Diodes

Last updated 1/10/24

Ideal Diode Equation

$$I_D = I_S\left[e^{\left(\frac{qV_A}{nkT}\right)} - 1\right] = I_S\left[e^{\left(\frac{V_A}{nV_T}\right)} - 1\right]$$

$$I_S = qA\left[\frac{D_N}{L_N}n_{p0} + \frac{D_P}{L_P}p_{n0}\right]$$

Proportional to Area (A)
Inversely proportional to Doping (n_{po}, p_{no})
Typically, 10^{-12}A – 10^{-18}A

n

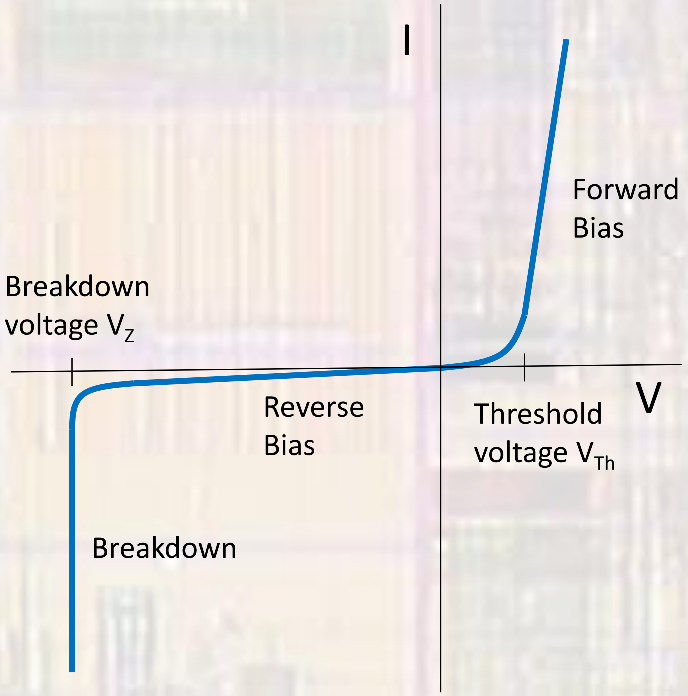
Accounts for non-idealities
Typically, between 1 and 2

