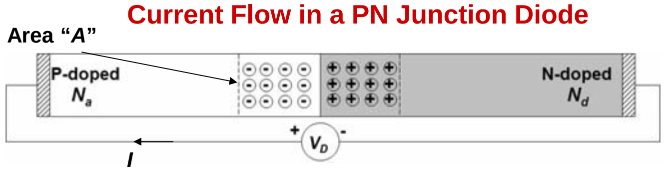
Lecture 7

Large and Small Signal Modelling of PN Junction Diodes

In this lecture you will learn:

- Circuit models of PN junction diodes
- Small signal models of PN junction diodes
- Junction resistance and capacitances
- Light emitting PN junction diodes (LEDs)

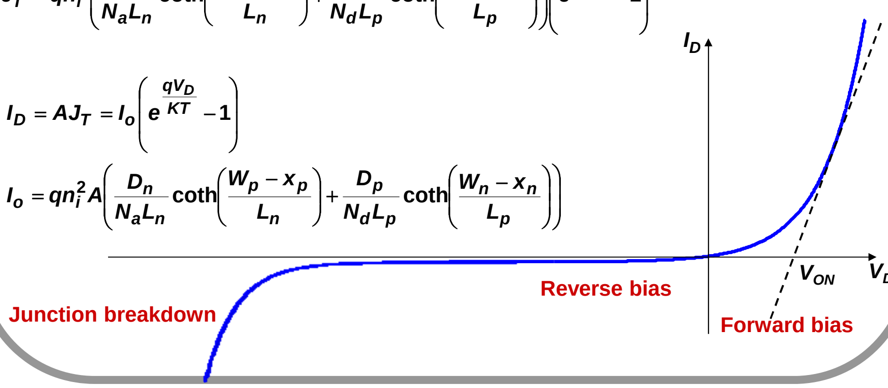
Current Flow in a PN Junction Diode



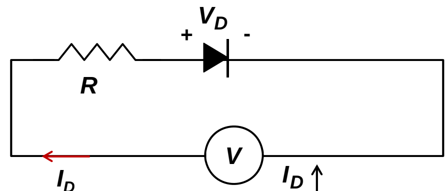
$$J_T = qn_i^2\left(\frac{D_n}{N_a L_n}\coth\left(\frac{W_p - x_p}{L_n}\right) + \frac{D_p}{N_d L_p}\coth\left(\frac{W_n - x_n}{L_p}\right)\right)\left(e^{\frac{qV_D}{KT}} - 1\right)$$

$$I_D = AJ_T = I_o\left(e^{\frac{qV_D}{KT}} - 1\right)$$

$$I_o = qn_i^2 A\left(\frac{D_n}{N_a L_n}\coth\left(\frac{W_p - x_p}{L_n}\right) + \frac{D_p}{N_d L_p}\coth\left(\frac{W_n - x_n}{L_p}\right)\right)$$



Simplest Circuit Model for a PN Junction Diode

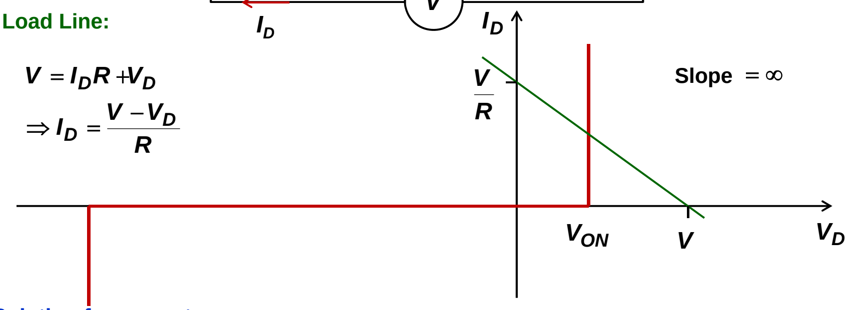


For most diodes:
$0.4 \le V_{ON} \le 0.8$

Load Line:

$V = I_D R + V_D$

$\Rightarrow I_D = \dfrac{V - V_D}{R}$



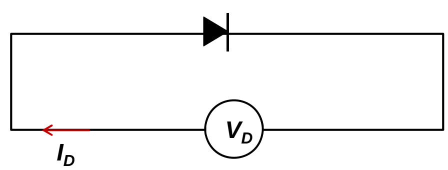
Slope $= \infty$

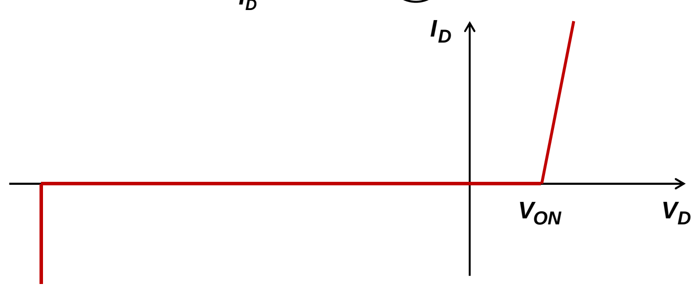
Solution for current:

