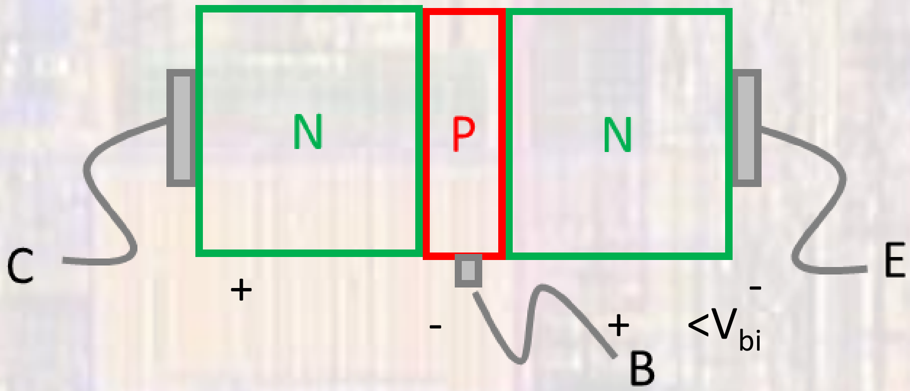
Bipolar Transistors

Last updated 1/10/24

BJT Cutoff

- Cutoff - NPN
  - B-E junction < V_{bi}, C-B junction reverse biased



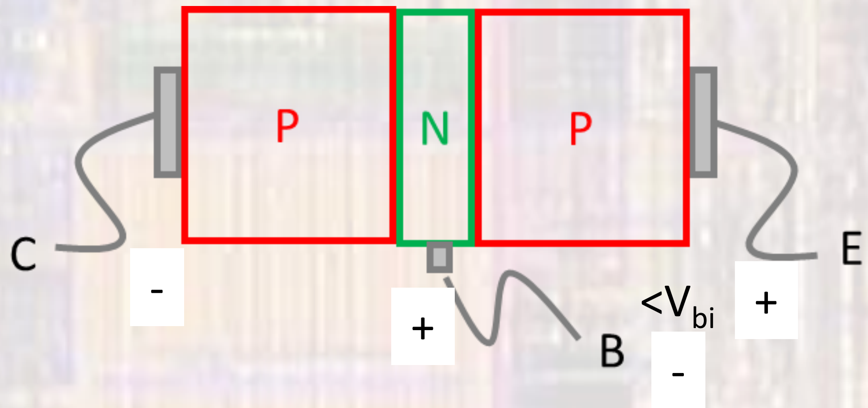
  - Both diodes are 'off'
  - No current flow

$$I_C = I_E = I_S \left[e^{\left(\frac{V_{BE}}{nV_T}\right)}\right] = I_S$$

$$I_B = 0$$

BJT Cutoff

- Cutoff - PNP
  - E-B junction < V_{bi}, C-B junction reverse biased



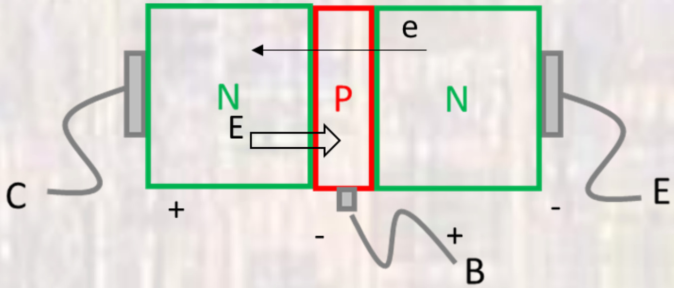
  - Both diodes are 'off'
  - No current flow

$$I_C = I_E = I_S\left[e^{\left(\frac{V_{EB}}{nV_T}\right)}\right] = I_S$$

$$I_B = 0$$

BJT Forward Active

- Forward Active Mode - NPN
  - B-E junction forward biased, C-B junction reverse biased
  - Collector Current
    - By convention we reference all the the currents to the collector



$$I_C = I_S\left[e^{\left(\frac{V_{BE}}{nV_T}\right)}\right]$$

for V_{BE} > few V_T , n and I_S device dependent

$$I_B = \frac{I_C}{\beta} = \frac{1}{\beta} I_S\left[e^{\left(\frac{V_{BE}}{nV_T}\right)}\right]$$

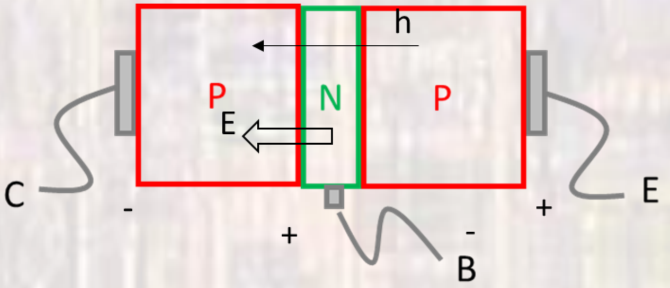
$$I_E = \frac{1}{\alpha} I_C = \frac{1}{\alpha} I_S\left[e^{\left(\frac{V_{BE}}{nV_T}\right)}\right]$$

$$I_C = \beta I_B$$

$$I_E = I_C + I_B$$

BJT Forward Active

- Forward Active Mode - PNP
  - B-E junction forward biased, C-B junction reverse biased
  - Collector Current
    - By convention we reference all the the currents to the collector



$$I_C = I_S\left[e^{\left(\frac{V_{EB}}{nV_T}\right)}\right]$$

for V_{BE} > few V_T, n and I_S device dependent

$$I_B = \frac{I_C}{\beta} = \frac{1}{\beta}I_S\left[e^{\left(\frac{V_{EB}}{nV_T}\right)}\right]$$

