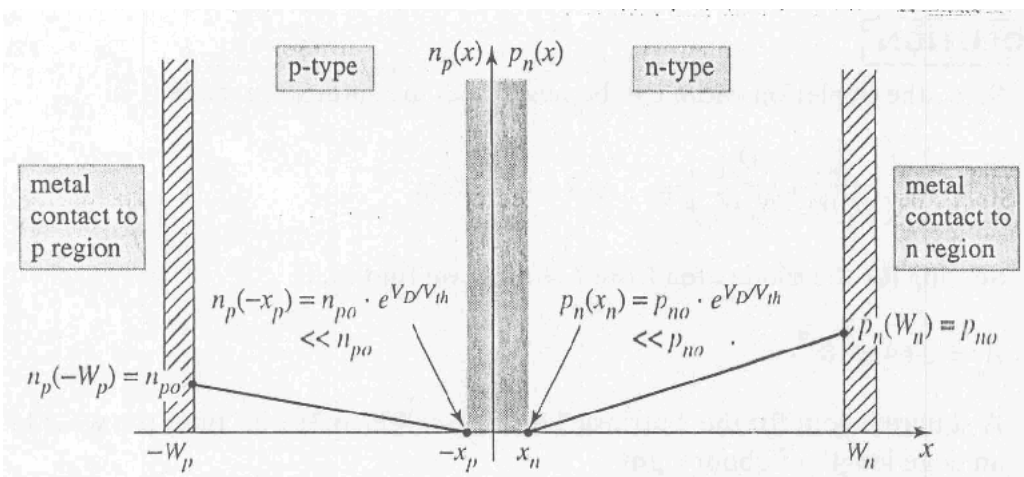
Diode under reverse bias

- Under a reverse bias >0.1mV, minority carriers become negligible
- `

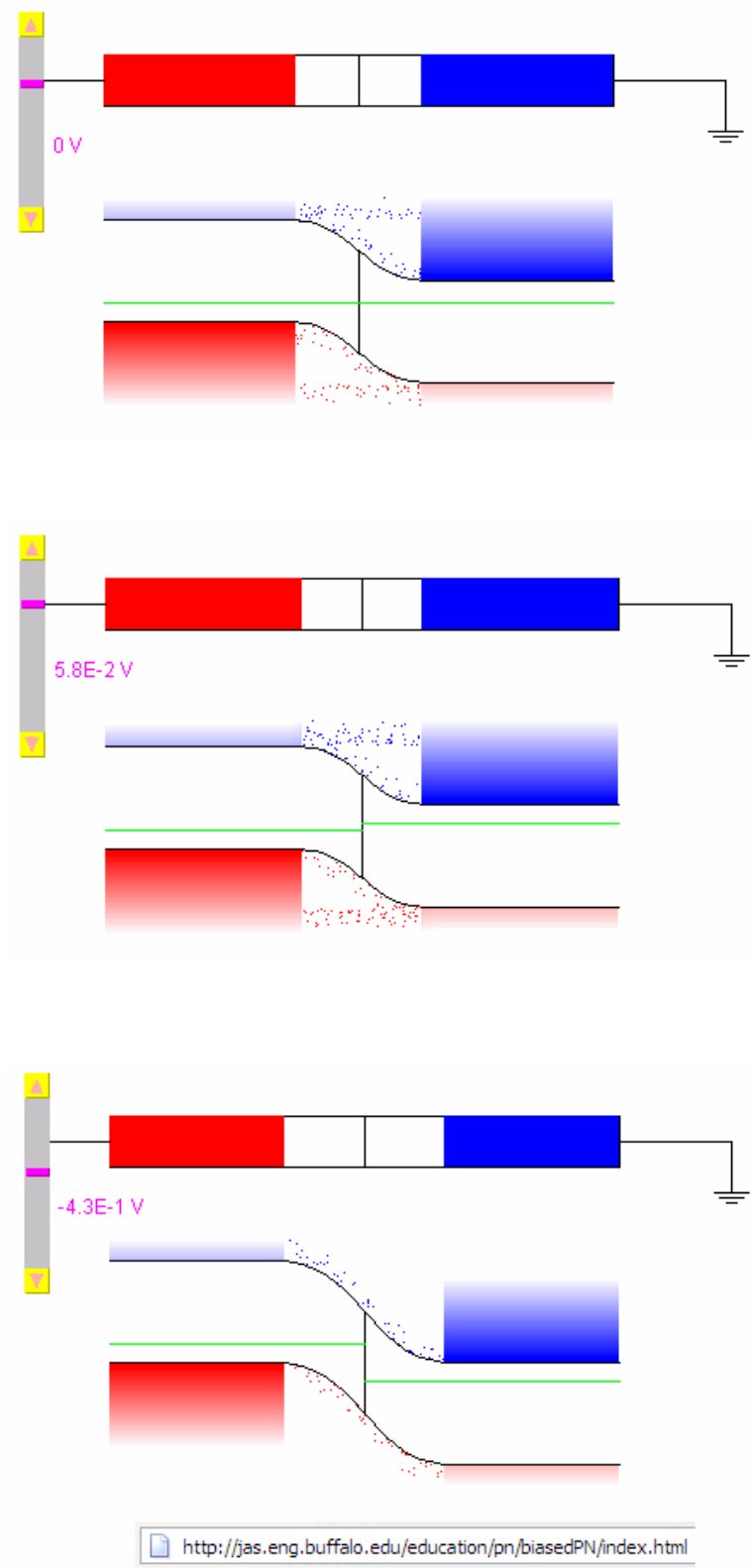
$$p_n(x_n) = p_{no} e^{V_D/V_{th}} \ll p_{no} \text{ and } n_p(-x_p) = n_{po} e^{V_D/V_{th}} \ll n_{po} \; (V_D < -0.1 \text{ V})$$



