{dx^2} = \frac{p'}{{L_p}^2}$$

with boundary conditions:

$$p'(\infty) = 0$$
$$p'(x_N) = p_{N0}\left(e^{qV/kT} - 1\right)$$

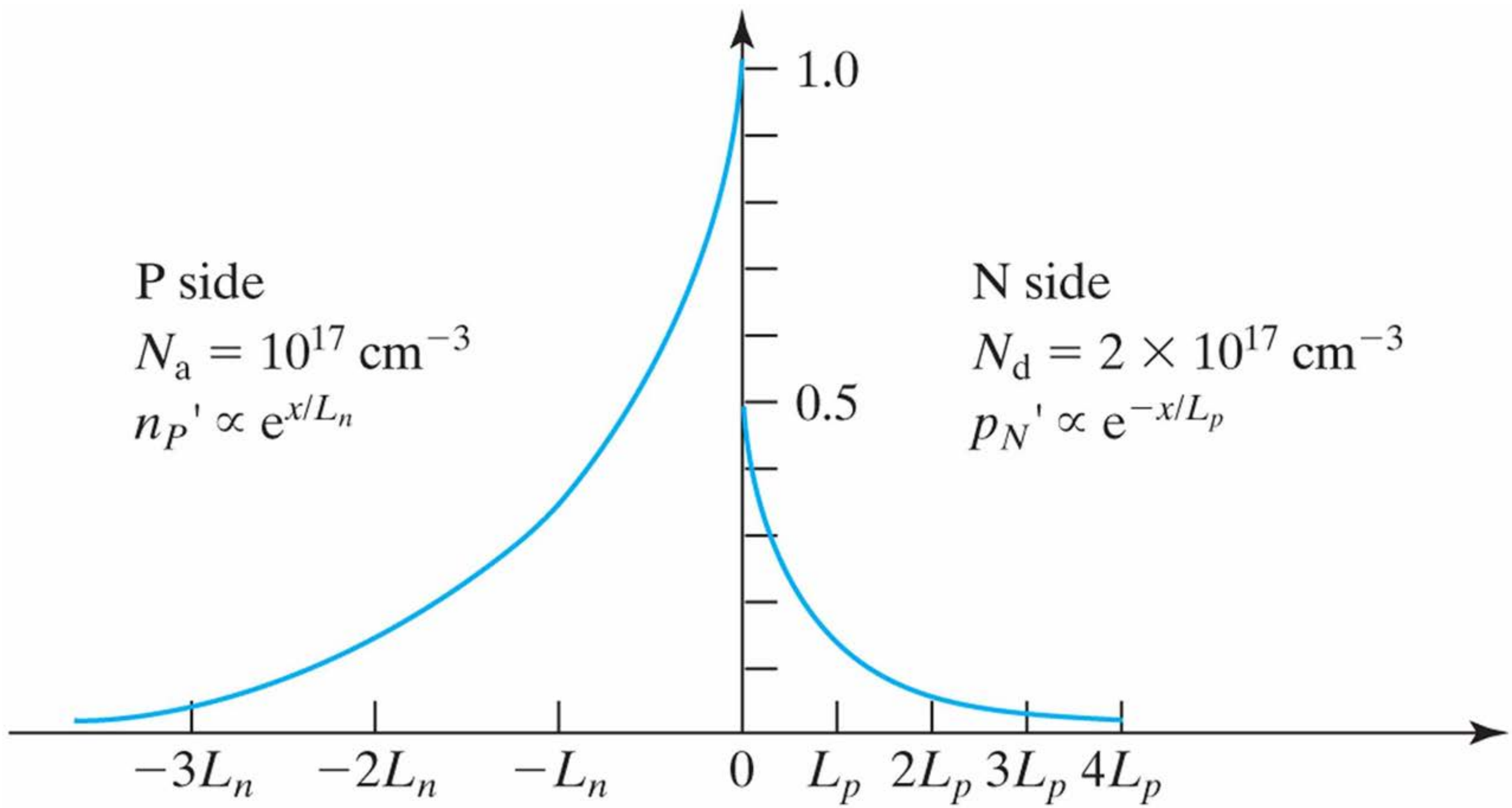
- General solution is $$p'(x) = A.e^{x/L_p} + B.e^{-x/L_p}$$
  - First boundary condition implies A=0, second determines B:

$$p'(x) = p_{N0}\left(e^{qV/kT} - 1\right).e^{-(x-x_N)/L_p}, \qquad x > x_N$$

Excess Carrier Distribution

$$p'(x) = p_{N0}\left(e^{qV/kT} - 1\right).\, e^{(x_N - x)/L_p}\,, \qquad x > x_N$$