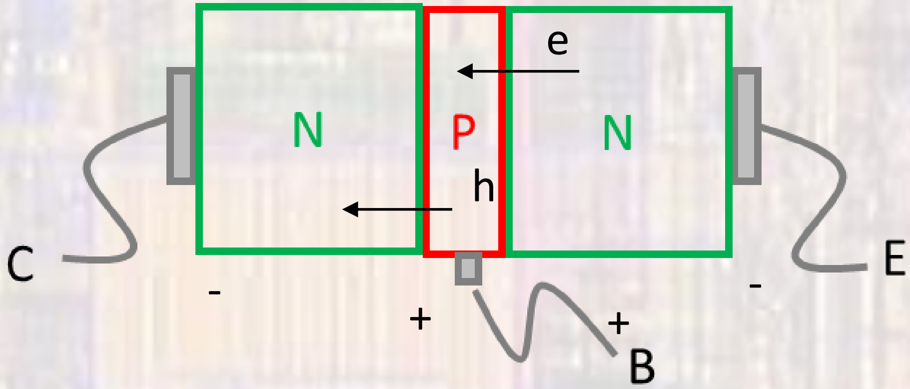
$$I_E = \frac{1}{\alpha}I_C = \frac{1}{\alpha}I_S\left[e^{\left(\frac{V_{EB}}{nV_T}\right)}\right]$$

$$I_C = \beta I_B$$

$$I_E = I_C + I_B$$

BJT Saturation

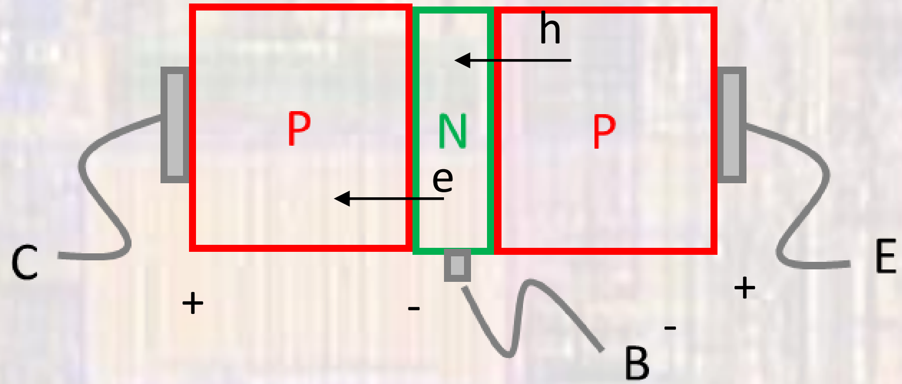
- Saturation - NPN
  - B-E junction forward biased, C-B junction forward biased



- Due to the relative doping concentrations $D_E > D_B > D_C$, Both diodes forward biased leads to
  - Electron diffusion dominant in the B-E junction
  - Hole diffusion dominant in the B-C junction
    - but smaller than B-E electron diffusion
  - Net C-E current, linearly dependent on the C-E voltage

BJT Saturation

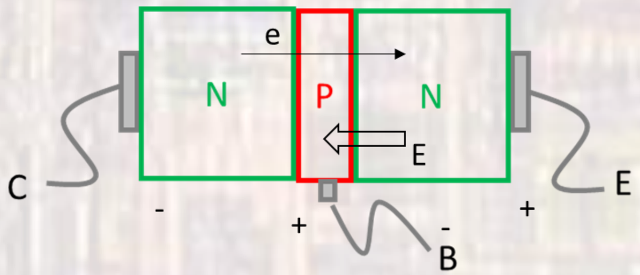
- Saturation - PNP
  - B-E junction forward biased, C-B junction forward biased



- Due to the relative doping concentrations $D_E > D_B > D_C$, Both diodes forward biased leads to
  - Hole diffusion dominant in the E-B junction
  - Electron diffusion dominant in the C-B junction
    - but smaller than E-B electron diffusion
  - Net E-C current, linearly dependent on the C-E voltage

BJT Reverse Active

- Reverse Active Mode - NPN
  - B-E junction reverse biased, C-B junction forward biased
  - The Emitter acts as the Collector and the Collector acts as the Emitter
  - Emitter Current
    - By convention we reference all the the currents to the emitter



$$I_E = I_S\left[e^{\left(\frac{V_{BC}}{nV_T}\right)}\right]$$

for V_{BE} > few V_T, n and I_S device dependent

$$I_B = \frac{I_E}{\beta} = \frac{1}{\beta} I_S\left[e^{\left(\frac{V_{BC}}{nV_T}\right)}\right]$$

