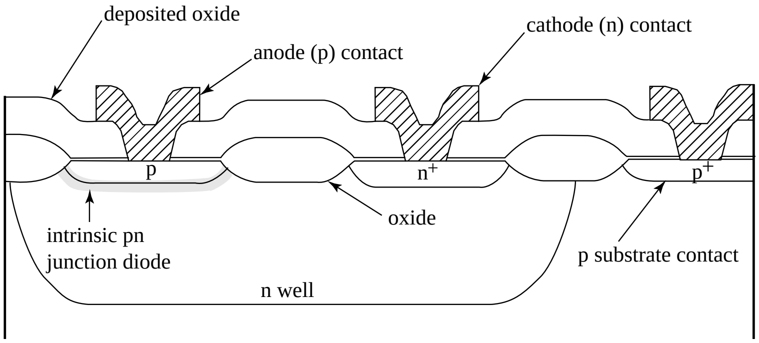
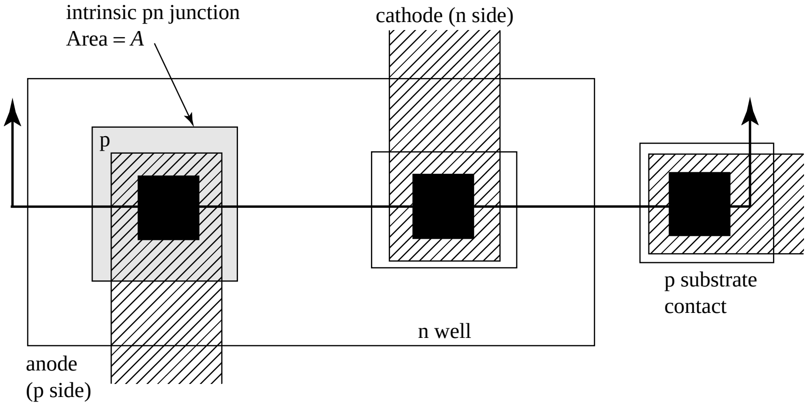
I. PN Junction Diode