$$V_T = \frac{q}{kT}$$

$V_T \cong 26mV$ @ RT

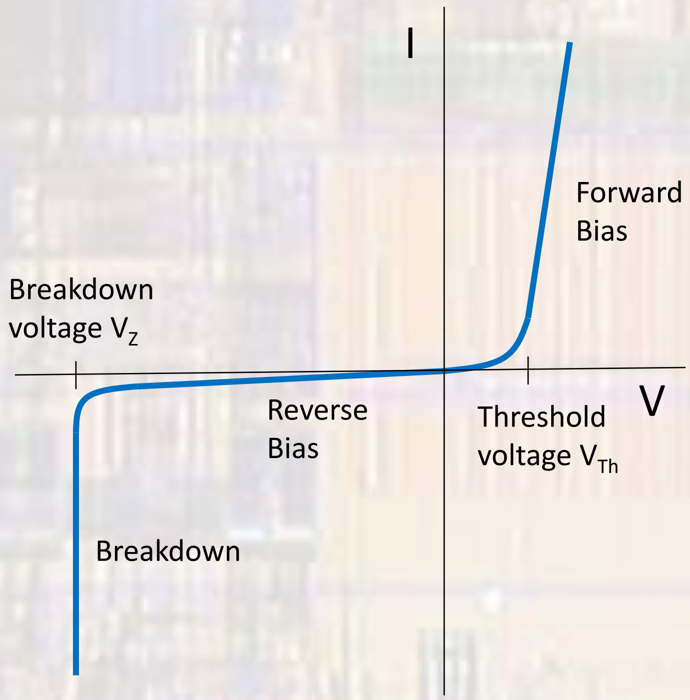
Diode Models

- Real diode behavior



Diode Models

- Real diode behavior

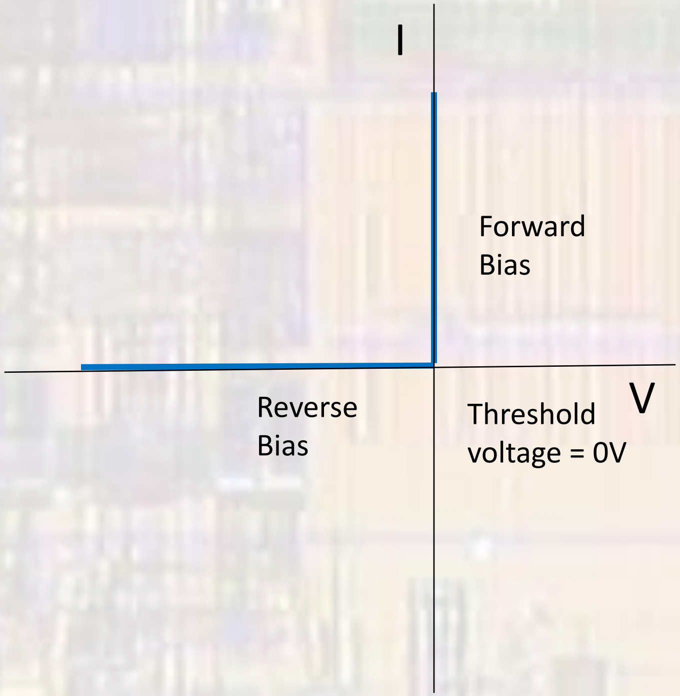


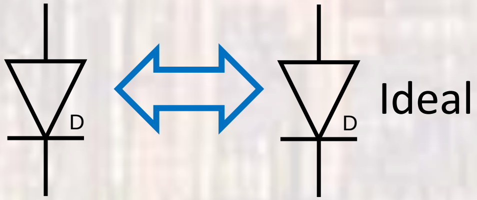
$V_D > V_Z$

$$I_D = I_S\left(e^{\frac{V_D}{nV_T}} - 1\right)$$

Diode Models

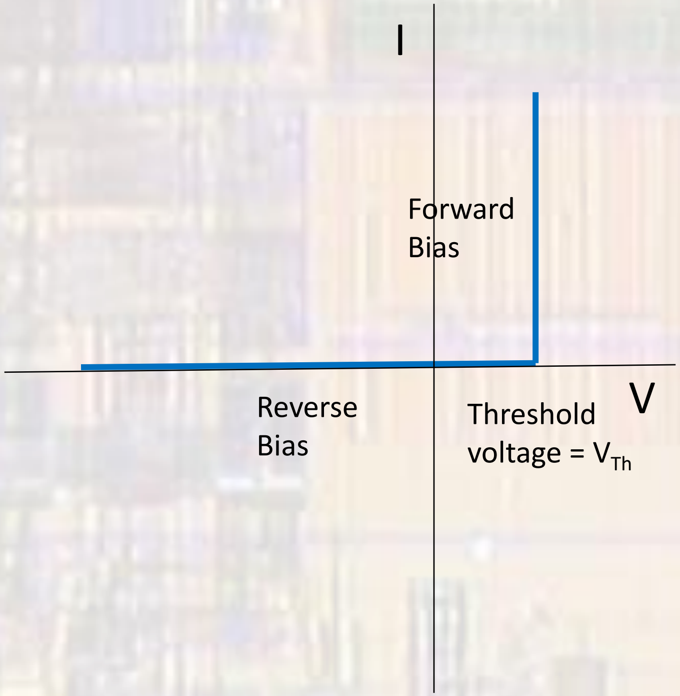
- Ideal diode models
  - Switch model

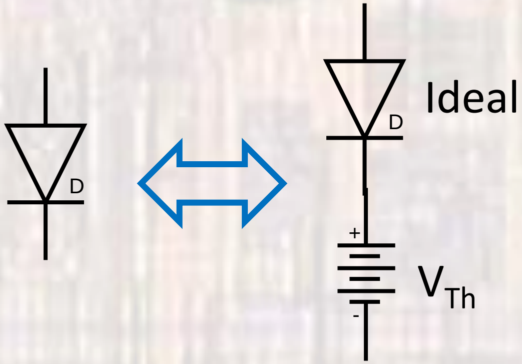




Diode Models

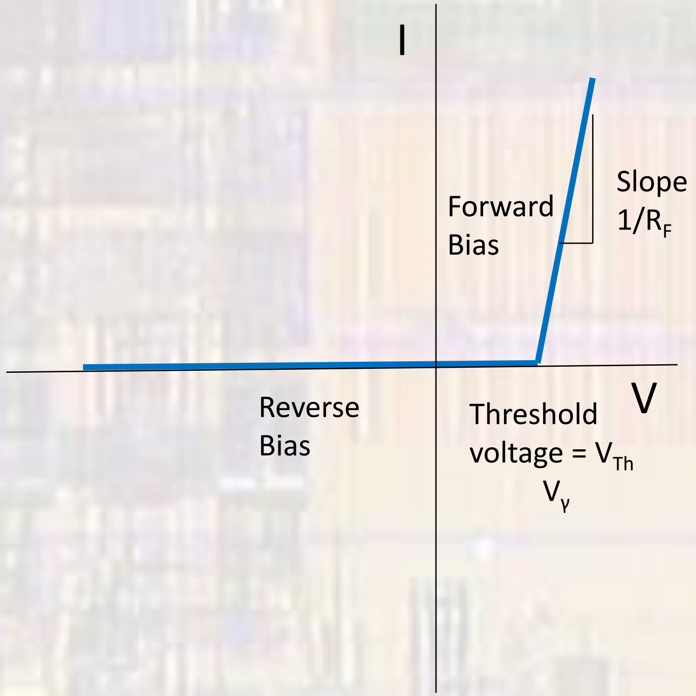
- Ideal diode models
  - Switch model with Turn-on voltage