If $V \le V_{ON}$:
$$\begin{cases} V_D = V \\ I_D \approx 0 \end{cases}$$

If $V > V_{ON}$:
$$\begin{cases} V_D = V_{ON} \\ I_D = \dfrac{V - V_{ON}}{R} \end{cases}$$

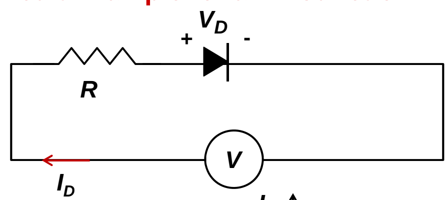
Better Circuit Model a PN Junction Diode





Slope
$$\frac{dI_D}{dV_D} = g_d$$

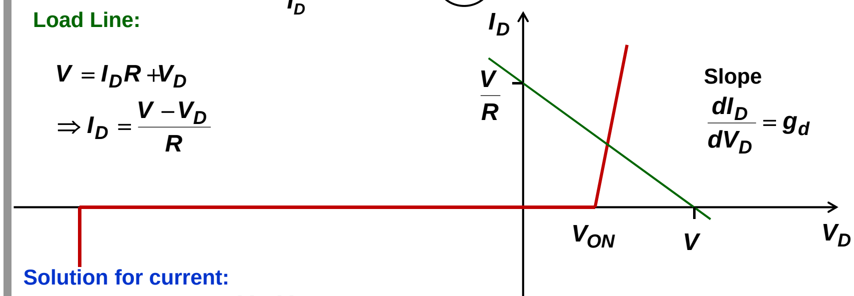
Circuit Example for a PN Junction Diode



Load Line:

$$V = I_D R + V_D$$

$$\Rightarrow I_D = \frac{V - V_D}{R}$$



Solution for current:

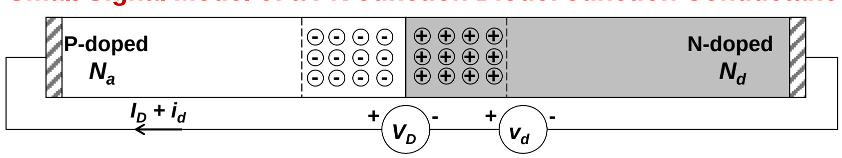
If $V \le V_{ON}$:

$$\begin{cases} V_D = V \\ I_D \approx 0 \end{cases}$$

If $V > V_{ON}$:

$$\begin{cases} V_D = \dfrac{V}{1 + g_d R} + V_{ON}\dfrac{g_d R}{1 + g_d R} \\ I_D = (V - V_{ON})\dfrac{g_d}{1 + g_d R} \end{cases}$$

Small Signal Model of a PN Junction Diode: Junction Conductance



$$I_D = I_o\left(e^{\frac{qV_D}{KT}} - 1\right)$$

$$\Rightarrow I_D + i_d = I_o\left(e^{\frac{q(V_D + v_d)}{KT}} - 1\right) \approx I_D + \frac{\partial I_D}{\partial V_D} v_d + \ldots\ldots\ldots = I_D + g_d v_d$$

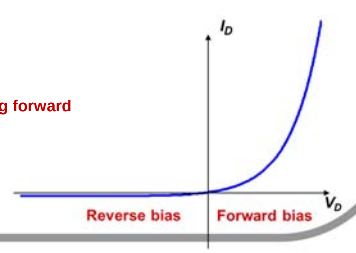
$$\Rightarrow i_d = g_d v_d$$

$$g_d = \frac{1}{r_d} = \frac{\partial I_D}{\partial V_D} = \frac{qI_o}{KT} e^{\frac{qV_D}{KT}} = \frac{q(I_D + I_o)}{KT} \approx \frac{qI_D}{KT}$$