β_R is much smaller than β_F
due to the relative doping of C and E

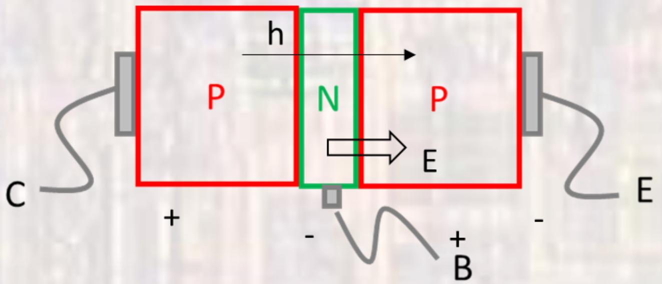
$$I_C = \frac{1}{\alpha} I_E = \frac{1}{\alpha} I_S\left[e^{\left(\frac{V_{BC}}{nV_T}\right)}\right]$$

$$I_E = \beta I_B$$

$$I_C = I_E + I_B$$

BJT Forward Active

- Forward Active Mode - PNP
  - B-E junction reverse biased, C-B junction forward biased
  - The Emitter acts as the Collector and the Collector acts as the Emitter
  - Emitter Current
    - By convention we reference all the the currents to the emitter



$$I_E = I_S \left[e^{\left(\frac{V_{CB}}{nV_T}\right)} \right]$$

for V_{BE} > few V_T, n and I_S device dependent

$$I_B = \frac{I_E}{\beta} = \frac{1}{\beta} I_S \left[e^{\left(\frac{V_{CB}}{nV_T}\right)} \right]$$

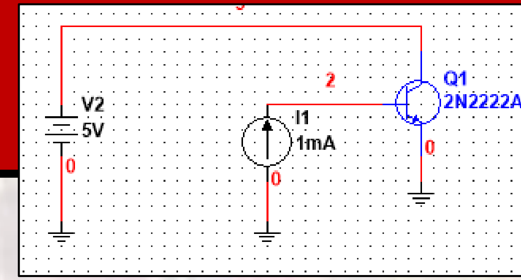
β_R is much smaller than β_F due to the relative doping of C and E

$$I_C = \frac{1}{\alpha} I_E = \frac{1}{\alpha} I_S \left[e^{\left(\frac{V_{CB}}{nV_T}\right)} \right]$$