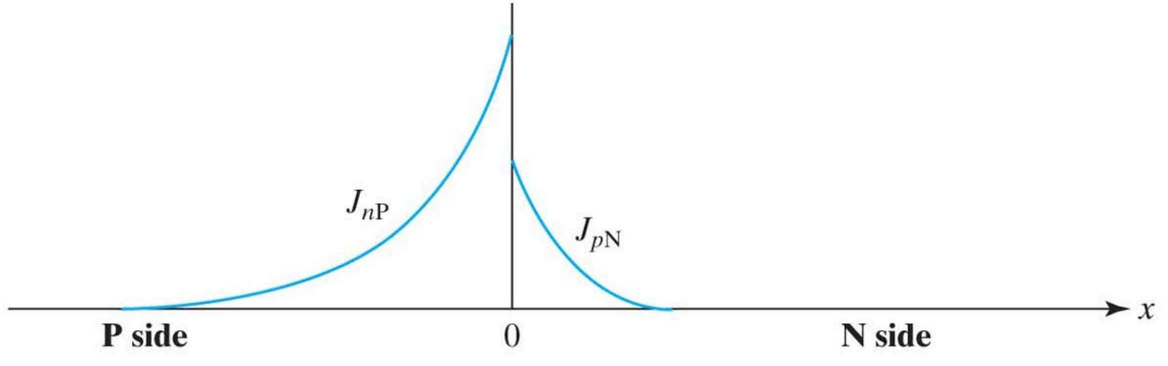
- Similarly: $$n'(x) = n_{P0}\left(e^{qV/kT} - 1\right).\, e^{(x - x_P)/L_n}\,, \qquad x < x_P$$



Excess Minority Carrier Current

$$J_{pN} = -q.D_p \frac{dp'(x)}{dx} = q.\frac{D_p}{L_p}.p_{N0}\left(e^{qV/kT} - 1\right).e^{-(x-x_N)/L_p}$$

$$J_{nP} = \ q.D_n \frac{dn'(x)}{dx} = q.\frac{D_n}{L_n}.n_{P0}\left(e^{qV/kT} - 1\right).e^{(x-x_P)/L_n}$$

