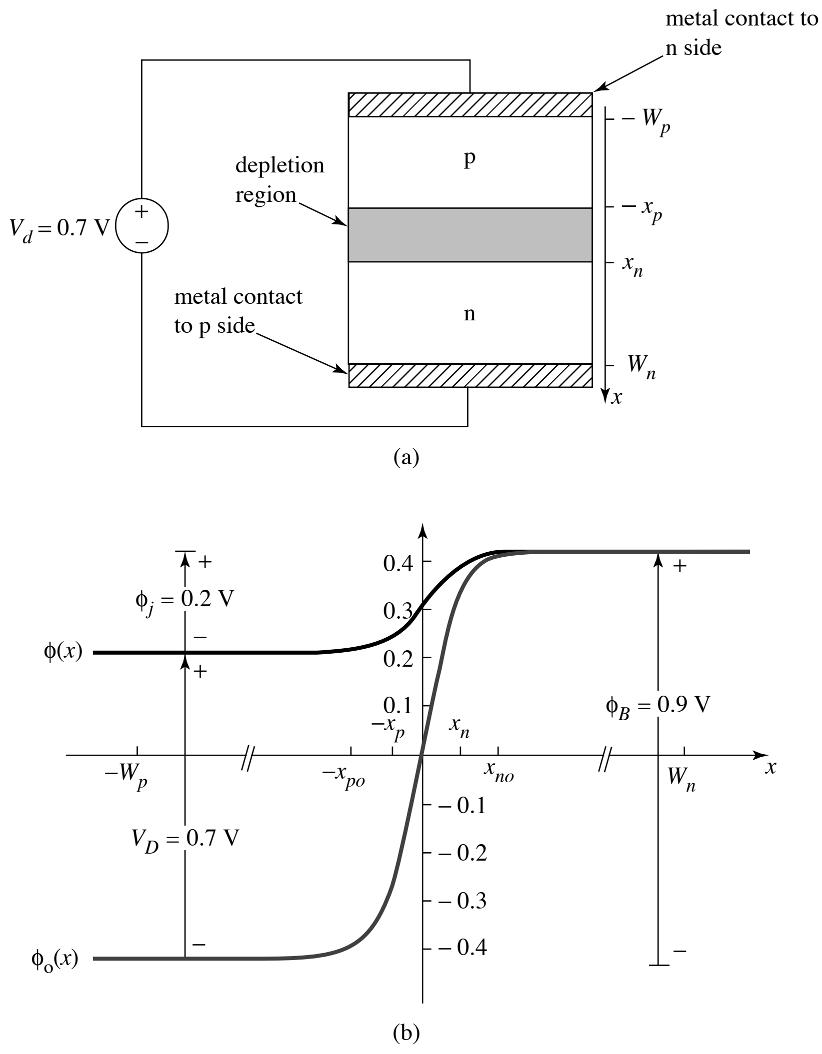
The pn Junction under Forward Bias

- $V_D > 0$ --> what happens?

  Many assumptions: from Chapter 6 (current not too big) --> resistive potential drops in bulk p & n regions can be neglected in KVL and $\phi_j = \phi_B - V_D$