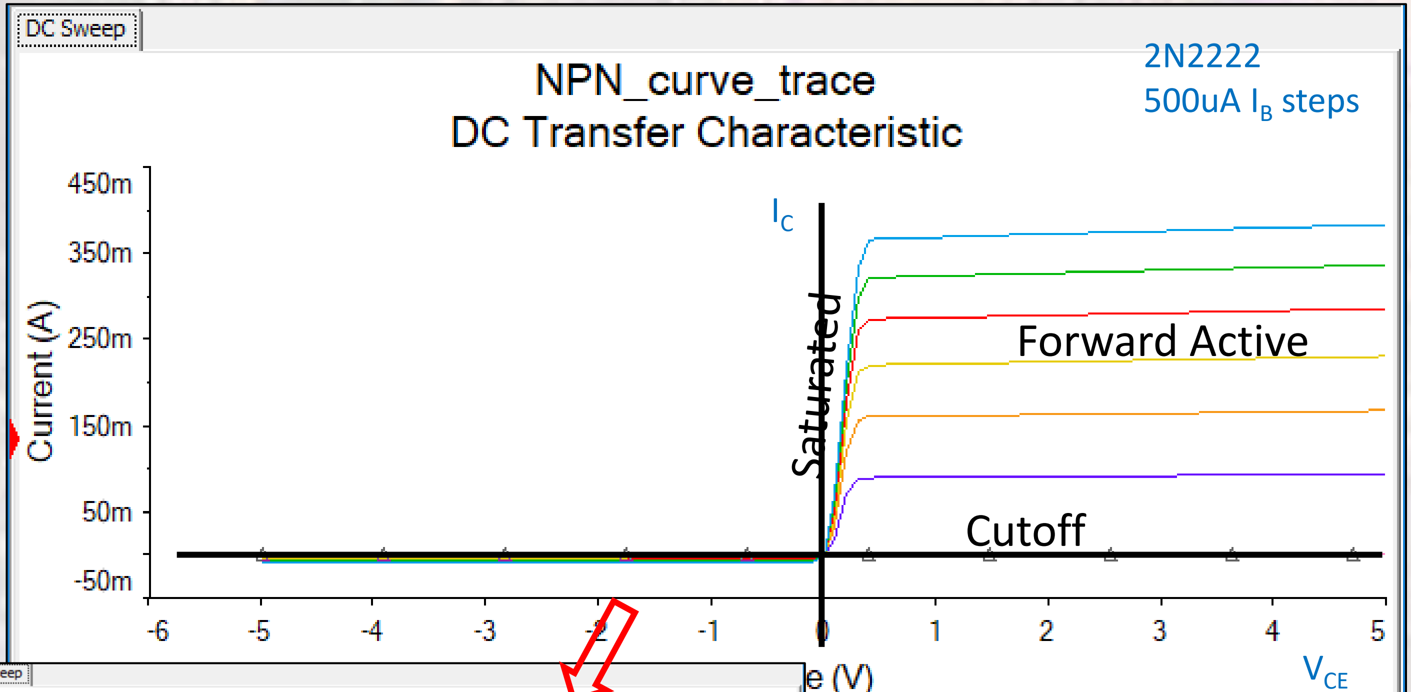
$$I_E = \beta I_B$$

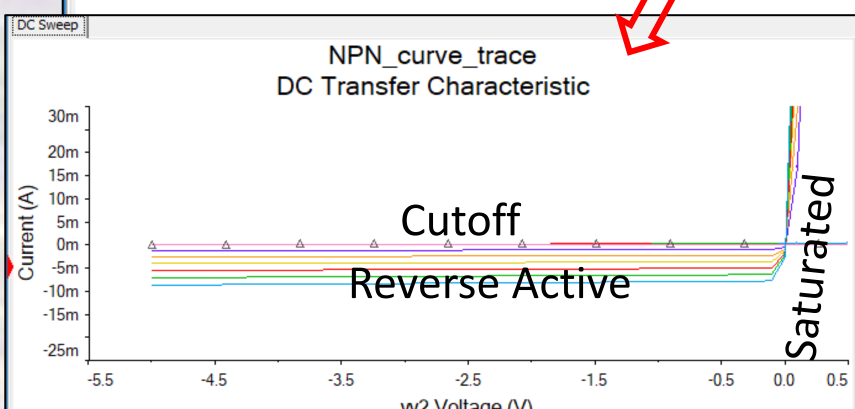
$$I_C = I_E + I_B$$

BJT IV Characteristics



- NPN – 4 regions of operation





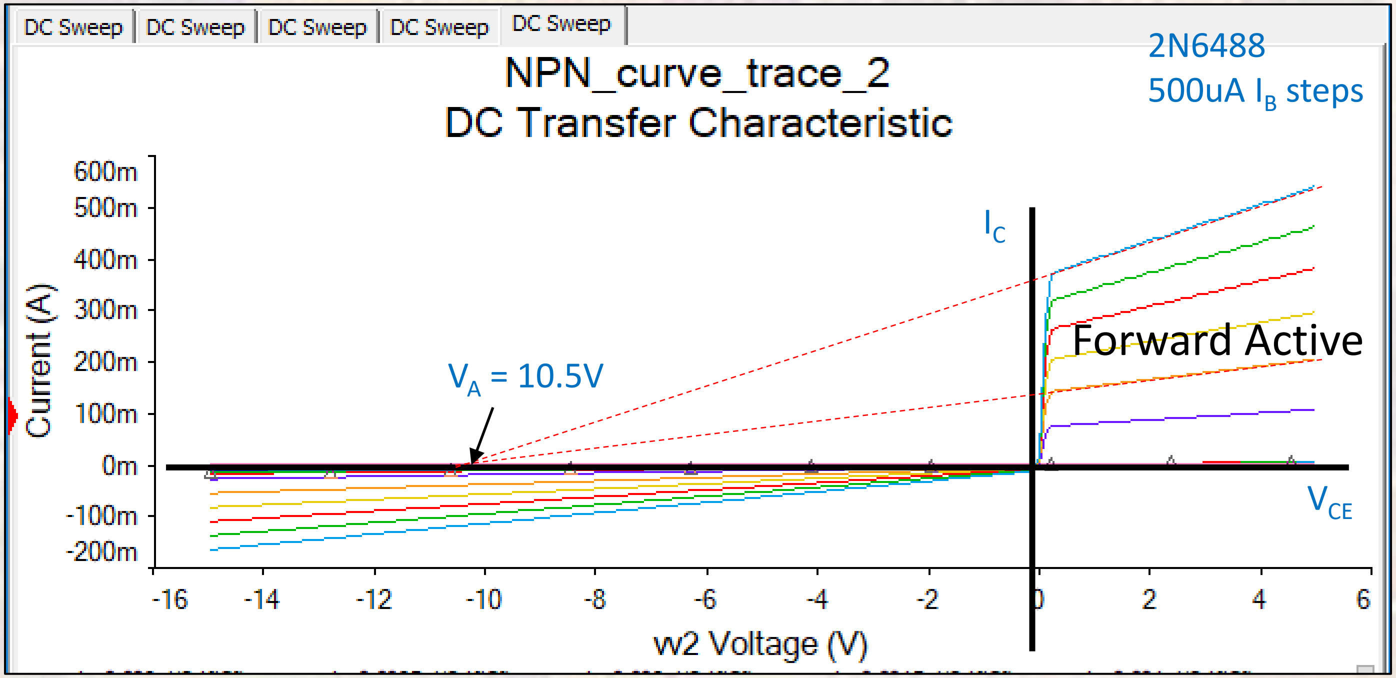
$$I_C = \beta I_B$$

Note: not exact, small slope to the I_C vs V_{CE} curve