$$J \approx -qD_p\left[\frac{p_n(W_n) - 0}{W_n - x_n}\right] + qD_n\left(\frac{0 - n_p(-W_p)}{W_p - x_p}\right) \approx -q\left(\frac{D_p p_{no}}{W_n} + \frac{D_n n_{po}}{W_p}\right)$$

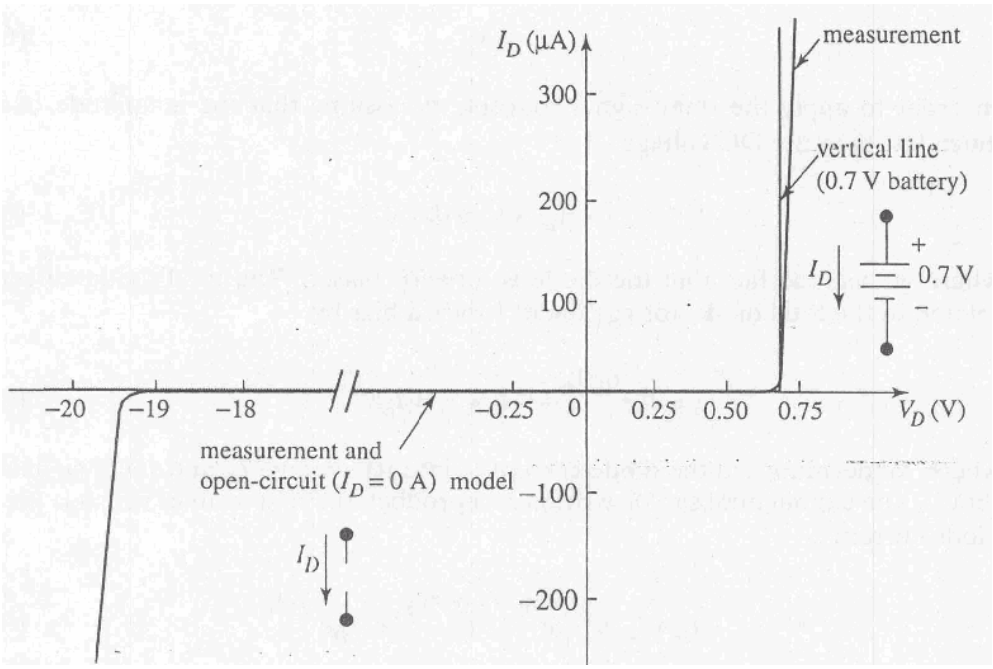
- Minority carriers are extracted
- This simple model predicts constant current. It actually increases with reverse bias, and is much larger than Io.