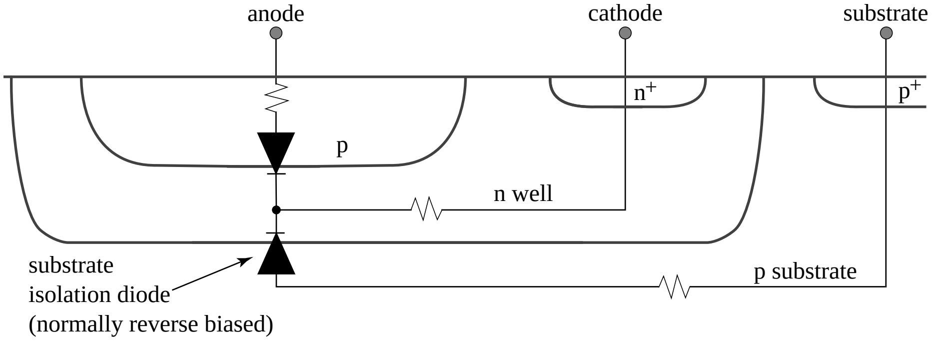
A. Physical Integrated Structure



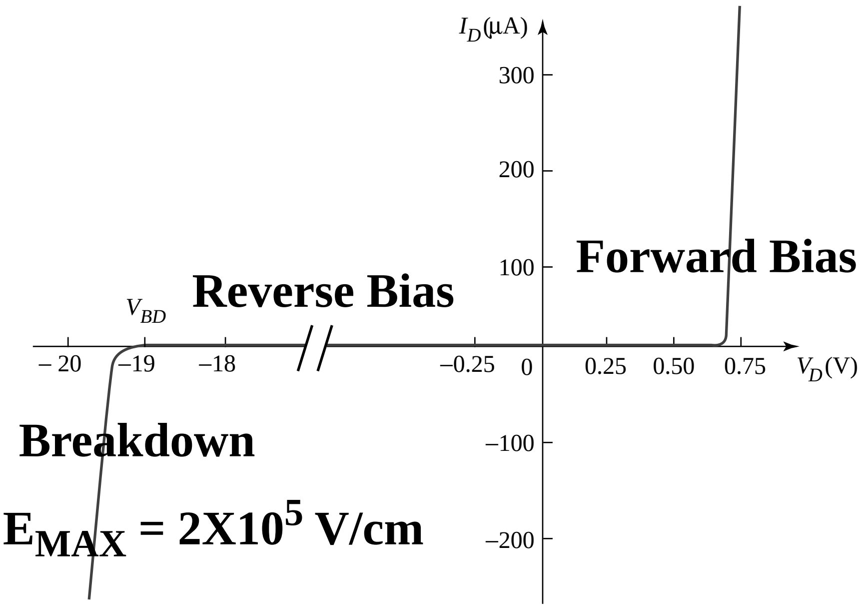
(a)



(b)



B. I-V Characteristics



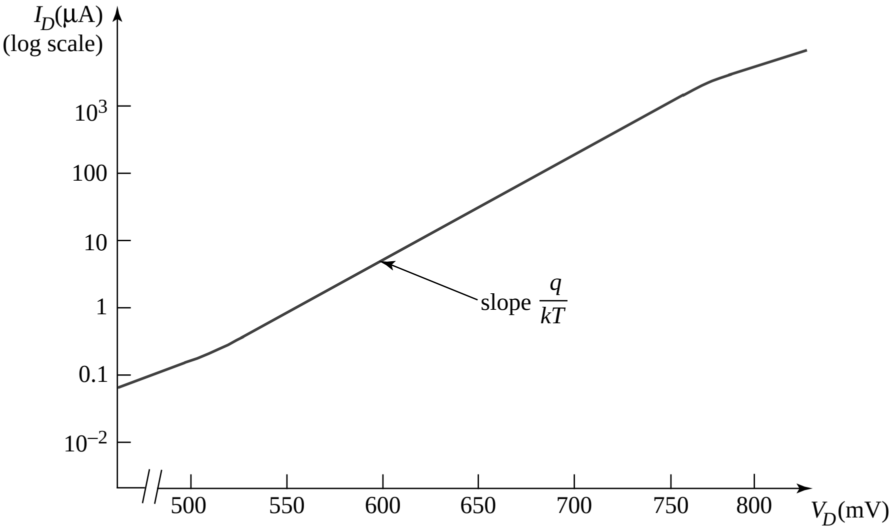
Reverse Bias

Forward Bias

Breakdown

$E_{MAX} = 2X10^5$ **V/cm**

(a)