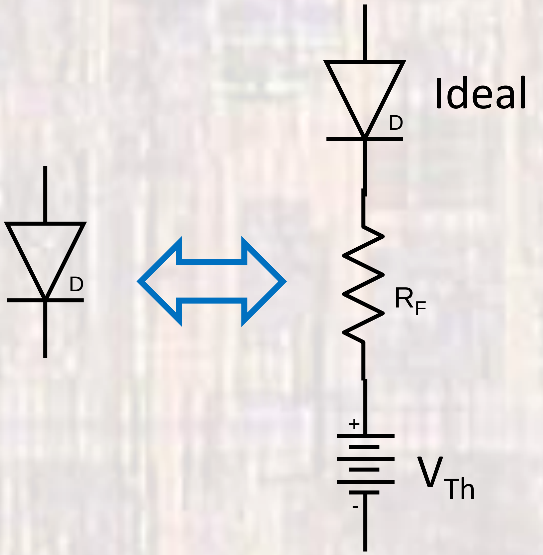




Diode Models

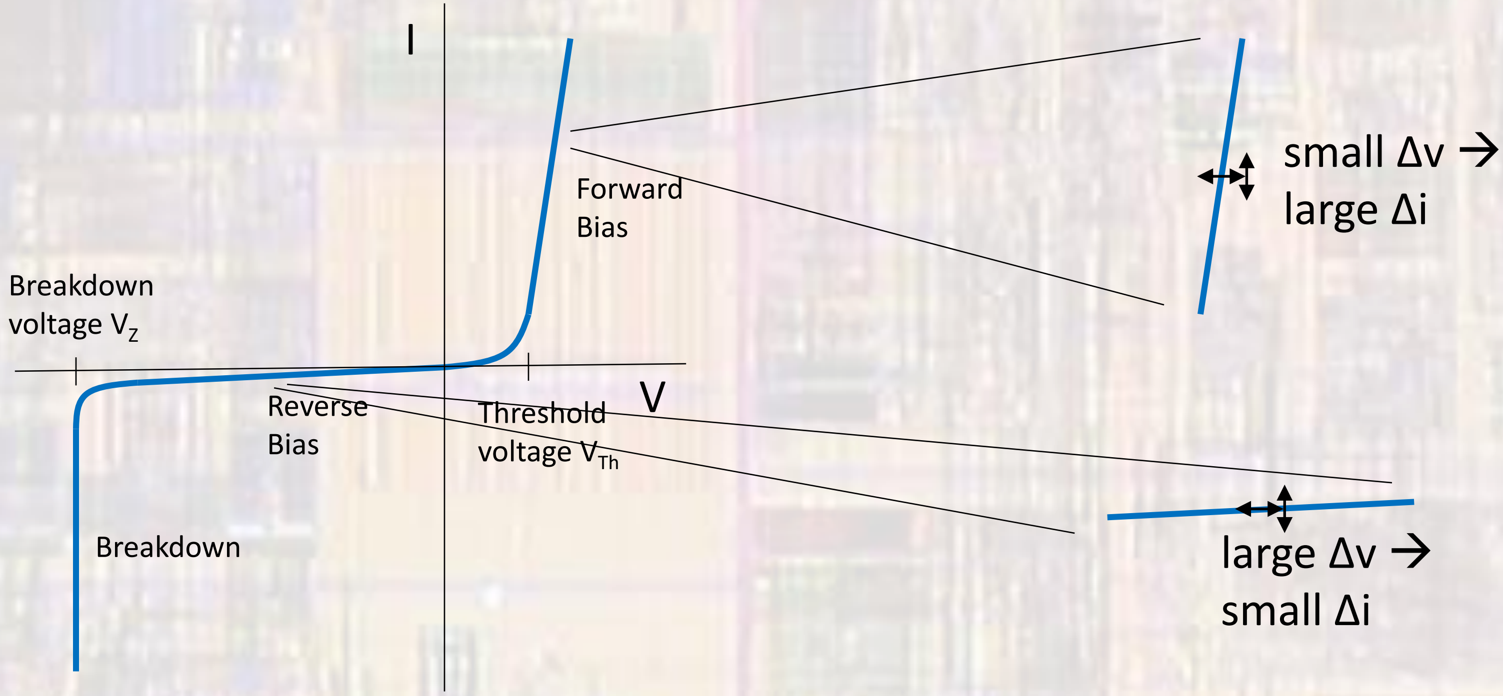
- Ideal diode models
  - Piecewise Linear model





Diode Models

- Small Signal Model
  - Consider the I-V characteristics constant

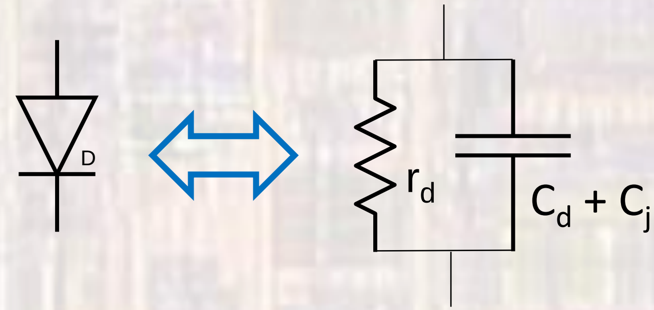


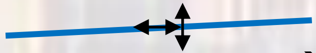
Diode Models

- Small Signal Model

small Δv → large Δi

I_D – DC current
V_D – DC voltage
i_d – small signal current
v_d – small signal voltage