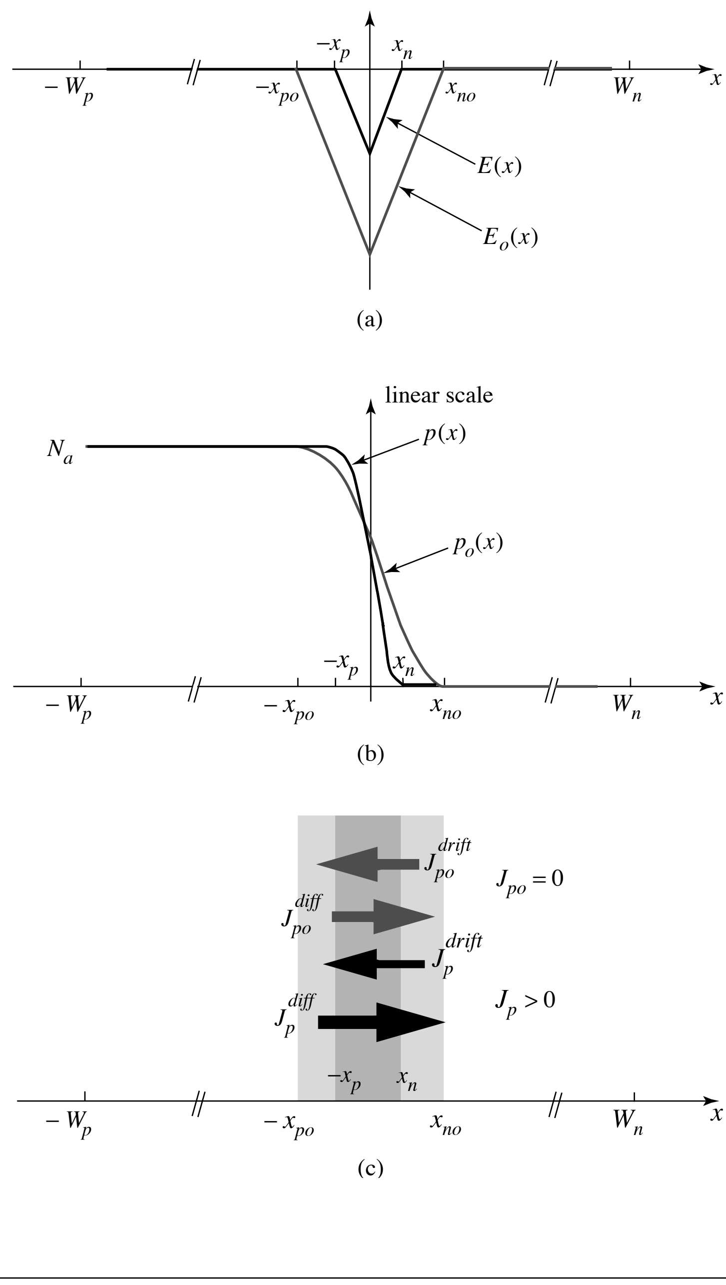
ϕ_B = thermal equilibrium barrier height = $\phi_n - \phi_p$

Physical Reasoning

- thermal equilibrium --> balance between drift and diffusion:

  $J = J^{drift} + J^{diff} = 0$ for holes and electrons

- forward bias upsets balance



Modelling Forward-Bias Diode Currents

- **Step 1**: find how minority carrier concentrations at the edges of depletion region change with forward bias V_D
- **Step 2**: what happens to the minority carrier concentration at the ohmic contacts under forward bias? *Answer*: no change from equilibrium.
- **Step 3**: find the minority carrier concentrations $n_p(x)$ in the p region and $p_n(x)$ in the n region.
- **Step 4**: find the minority carrier diffusion currents.
- **Step 5**: find the total current J.

Carrier Concentrations in Thermal Equilibrium at the pn Junction

- For the junction in thermal equilibrium,

$$\phi_B = \frac{kT}{q} ln\left(\frac{N_a N_d}{n_i^2}\right), \text{ where}$$

If we identify $p_{no} = n_i^2 / N_d$ and $n_{po} = n_i^2 / N_a$, we can reexpress this basic result in two ways --

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

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

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

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 ... !

Law of the Junction

- What happens under an applied bias?

  assume that the new potential barrier $\phi_j = \phi_B - V_D$ can substituted for the thermal equilibrium barrier to find the new minority carrier concentrations *at the depletion region edges* $-x_p$ (p-side) and x_n (n-side)

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

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

These results can be re-expressed in a simpler form, by expanding the exponentials:

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

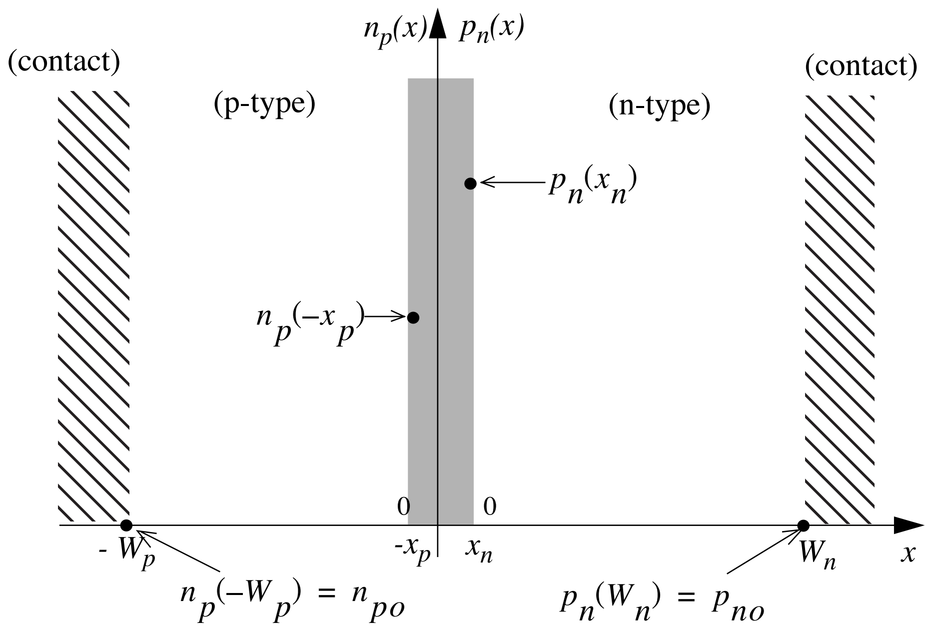
$$p_n(x_n) = N_a e^{-\phi_B / V_{th}} e^{V_D / V_{th}} = p_{no} e^{V_D / V_{th}}$$

- 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.

Carrier Concentrations under Forward Bias

- Apply the Law of the Junction at the edges of the depletion region



- Numerical values: $N_a = 10^{18}$ cm^{-3}, $N_d = 10^{17}$ cm^{-3}

  $V_D = 0.72$ V = 720 mV, $V_{th} = 26$ mV (warm room) ... example values; note that V_D must be known precisely to substitute into $\exp[V_D/V_{th}]$.

$$n_p(-x_p) = 10^2 \text{ cm}^{-3} \exp[720/26] = 10^{14} \text{ cm}^{-3}$$

$$p_n(x_n) = 10^3 \text{ cm}^{-3} \exp[720/26] = 10^{15} \text{ cm}^{-3}$$

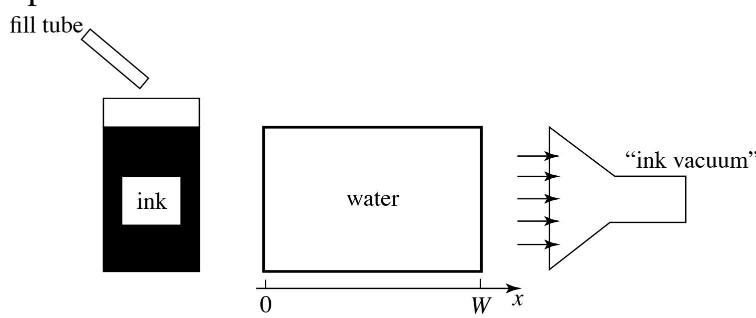
- The minority carrier concentration is maintained at thermal equilibrium at the ohmic contacts

Diffusion Transport in Steady-State

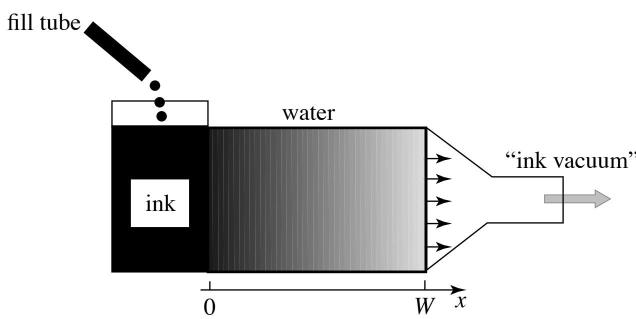
- How do we “fill in the blanks” between the contacts and the depletion region?