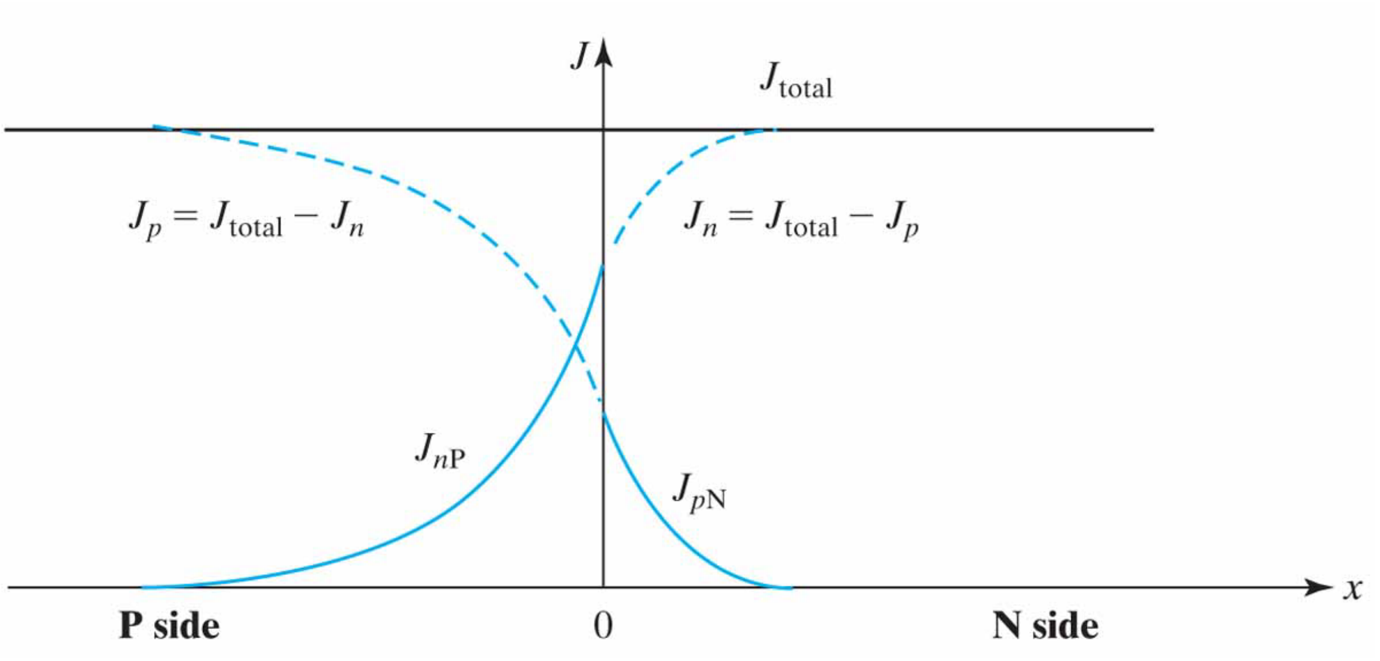


- At x=0, total current is due to injected minority carriers

$$J(0) = \ J_{pN}(x_N) + J_{nP}(x_P) = q.\left(\frac{D_p}{L_p}.p_{N0} + \frac{D_n}{L_n}.n_{P0}\right).\left(e^{qV/kT} - 1\right)$$

Majority Carrier Current

- Total current at *x=0* equals total current at all values of *x*
- As minority carrier current density decreases leaving the depletion region boundary, majority carrier current density increases to keep the total current density constant



PN Diode IV Characteristic

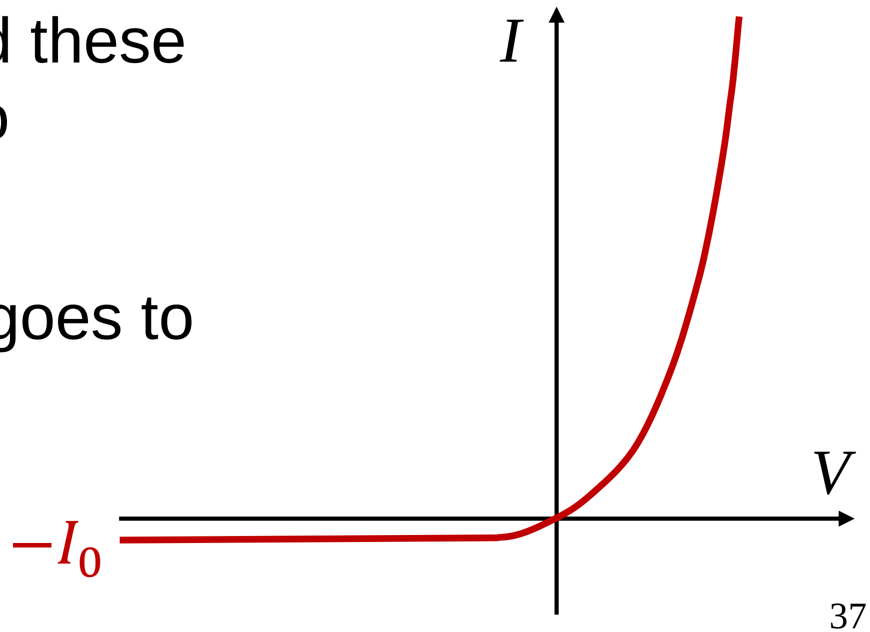
- Rewriting equation for total current density:

$$I = J.A = I_0\left(e^{qV/kT} - 1\right)$$

$$I_0 = A.q.{n_i}^2\left(\frac{D_p}{L_p.N_d} + \frac{D_n}{L_n.N_a}\right)$$

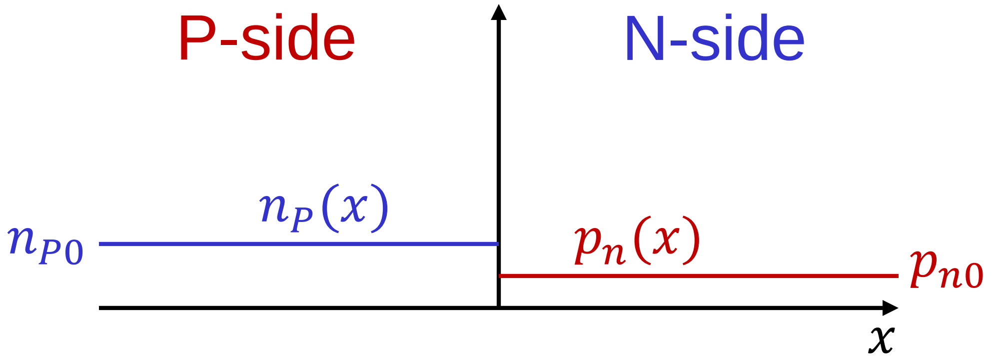
- Note that our analysis and these equations apply equally to reverse bias (V<0)

- For $V_r \gg kT$, exponential goes to zero and $I = -I_0$
  (reverse saturation current)