large Δv → small Δi

$$i_d = \left(\frac{I_D}{V_T}\right) v_d = \left(\frac{1}{r_d}\right) v_d$$

$$r_d = \left(\frac{V_T}{I_D}\right)$$

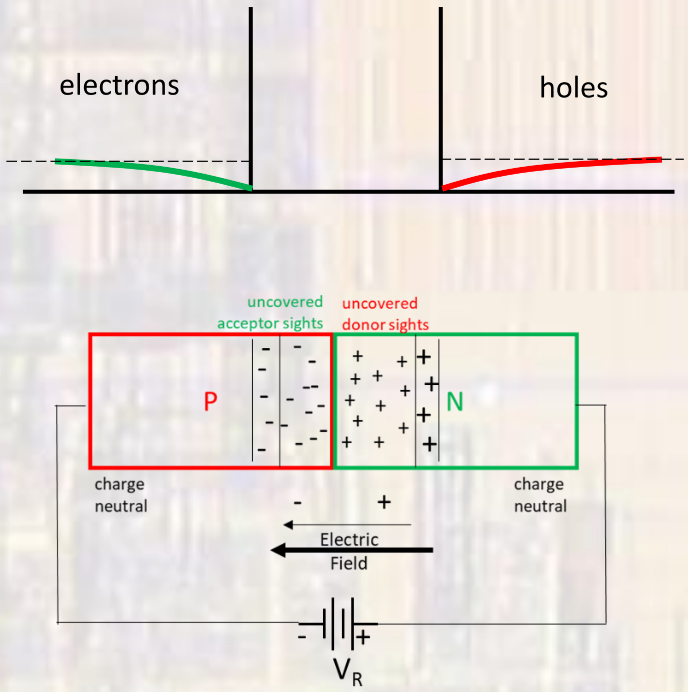
C_j – Junction Capacitance
C_d – Diffusion Capacitance

C_j – dominant in reverse bias
C_d – dominant in forward bias

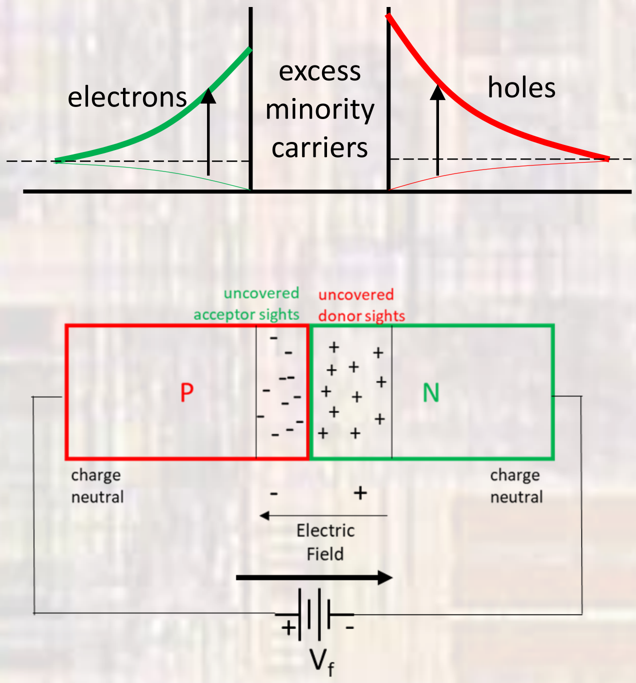
Diode Switching

- In forward bias, carriers are traversing the depletion region and create an excess of minority carriers in the N and P regions