  Steady-state --> minority carriers must be continuously injected across the junction to keep $p_n(x_n) >> p_{no}$ and $n_p(-x_p) >> n_{po}$ and continously extracted at the contacts; huge gradient in minority carrier concentrations across the n and p regions --> transport occurs by *diffusion*.

- Conceptual experiment:



(a)



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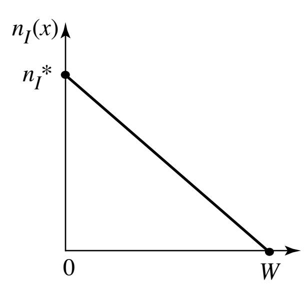


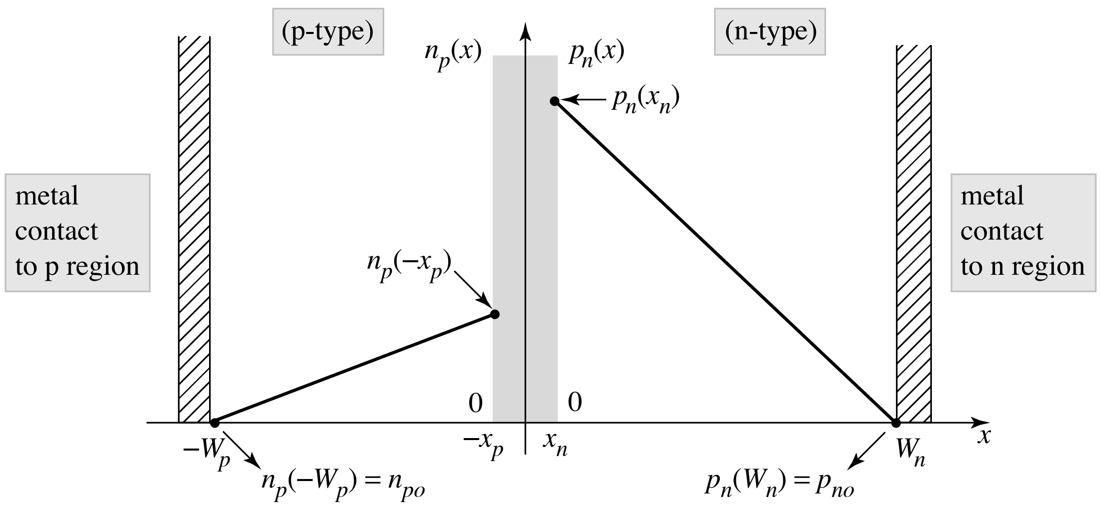
(c)

The Short-Base Solution

- Carrier concentrations --> linear solutions if we assume that the p-type and n-type regions are so short that all of the diffusing minority carriers "make it" across to the ohmic contacts

  In n-type region: $J_p^{diff} = - qD_p dp_n / dx$ = constant --> $p_n(x)$ is *linear*

  In p-type region: $J_n^{diff} = qD_n dn_p / dx$ = constant --> $n_p(x)$ is *linear*