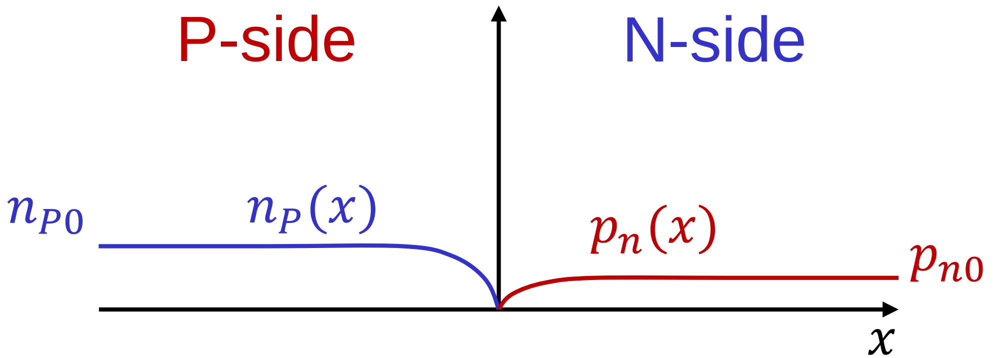


Minority Carrier Concentrations

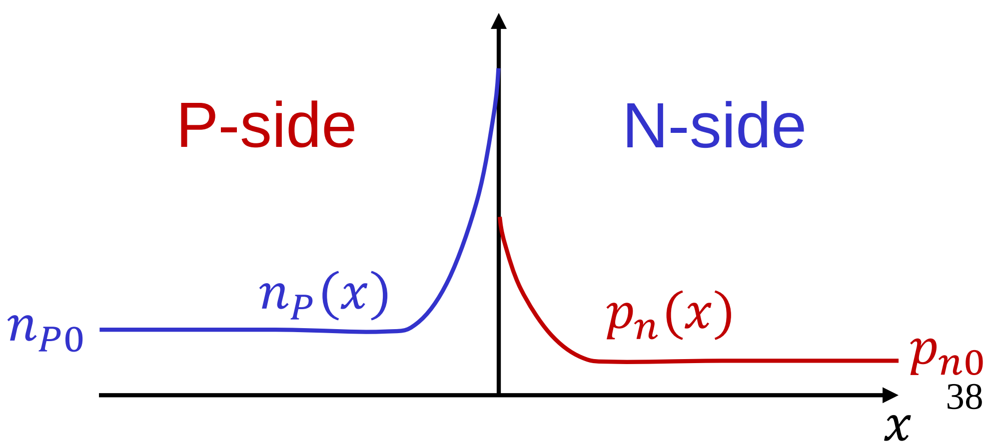
zero bias



reverse bias

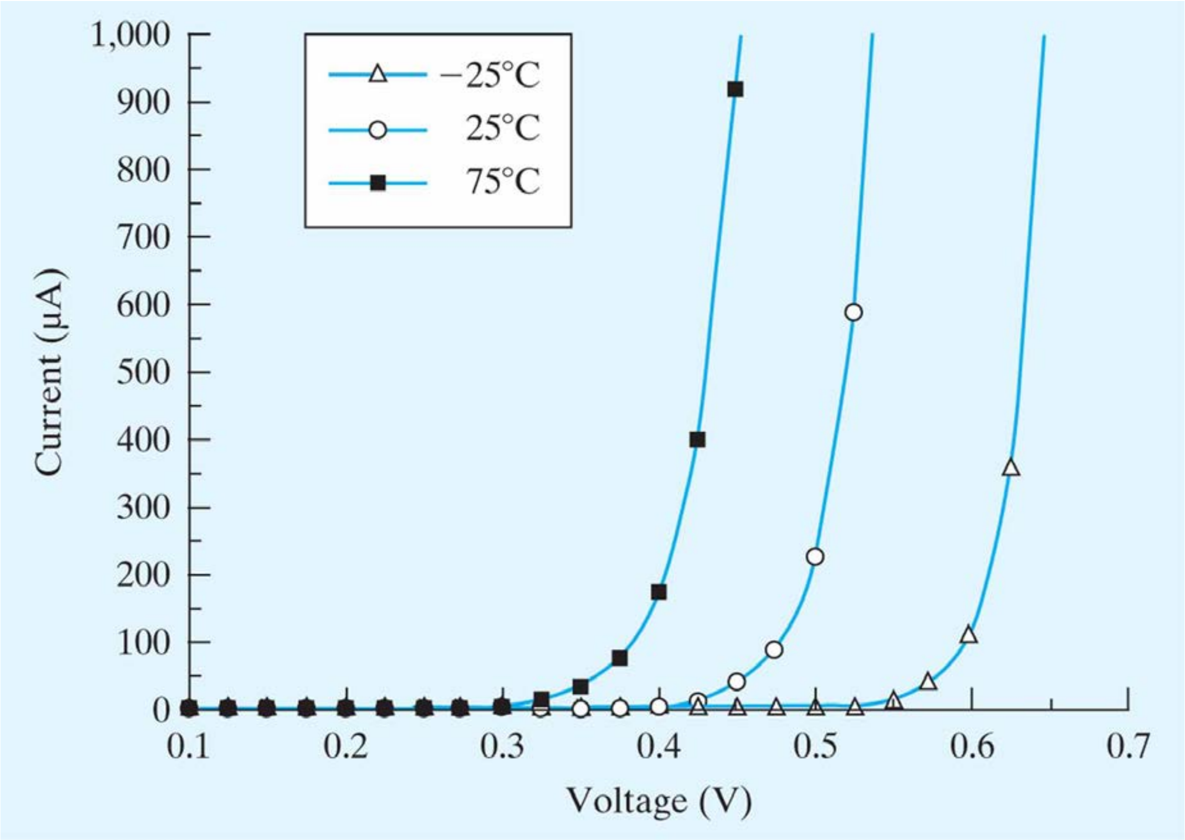


forward bias*



** in forward bias, injected majority carriers orders of magnitude greater than equilibrium concentration*

PN Diode IV *vs.* Temperature



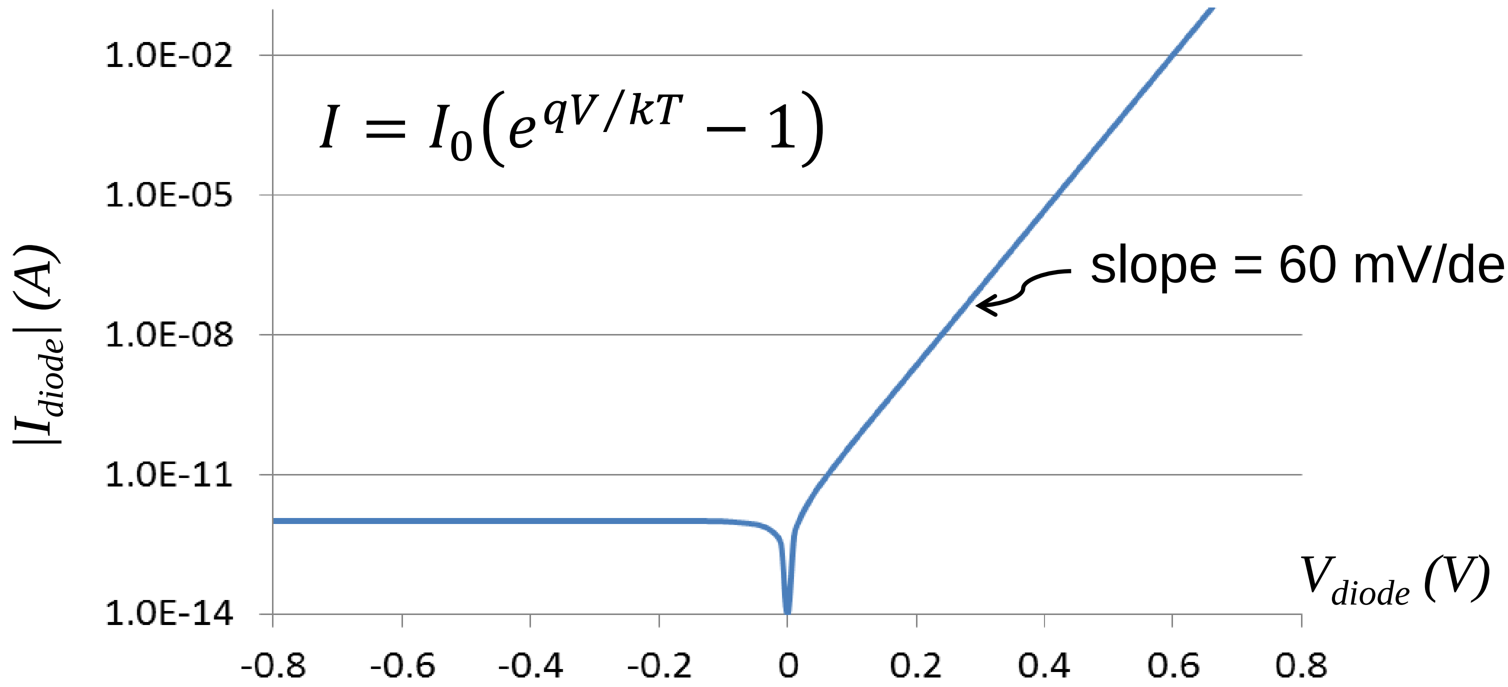
$$I = I_0\left(e^{qV/kT} - 1\right)$$

- Why does current increase with temperature?

$$I_0 = A.q.{n_i}^2\left(\frac{D_p}{L_p.N_d} + \frac{D_n}{L_n.N_a}\right)$$

Semi-log plot of IV for ideal diode

- Ideal diode characteristic for $I_0 = 10^{-12}$ A and T=300°K



$$For\ V \gg kT, \qquad \ln(I) = \ln(I_0) + \frac{qV}{kT}$$

- plotting *ln(I) vs. V*, slope = *q/kT*
- diode can be used as temperature sensor