Reverse Bias

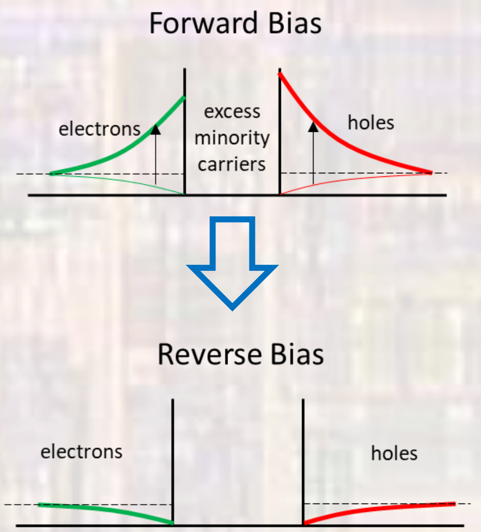


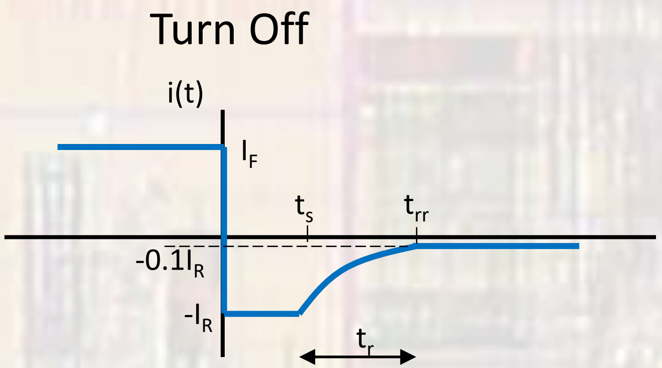
Forward Bias



Diode Switching

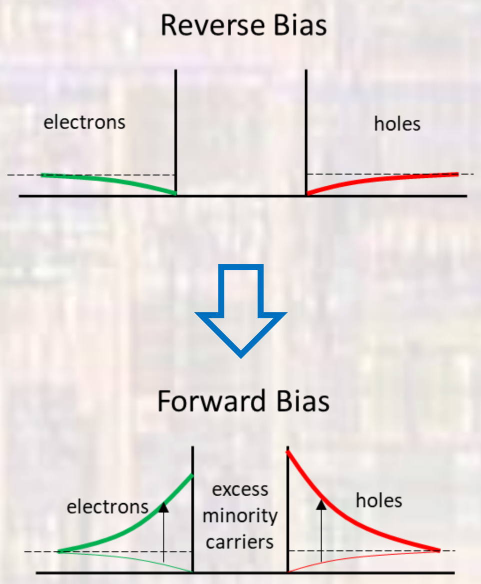
- Switching from forward bias to reverse bias
  - Excess minority carriers must be removed
  - → reverse (negative) current flow
    - Amplitude is a function of V_F and minority carrier lifetimes
    - Storage Time – t_s
      - Time for concentrations to reach their 0V bias level
    - Recovery Time – t_r
      - Time for concentrations to reach their reverse bias level
    - Reverse Recovery Time – t_{rr}
      - Sum of t_s and t_r



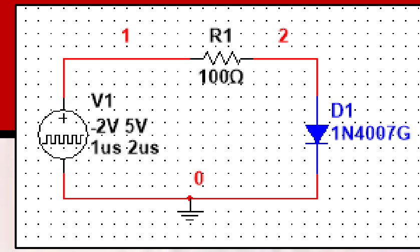


Diode Switching

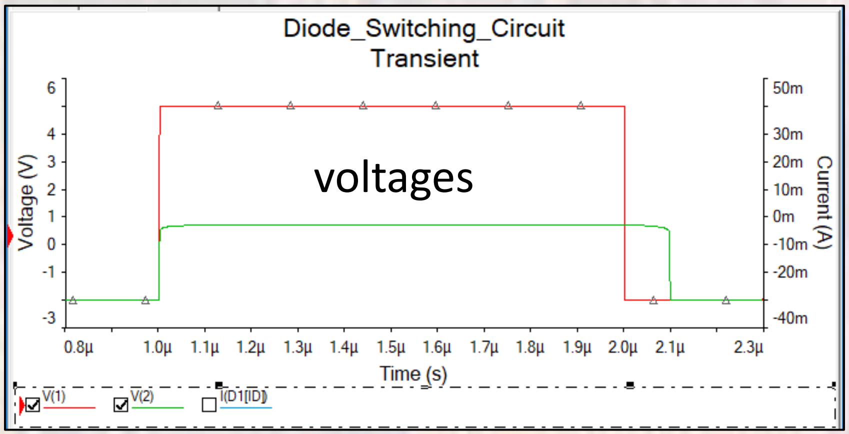
- Switching from reverse bias to forward bias
  - No excess minority carriers to be removed
  - → No storage time
    - Fast transitions