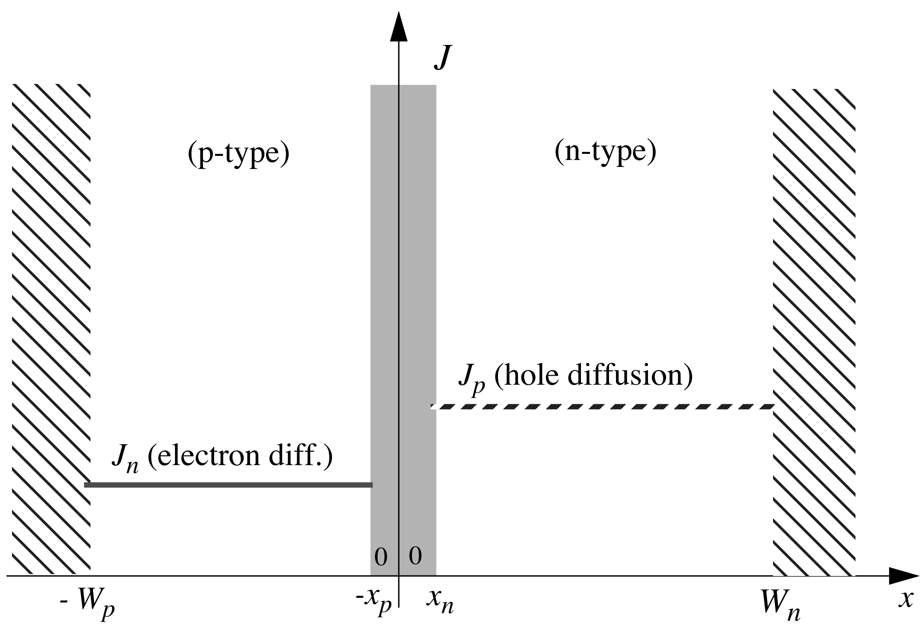
Current Densities

- Minority carrier diffusion currents

$$J_n^{diff} = qD_n \frac{dn_p}{dx} = qD_n \left(\frac{n_p(-x_p) - n_p(-W_p)}{W_p - x_p} \right) = qD_n n_{po} e^{V_D / V_{th}}$$

$$J_p^{diff} = -qD_p \frac{dp_n}{dx} = -qD_p \left(\frac{p_n(W_n) - p_n(x_n)}{W_n - x_n} \right) = qD_p p_{no} e^{V_D / V_{th}}$$

- Plot of minority carrier diffusion current densities

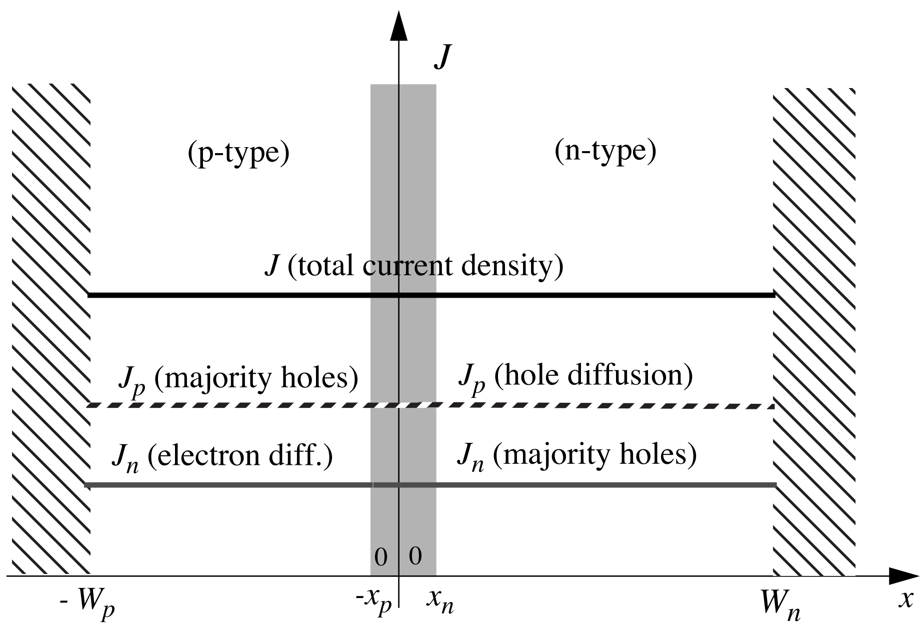


- Minority carriers are injected from the other side of the junction ... how do they get there? *by a majority carrier current density*

Total Current Density

- The total current density is the sum of the minority electron and hole diffusion current densities at the junction ... and is constant through the diode

$$J = J_n^{diff} + J_p^{diff}$$



$$J = q\left(\frac{D_n n_{po}}{W_p - x_p} + \frac{D_p p_{no}}{W_n - x_n}\right)(e^{V_D/V_{th}} - 1)$$

- Diode current: multiply by area A and note that $x_n, x_p << W_n, W_p$

$$I = qn_i^2\left(\frac{D_n}{N_a W_p} + \frac{D_p}{N_d W_n}\right)(e^{V_D/V_{th}} - 1) = I_o(e^{V_D/V_{th}} - 1)$$