Note: not constant for large I_C

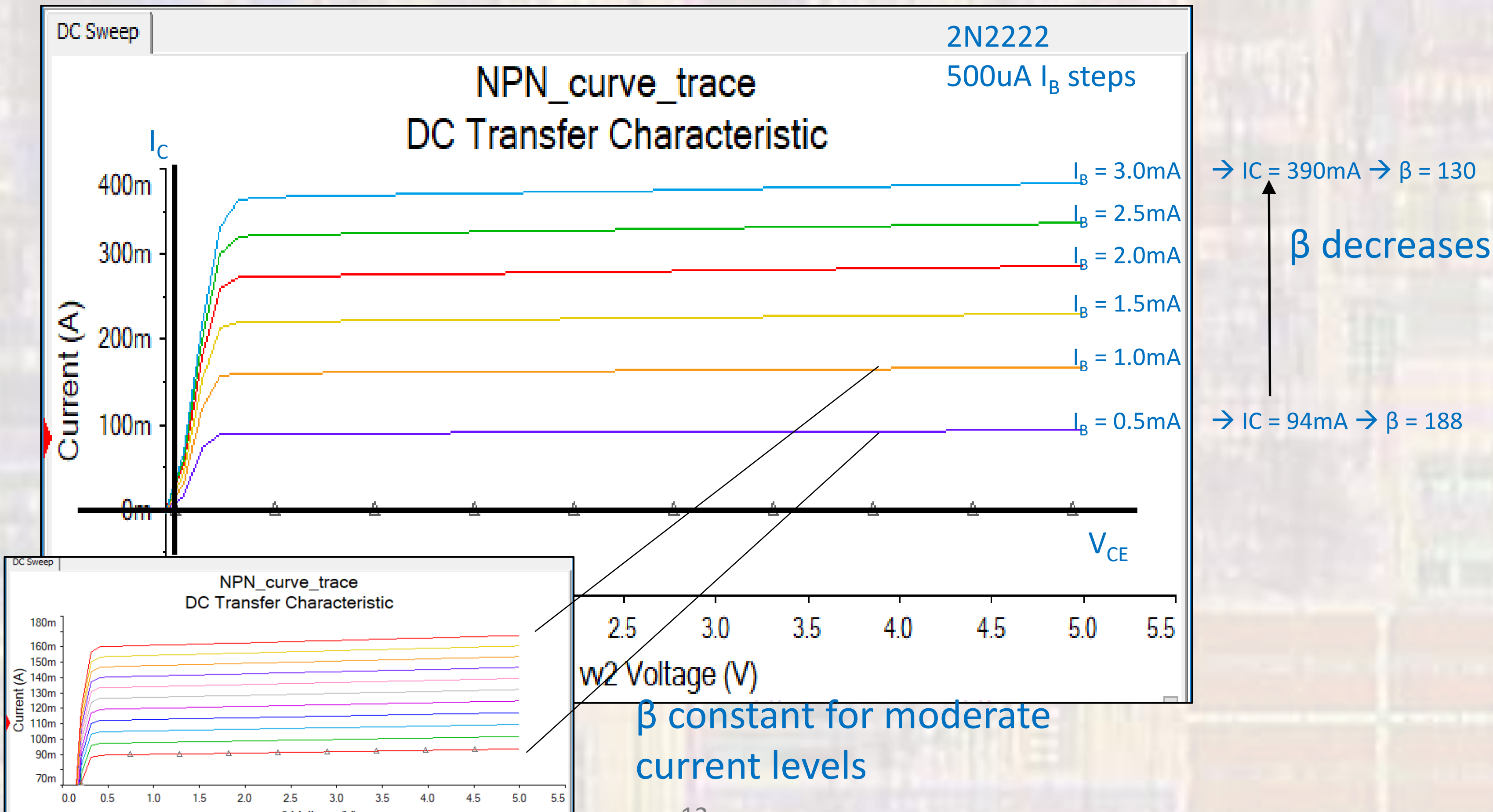
BJT IV Characteristics

- NPN – Early Voltage
  - Increasing V_{CE} → wider depletion region and greater electric field
  - → increasing I_C
  - The curves converge on the Early Voltage, $-V_A$