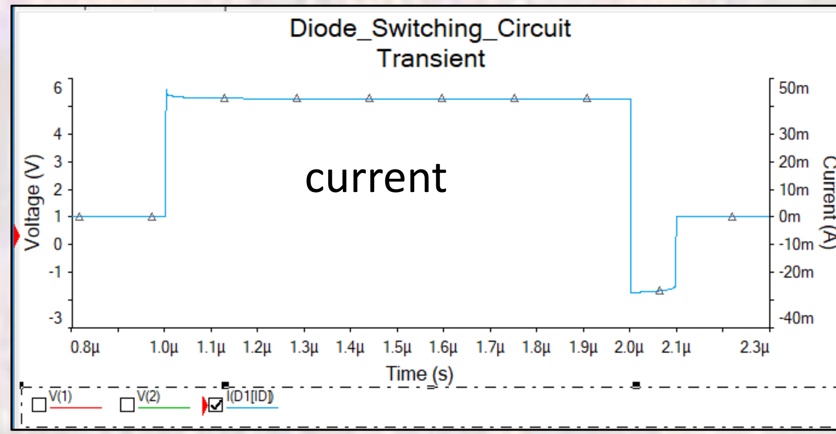


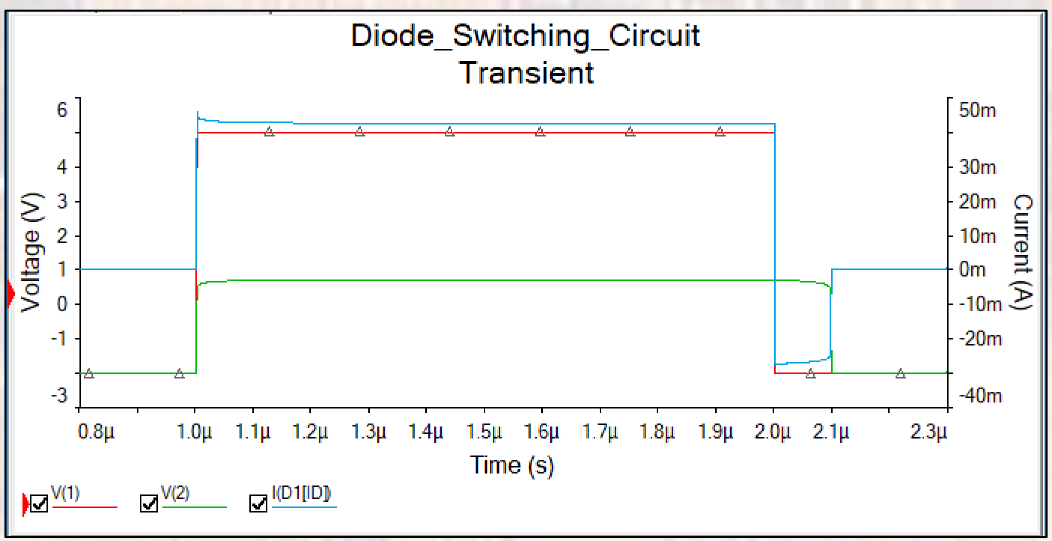
Diode Switching



- Simulation Example – 5V

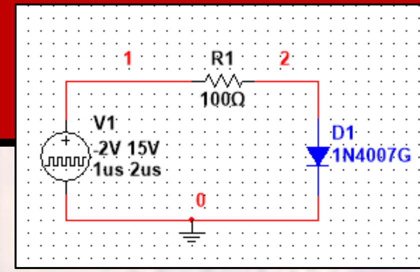




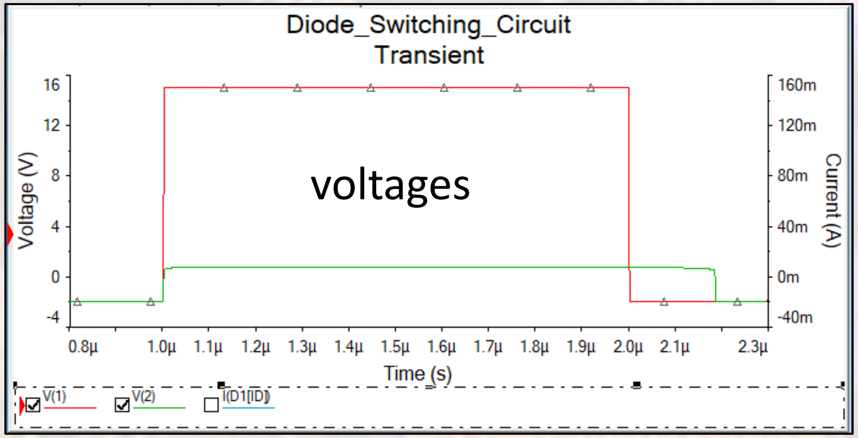


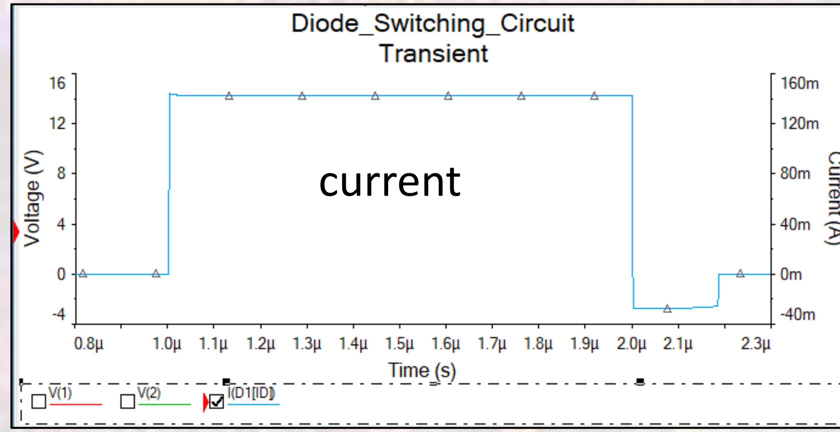
t_{rr} = 100ns

Diode Switching

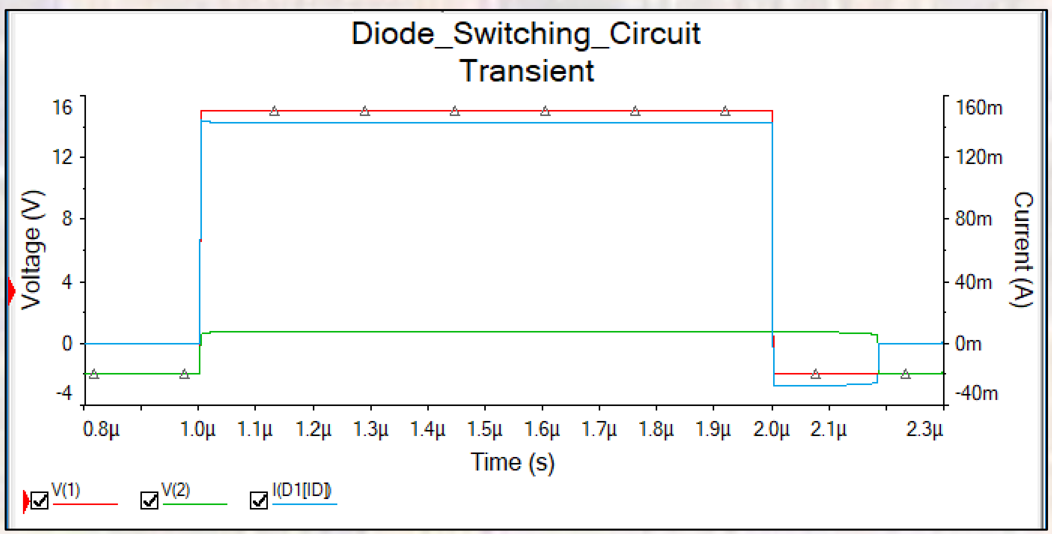


- Simulation Example – 15V



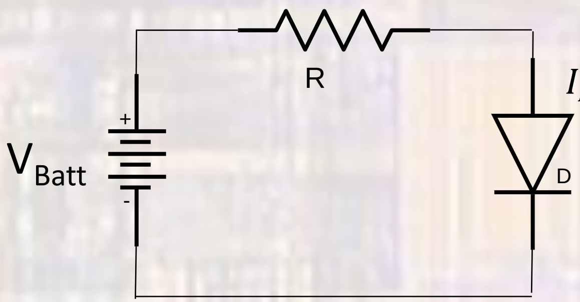


t_{rr} = 200ns



Diode Circuit Analysis

- "Exact" Solution
  - Transcendental Equation
    - You have the tools to solve this



$$I_D = I_S\left(e^{\frac{V_D}{nV_T}} - 1\right)$$

$$V_{Batt} = I_D R + V_D$$

$$V_{Batt} = I_S\left(e^{\frac{V_D}{nV_T}} - 1\right) R + V_D$$

I_S = 5.3e-15, n = 1, V_{batt} = 3.3V, R = 1KΩ
V_D = 0.6999V, I_D = 2.601mA

Diode Circuit Analysis