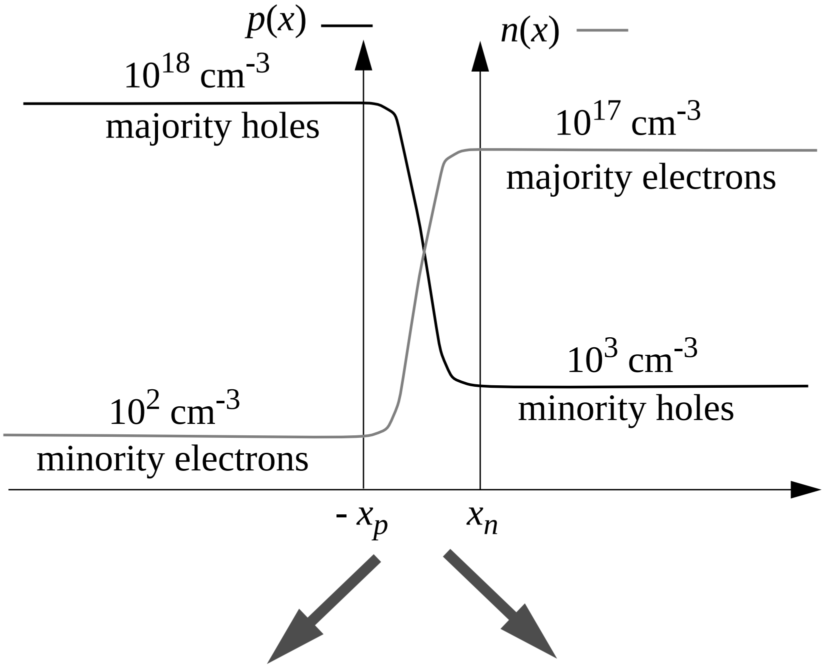


- To model foward bias region we need 2 new concepts
- The Law of the Junction
- Steady - State Diffusion

C. Physical Reasoning

- In thermal equilibrium there is a balance between drift and diffusion current for **BOTH** holes and electrons

$$J = J^{drift} + J^{diff} = 0$$



huge electron and hole diffusion currents in depletion region

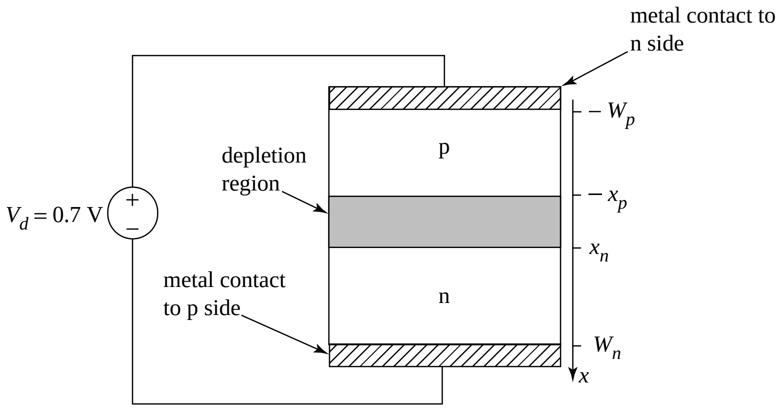
high electric field --> balancing drift currents

- Forward bias --> reduction in potential barrier --> reduction in electric field in depletion region --> reduction in drift current component in the depletion region for both holes and electrons
- Since diffusion current component in the depletion region is nearly unaffected by bias--->We have a net current.

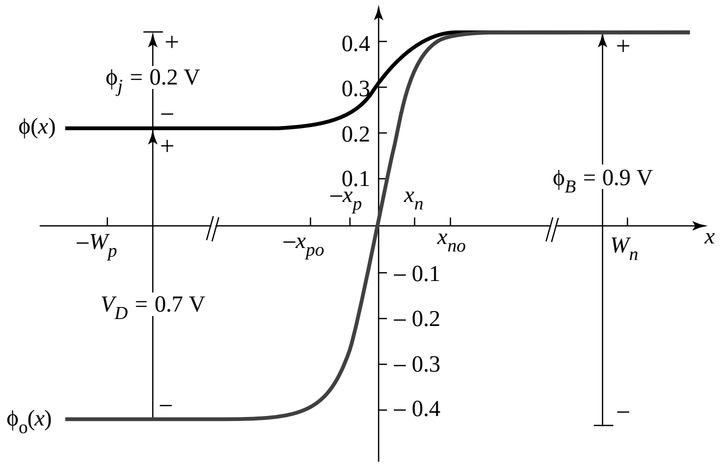
$$\boxed{I = I_s\left(e^{V_D/V_{th}} - 1\right)}$$

D. Qualitative Understanding

- Current is small enough to ignore resistive potential drops in bulk p & n regions
- $\phi_j = \phi_B - V_D$ where $\phi_B = \phi_n - \phi_p$ $\qquad \phi_B = \frac{kT}{q} ln(\frac{N_a N_d}{n_i^2})$
- Positive V_D reduces potential barrier height - minority carriers injected across junction
- Minority carrier diffusion is the bottleneck
- **FOCUS ON MINORITY CARRIERS**