Summary


0 V
5.8E-2 V
-4.3E-1 V
http://jas.eng.buffalo.edu/education/pn/biasedPN/index.html

P-N junction diode circuit models

- Large signal static model



P-N junction diode circuit models

- Small signal model

$$i_D = I_O e^{v_D/V_{th}} \rightarrow I_D + i_d = I_O e^{(V_D + v_d)/V_{th}}$$

$$I_D + i_d = I_D\left(1 + \frac{v_d}{V_{th}} + \frac{1}{2}\left(\frac{v_d}{V_{th}}\right)^2 + \frac{1}{6}\left(\frac{v_d}{V_{th}}\right)^3 + \ldots\right)$$

$$i_d = I_D\left(\frac{v_d}{V_{th}}\right) + \frac{I_D}{2}\left(\frac{v_d}{V_{th}}\right)^2 + \frac{I_D}{6}\left(\frac{v_d}{V_{th}}\right)^3 + \ldots$$

$$i_d \cong \left(\frac{I_D}{V_{th}}\right) v_d = g_d v_d$$

$$r_d = \frac{1}{g_d} = \frac{V_{th}}{I_D}$$

P-N junction diode circuit models

- Depletion Capacitance
  - With reverse bias

$$C_j = \frac{C_{jo}}{\sqrt{1 - V_D/\phi_B}}$$

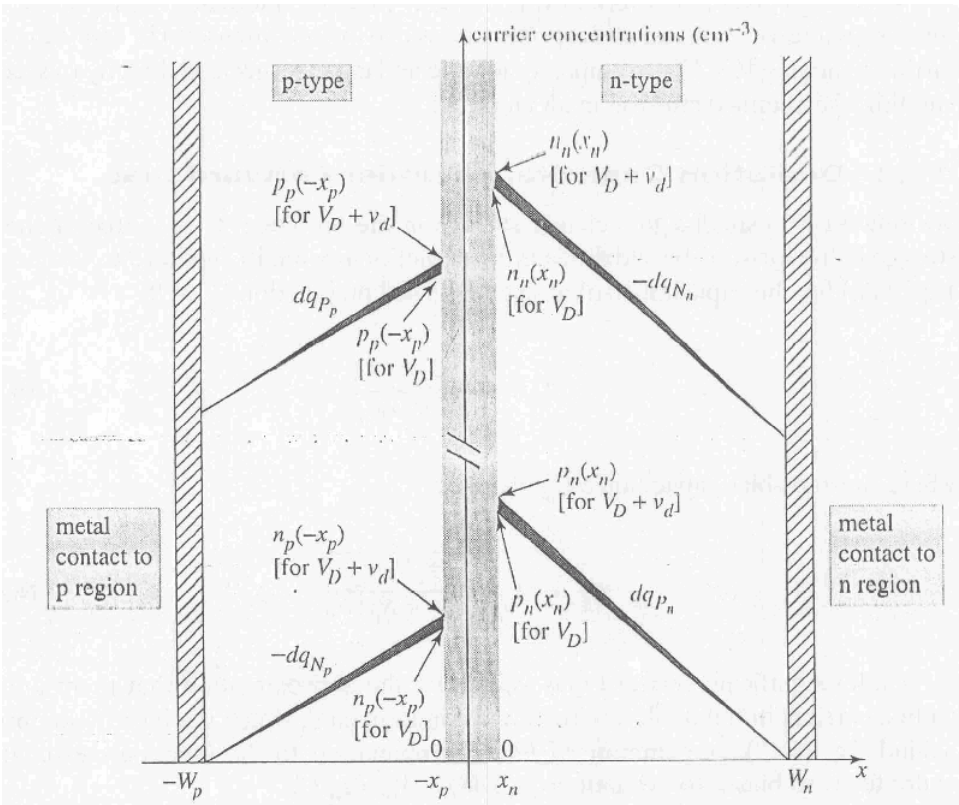
$$C_{jo} = A\sqrt{\frac{q\varepsilon_s N_a N_d}{2(N_a + N_d)\phi_B}}$$