- Ideal Solution
  - $V_D = V_{Th} = 0V$

$$V_{Batt} = I_D R + V_D$$

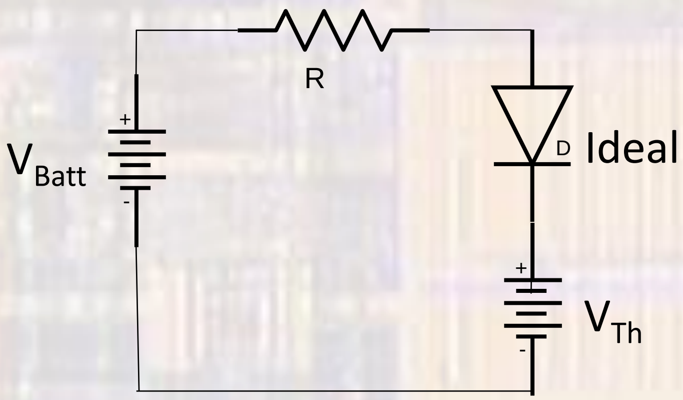
$$V_{Batt} = I_D R$$

$$I_D = V_{Batt}/R$$

V_{batt} = 3.3V, R = 1KΩ, ~~V_{TH} = 0.7V~~, ~~R_F = 5Ω~~
I_D = 3.3mA

Diode Circuit Analysis

- Ideal Solution (with V_{Th})
  - $V_D = V_{Th} = 0.7V$



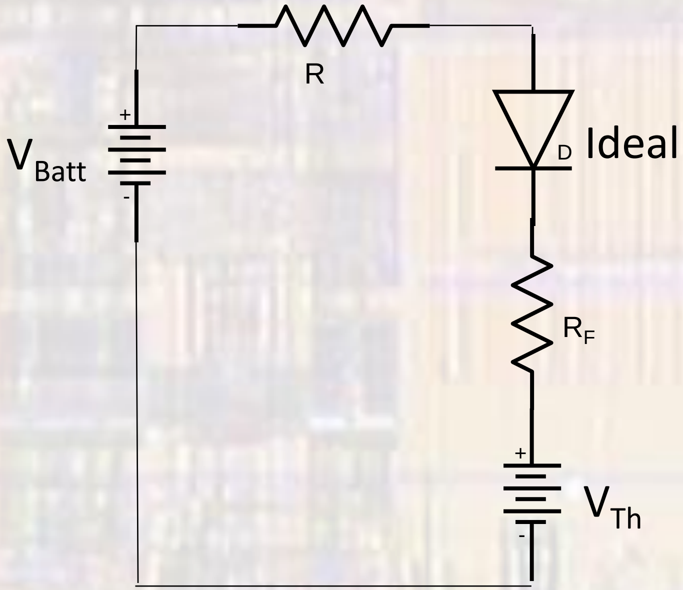
$$V_{Batt} = I_D R + V_{Th}$$

$$I_D = (V_{Batt} - V_{Th})/R$$

$V_{batt} = 3.3V$, $R = 1K\Omega$, $V_{TH} = 0.7V$, ~~$R_F = 5\Omega$~~
$I_D = 2.60mA$

Diode Circuit Analysis

- Piecewise Linear Solution
  - $V_{Th} = V_{\gamma} = 0.7V$
  - $R_F = 5\Omega$



$$V_{Batt} = I_D R + I_D R_F + V_{Th}$$

$$I_D = (V_{Batt} - V_{Th})/(R + R_F)$$

$V_{batt} = 3.3V$, $R = 1K\Omega$, $V_{TH} = 0.7V$, $R_F = 5\Omega$
$I_D = 2.587mA$