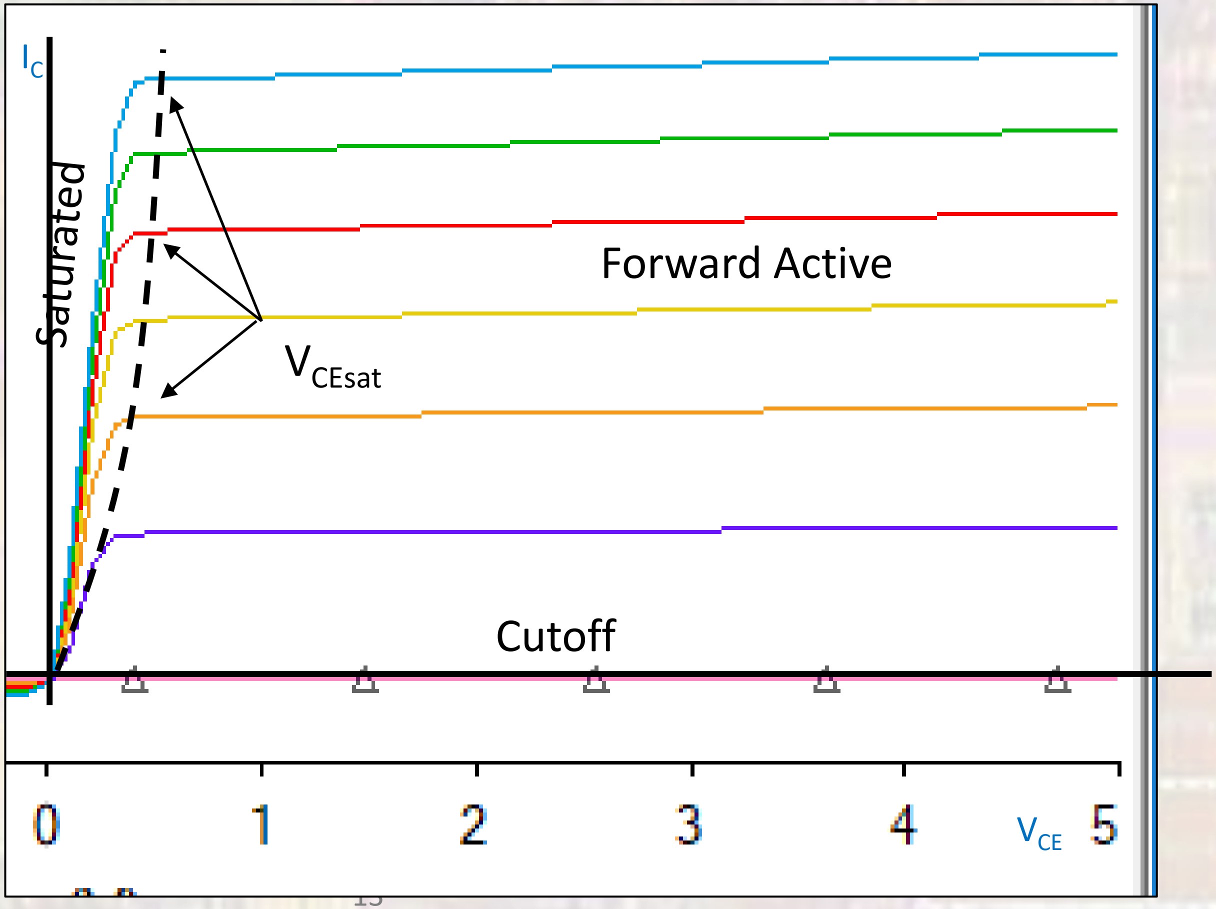
BJT IV Characteristics

- NPN – Beta variation
  - Excess carriers in the base cause ↑ base current → ↓β



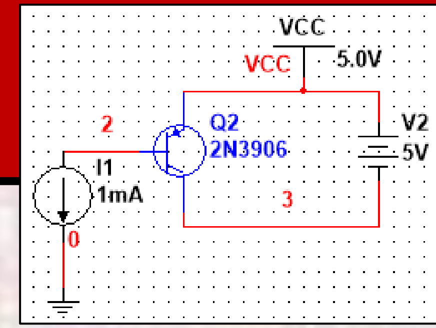
BJT IV Characteristics

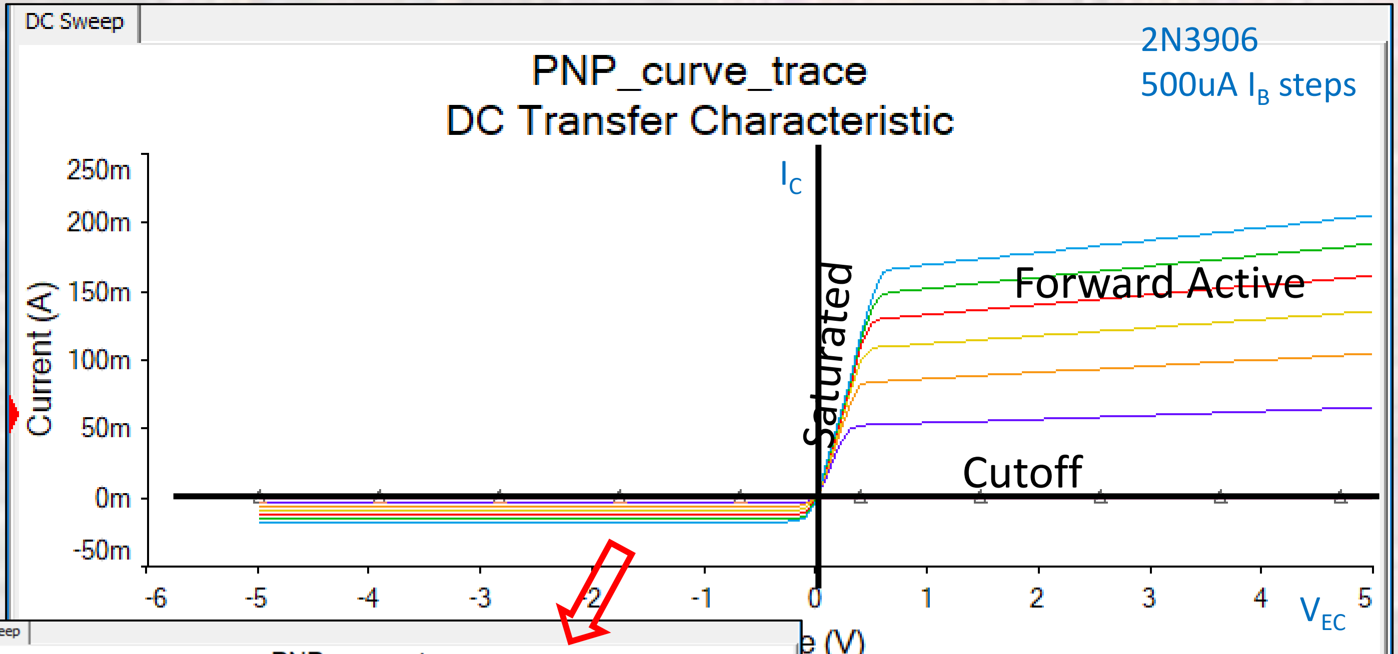
- NPN - V_{CEsat}
  - Saturation voltage
  - Lowest the collector will “pull down” while still providing current