Under significant forward bias $V_D > \phi_B / 2$ the approximation that there are no mobile carriers in the depletion region becomes invalid, which is a basic assumption behind Eq. (6.48). A common *ad hoc* approximation to the junction capacitance under forward bias is to evaluate Eq. (6.48) at $V_D = \phi_B / 2$

$$\boxed{C_j \cong \frac{C_{jo}}{\sqrt{1 - 1/2}} = \sqrt{2}C_{jo}} \text{ for forward bias}$$

P-N junction diode circuit models

- Diffusion Capacitance



Charge stored at both sides

$$q_{N_p}(v_D) = A\int_{-W_p}^{-x_p} -qn_p'(x)\,dx = -qAn_{po}\left(e^{v_D/V_{th}}-1\right)\int_{-W_p}^{-x_p}\left[1+\left(\frac{x+x_p}{W_p-x_p}\right)\right]dx$$

$$q_{P_n}(v_D) = A\int_{x_n}^{W_n} qp'_n(x)dx = \frac{qA}{2}(W_n-x_n)\,p_{no}\left(e^{v_D/V_{th}}-1\right)$$

$$C_d = \left.\frac{-dq_{N_p}}{dv_D}\right|_{V_D} + \left.\frac{dq_{P_n}}{dv_D}\right|_{V_D}$$

$$\boxed{C_d = \frac{qA}{2V_{th}}\left((W_p - x_p)\,n_{po} + (W_n - x_n)\,p_{no}\right)e^{V_D/V_{th}}}$$

$N_a \gg N_d,$

$$C_d \approx \frac{qA}{2V_{th}}(W_n - x_n)\,p_{no}e^{V_D/V_{th}}$$

$$I_D \approx \left(\frac{qAD_p p_{no}}{W_n - x_n}\right)e^{V_D/V_{th}}$$

$$C_d \approx \frac{I_D}{V_{th}}\left[\frac{(W_n - x_n)^2}{2D_p}\right] \approx g_d\left[\frac{W_n^2}{2D_p}\right]$$

Diffusion capacitance is prop. to current

$$\tau_T = \frac{W_n^2}{2D_p}$$

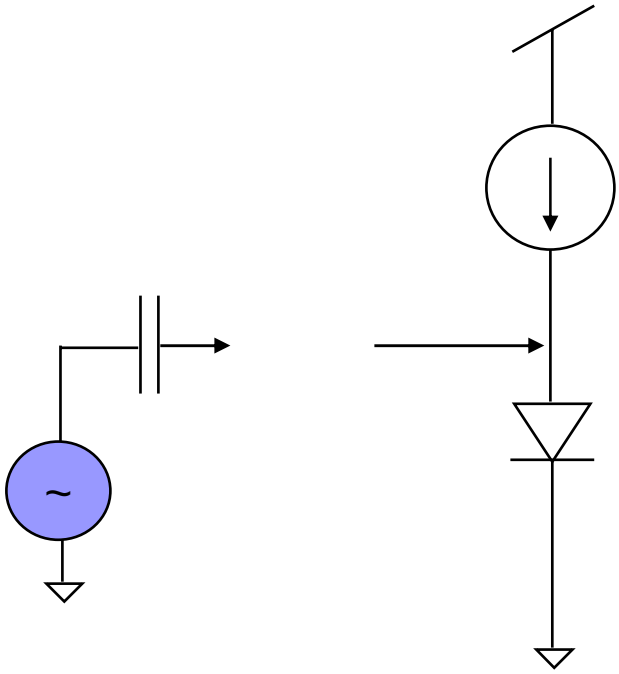
$$\tau_T = \frac{\text{distance}}{\text{average velocity}} = \frac{W_n}{(2D_p/W_n)}$$

$$\tau_T = \frac{C_d}{g_d} = \frac{C_d V_{th}}{I_D}$$

For diodes not one-sided

Example

- Io=1e-9
- I bias = 1mA
- τ = 40ns



Log(1e-3/1e-9)=13.8