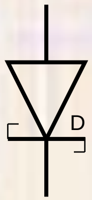
Diode Circuit Analysis

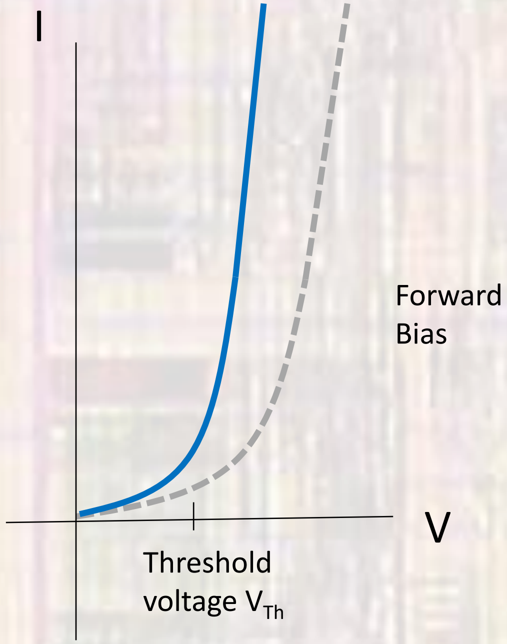
- Comparison

Exact	Simulate instead	$V_{Batt} = I_S\left(e^{\frac{V_D}{nV_T}} - 1\right)R + V_D$ I_S = 5.3e-15, n = 1, V_{batt} = 3.3V, R = 1KΩ V_D = 0.6999V, I_D = 2.601mA
Ideal	Only acceptable for determining functionality	$V_{Batt} = I_D R$ V_{batt} = 3.3V, R = 1KΩ, ~~V_{TH} = 0.7V~~, ~~R_F = 5Ω~~ I_D = 3.3mA
Ideal w/V_{Th}	The best choice for almost all situations	$V_{Batt} = I_D R + V_{Th}$ V_{batt} = 3.3V, R = 1KΩ, V_{TH} = 0.7V, ~~R_F = 5Ω~~ I_D = 2.60mA
Piecewise linear		$V_{Batt} = I_D R + I_D R_F + V_{Th}$ V_{batt} = 3.3V, R = 1KΩ, V_{TH} = 0.7V, R_F = 5Ω I_D = 2.587mA

Other Diodes

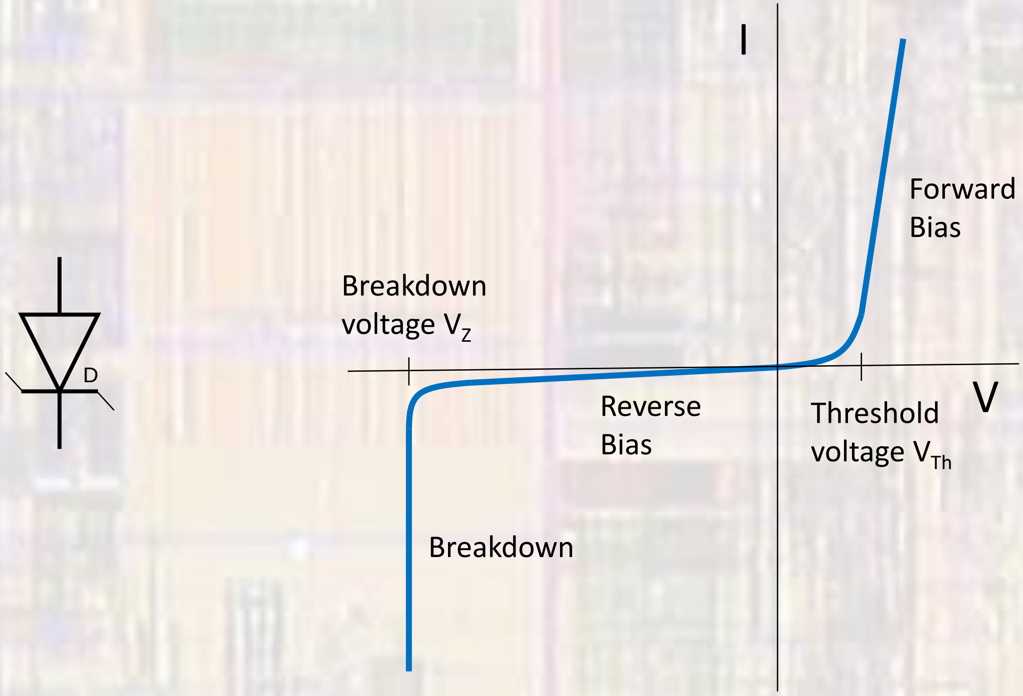
- Schottky Barrier Diode
  - Metal – Semiconductor junction
  - Lower turn on voltage (0.2V to 0.3V)





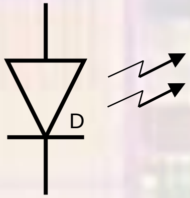
Other Diodes

- Zener Diode
  - Well managed breakdown voltage



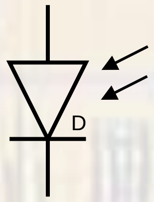
Other Diodes

- Light Emitting Diode
  - Direct bandgap semiconductor
  - When holes and electrons recombine in the bulk region photons are emitted
  - Typically higher turn on voltages (1.2V – 1.8V)



Other Diodes

- Photo Diode
  - P-I-N Diode
  - I is an intrinsic layer
  - Light applied to the intrinsic layer creates hole-electron pairs
  - These holes and electrons are swept away due to the electric field → current



Solar Cell