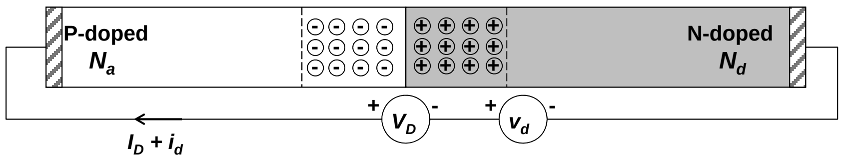
In strong forward bias

Differential resistance

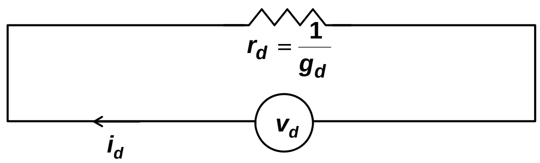
Differential conductance



Small Signal Model of a PN Junction Diode: Junction Conductance

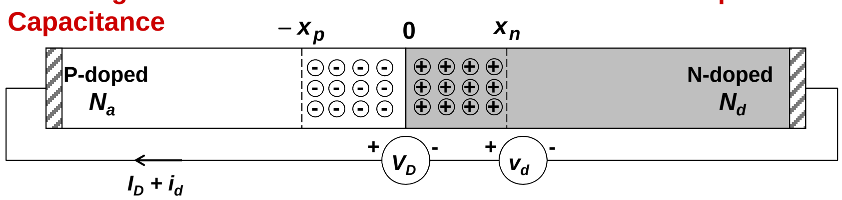


$$I_D + i_d \approx I_D + g_d v_d$$
$$\Rightarrow i_d \approx g_d v_d$$



Small signal circuit model of a PN diode

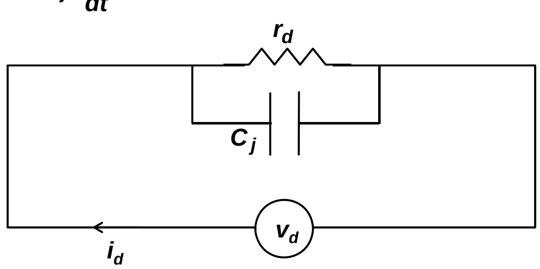
Small Signal Model of a PN Junction Diode: Junction Depletion Capacitance



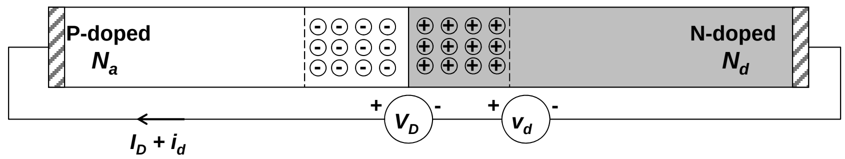
At high frequencies, part of the current i_d flows through the junction but part of it also charges up the junction capacitance

$$i_d \approx g_d v_d + C_j \frac{dv_d}{dt}$$

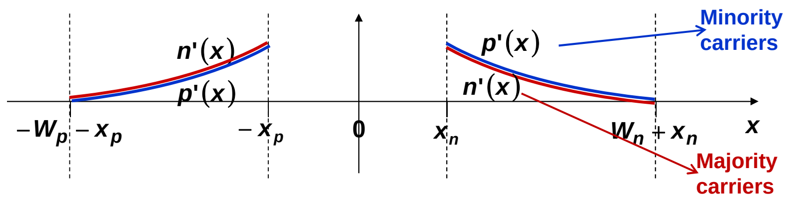
$$C_j = \frac{\varepsilon_s A}{(x_p + x_n)}$$



Small Signal Model of a PN Junction Diode: Diffusion Capacitance



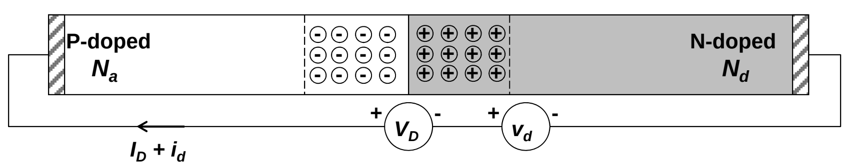
There is also charge stored in the quasi-neutral regions that changes as the junction voltage is varied (negative and positive charge stored at the same location!!)



Charge stored:

$$Q_d = qA\int_{x_n}^{W_n+x_n} p'(x)dx + qA\int_{-W_p-x_p}^{-x_p} p'(x)dx$$

Small Signal Model of a PN Junction Diode: Diffusion Capacitance



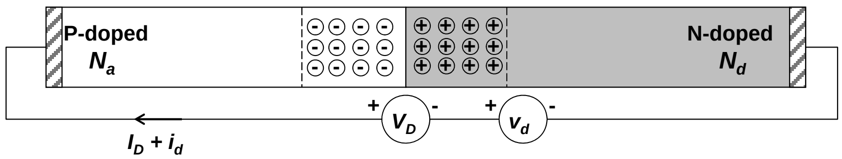
Charge stored: $Q_d = qA\int_{x_n}^{W_n+x_n} p'(x)dx + qA\int_{-W_p-x_p}^{-x_p} p'(x)dx$