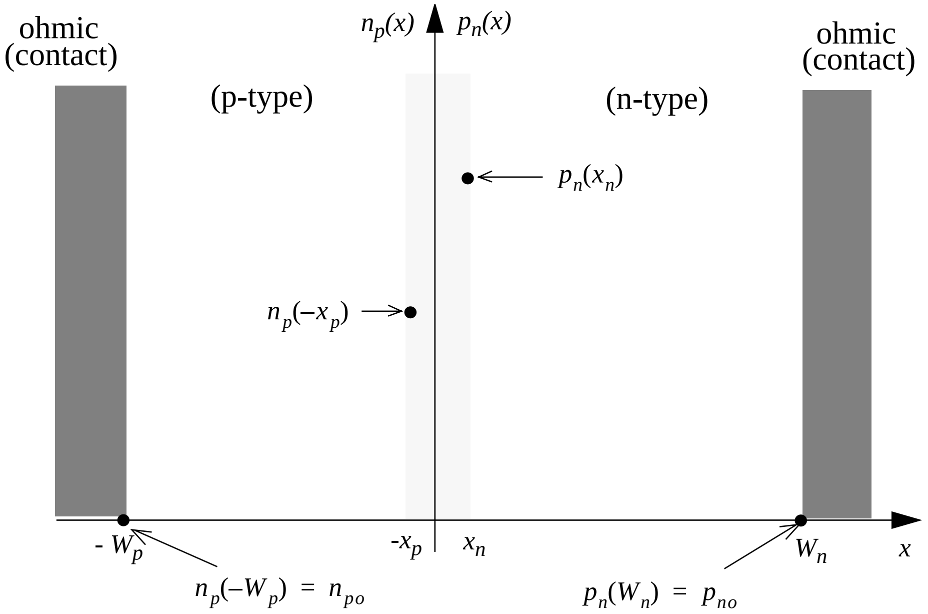


(a)



E. Derivation Steps

- Step 1: Find the minority carrier concentrations at the edges of depletion region as a function of forward bias V_D
- Step 2: Find the minority carrier concentration at the ohmic contacts. All excess carriers **recombine** at ohmic contacts. The carrier concentrations return to their equilibrium value.
- Step 3: Find the spatial distribution of the minority carrier concentrations, $n_p(x)$, (electrons in the p region), and $p_n(x)$, (holes in the n region.)
- Step 4: Find the minority carrier diffusion currents at the edges of the depletion region.
- Step 5: Find the total diode current $J = J_n^{diff}(-x_p) + J_p^{diff}(x_n)$



II. Carrier Concentrations - Connection across the Junction

A. Thermal Equilibrium

- For the junction in thermal equilibrium,

$$\phi_B = \frac{kT}{q} ln(\frac{N_a N_d}{n_i^2})$$

- Define $p_{no} \equiv n_i^2 / N_d$ **and** $n_{po} \equiv n_i^2 / N_a$
- Rexpress this basic result in two ways --

$$\phi_B = V_{th} ln(\frac{N_d}{n_{po}}) \qquad \text{and} \qquad \phi_B = V_{th} ln(\frac{N_a}{p_{no}}).$$

- Solving for the equilibrium minority carrier concentrations in terms of the built-in potential,

.

$$p_{no} = N_a e^{-\phi_B / (V_{th})} \qquad \text{and} \qquad n_{po} = N_d e^{-\phi_B / (V_{th})}$$

- This result is very important, since it relates the minority carrier concentration on one side of the junction to the majority carrier concentration on the *other side* of the junction ... !