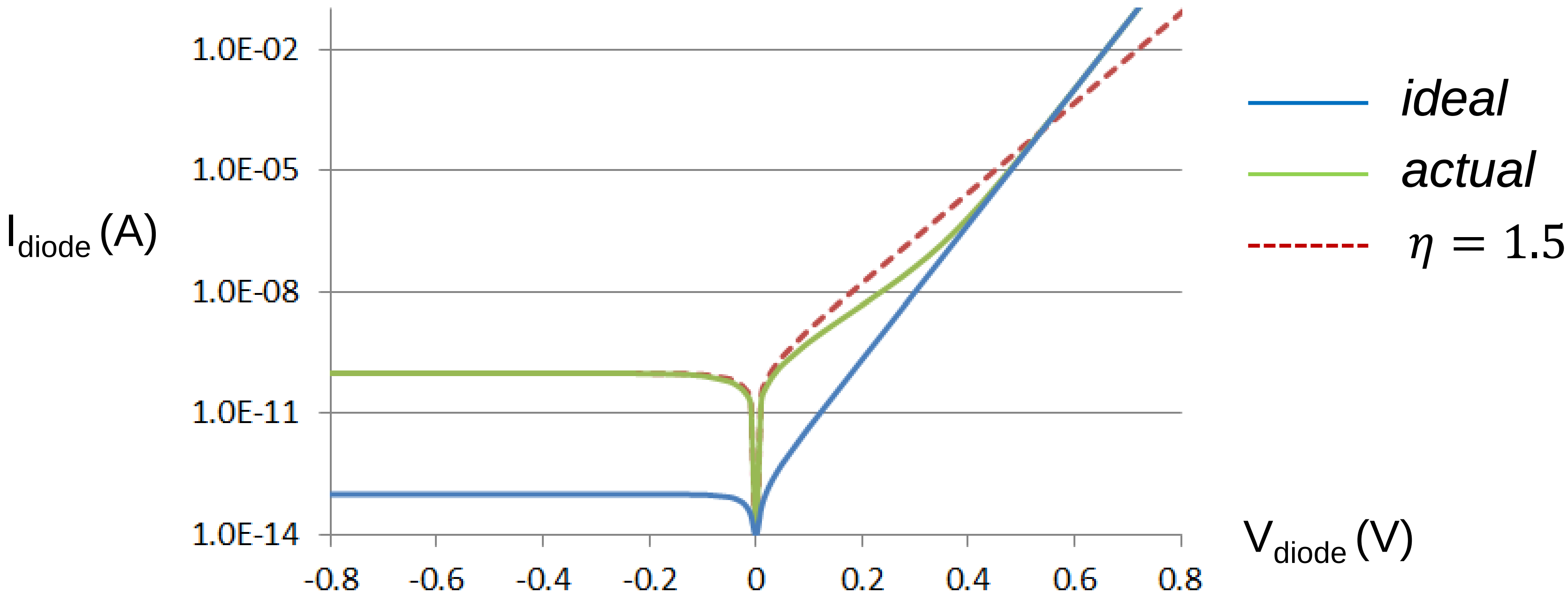
Generation-Recombination in Depletion Region

- Our analysis assumed that J_p and J_n did not change between x_P and x_N
  - There will be extra current due G-R within depletion region
  - Space Charge Region (SCR) or Generation-Recombination current
- Since there are no majority carriers, recombination requires presence of minority holes *and* electrons

$$I_{SCR} = I_{0,SCR}\left(e^{qV/\mathbf{2}kT} - 1\right)$$

  - Under forward bias, SCR current increases at only 120mV/decade
  - At high forward bias, diffusion current dominates
  - Under reverse bias, depletion region is devoid of carriers, so electron-hole pairs will be thermally generated and immediately swept across junction by electric field.
  - This significantly increases leakage current ($I_{0,SCR} \gg I_0$)

Non-Ideal Diode Behavior



- Account for this extra current with ideality factor η

$$I = I_{0,SCR}\left(e^{qV/\eta kT} - 1\right), \qquad 1 < \eta < 2$$

Example: PN Diode currents

- Consider a PN junction diode at 300° K with the following characteristics:

$$N_a = N_d = 10^{16}\ cm^{-3}$$

$$\tau_{p0} = \tau_{n0} = 5 \times 10^{-7} s$$

$$D_n = 25\ cm^2/s$$

$$area = 0.01\ mm^2$$

$$D_p = 10\ cm^2/s$$

a) Calculate ideal reverse saturation current
b) Calculate current with forward bias of 0.65V
c) Calculate electric field in N neutral region with forward bias of 0.65V