Diffusion Capacitance: $C_d = \dfrac{\partial Q_d}{\partial V_D}$

$$C_d = \frac{q^2A}{KT} e^{\frac{qV_D}{KT}} \left[\frac{n_i^2}{N_a} L_n \frac{\cosh\left(\frac{W_p}{L_n}\right) - 1}{\sinh\left(\frac{W_p}{L_n}\right)} + \frac{n_i^2}{N_d} L_p \frac{\cosh\left(\frac{W_n}{L_p}\right) - 1}{\sinh\left(\frac{W_n}{L_p}\right)} \right]$$

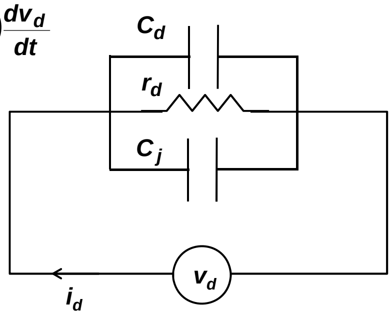
Increases exponentially with bias!

Small Signal Model of a PN Junction Diode: Total Capacitance



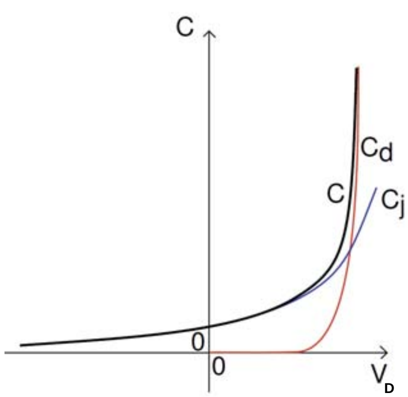
At high frequencies, part of the current i_d flows through the junction but part of it also charges up the junction capacitance and the diffusion capacitance

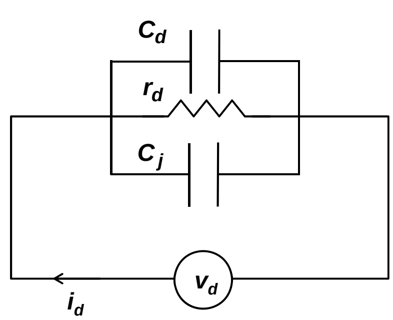
$$i_d \approx g_d v_d + (C_j + C_d)\frac{dv_d}{dt}$$



Capacitances of a PN Junction Diode

Total Capacitance: $C = C_j + C_d$

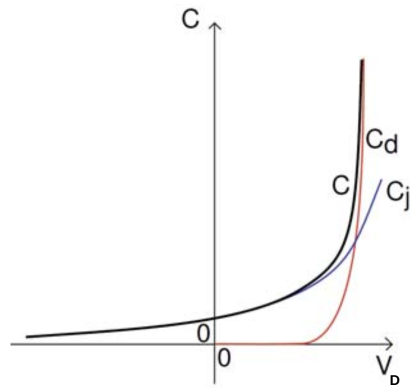


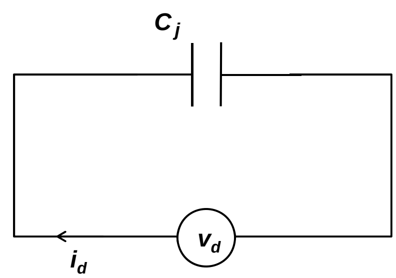


Small Signal Model of a PN Junction Diode in Revere Bias

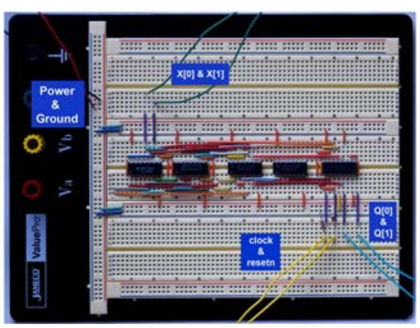
$$g_d = \frac{1}{r_d} = \frac{q(I_D + I_o)}{KT} \approx 0$$

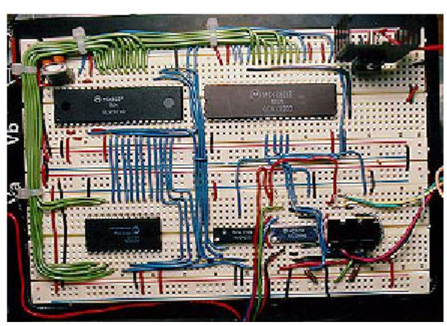
$$C_d \approx 0$$





Breadboard Wiring: Good Wiring





Breadboard Wiring: Bad Wiring