B. Applied bias

- The new potential barrier $\phi_j = \phi_B - V_D$ is substituted for the thermal equilibrium barrier to find the new minority carrier concentrations at the depletion region edges.
- Assume that detailed balance between drift and diffusion is not significantly perturbed. This says that electrons are in equilibrium with each other across the junction. SAME for holes.

$$n_p(-x_p) = N_d e^{-\phi_j / V_{th}} = N_d e^{-(\phi_B - V_D)/V_{th}}$$

$$p_n(x_n) = N_a e^{-\phi_j / V_{th}} = N_a e^{-(\phi_B - V_D)/V_{th}}$$

- These results can be re-expressed in a simpler form

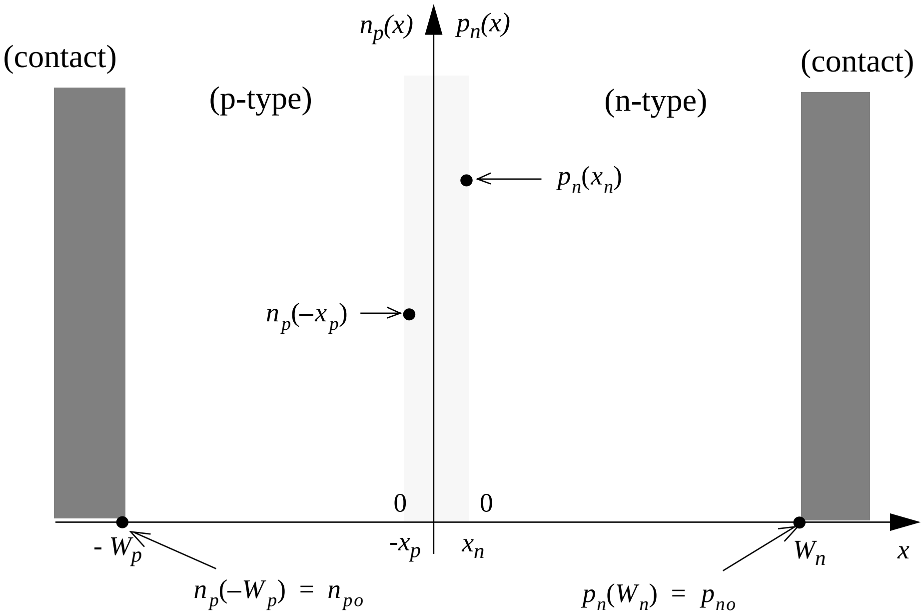
$$n_p(-x_p) = N_d e^{-\phi_B / V_{th}} e^{V_D / V_{th}} = n_{po} e^{V_D / V_{th}}$$

$$p_n(x_n) = N_a e^{-\phi_B / V_{th}} e^{V_D / V_{th}} = p_{no} e^{V_D / V_{th}}$$

- These two equations are known as the **Law of the Junction**. Note that the minority carrier concentration is an exponential function of the applied bias on the junction.

C. Minority Carrier Concentrations under Forward Bias

- Apply the Law of the Junction to find the minority carrier concentrations at the edges of the depletion region
- Minority carriers **injected** across depletion region
- Law of the Junction is valid if **minority carrier concentration is less than equilibrium majority concentration**. This condition is called **LOW LEVEL INJECTION (LLI).**
- LLI - $p_n < n_{no}$ and $n_p < p_{po}$



- The minority carrier concentration is maintained at thermal equilibrium at the ohmic contacts. All excess carriers **recombine** at the ohmic contact.

Example

- Numerical values: $N_a = 10^{18}$ cm^{-3}, $N_d = 10^{17}$ cm^{-3}, $V_D = 720$ mV
- $n_p(-x_p) = n_i^2/N_a \exp(V_D/V_{th}) = 10^{14}$ cm^{-3}
- $p_n(x_n) = n_i^2/N_d \exp(V_D/V_{th}) = 10^{15}$ cm^{-3}.

D. Minority Carrier Concentration under Reverse Bias

- Apply the Law of the Junction to find the minority carrier concentrations at the edges of the depletion region
- Minority carriers **extracted** near the depletion region edge

$$n_p(-x_p) = n_{po} e^{V_D / V_{th}} \approx 0 \, for V_D < 0$$

$$p_n(x_n) = p_{no} e^{V_D / V_{th}} \approx 0 \, for V_D < 0$$