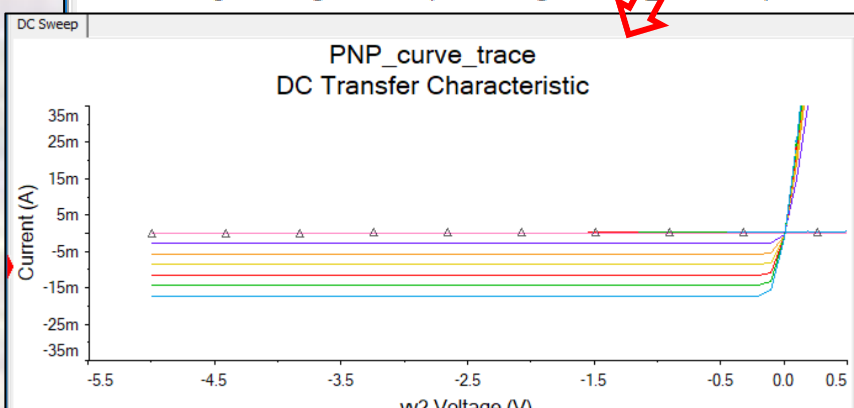


BJT IV Characteristics

- PNP – 4 regions of operation







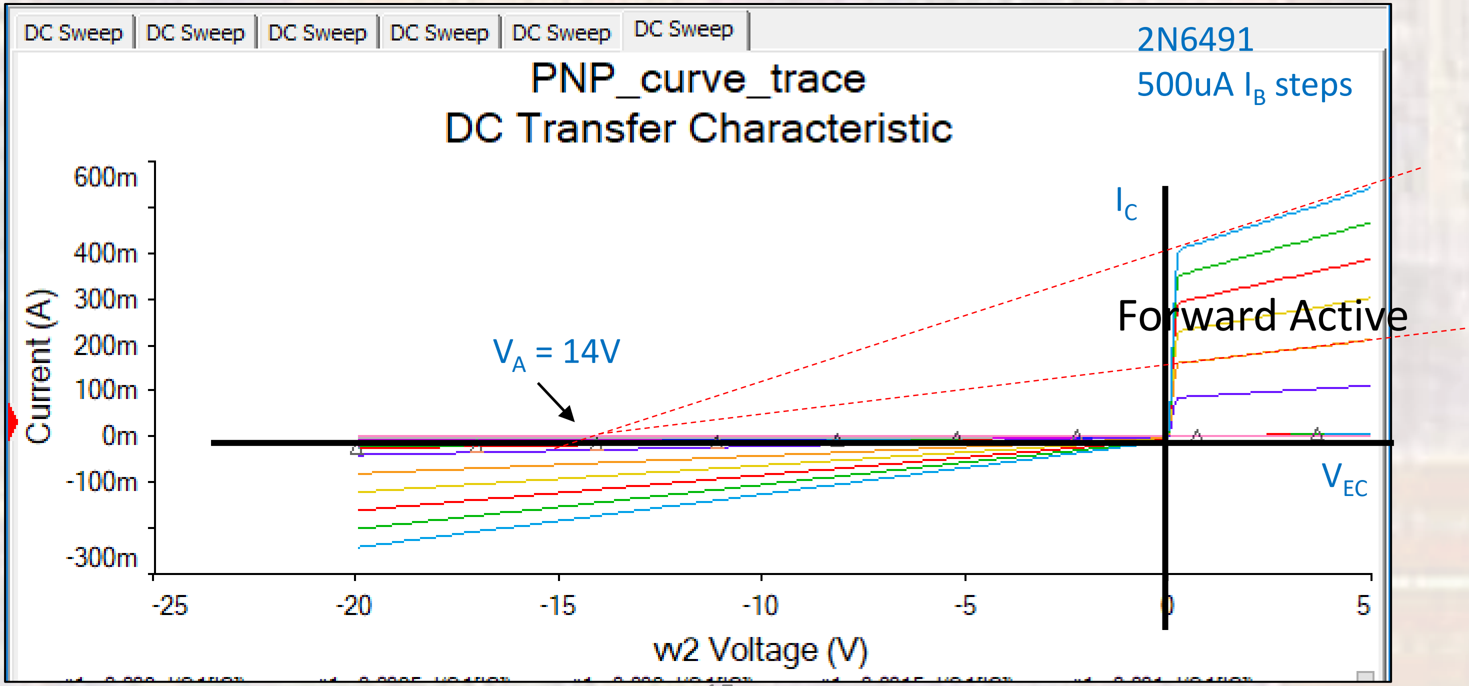
$$I_C = \beta I_B$$

Note: not exact, small slope to the I_C vs V_{CE} curve

Note: not constant for large I_C

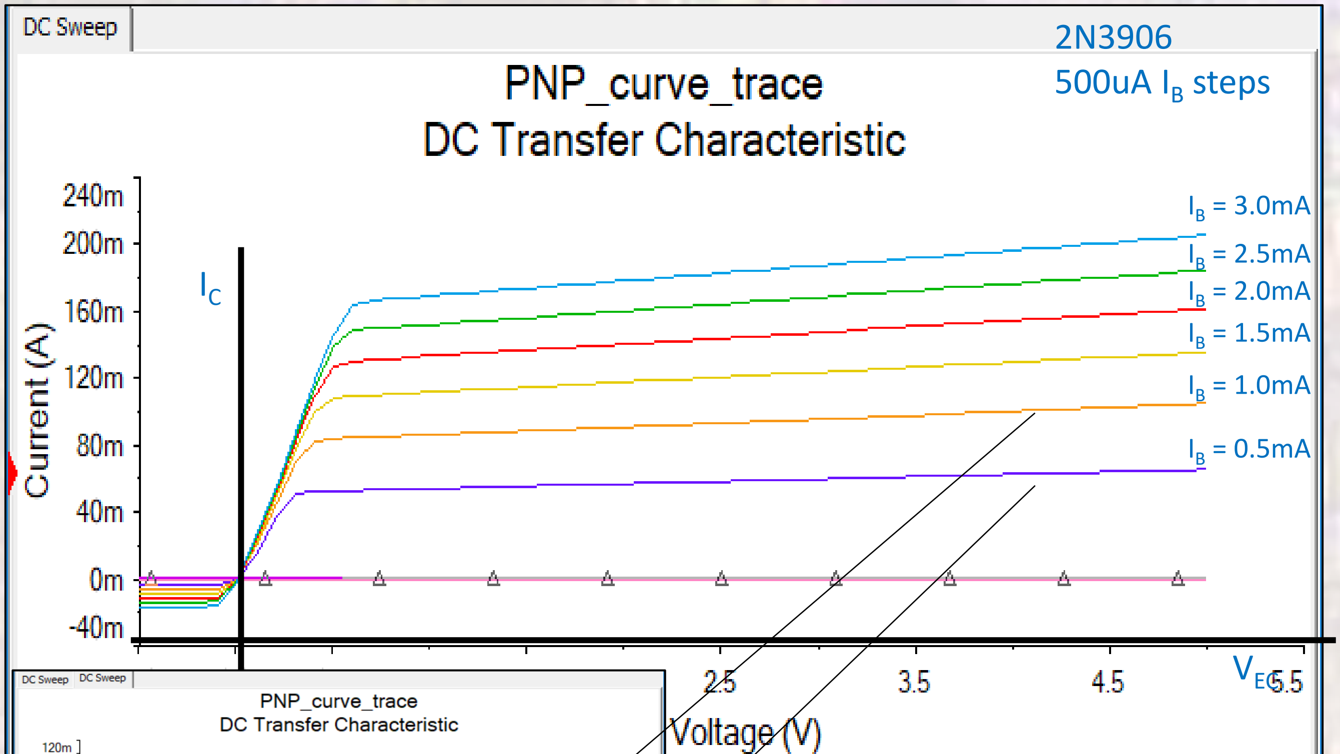
BJT IV Characteristics

- PNP – Early Voltage
  - Increasing V_{EC} → wider depletion region and greater electric field
  - → increasing I_C
  - The curves converge on the Early Voltage, $-V_A$



BJT IV Characteristics

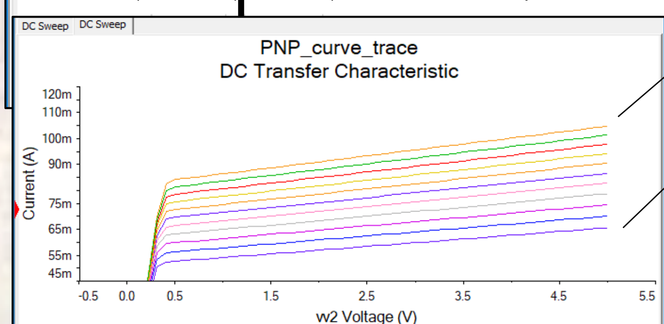
- PNP – Beta variation
  - Excess carriers in the base cause ↑ base current → ↓β



→ IC = 203mA → β = 68

β decreases

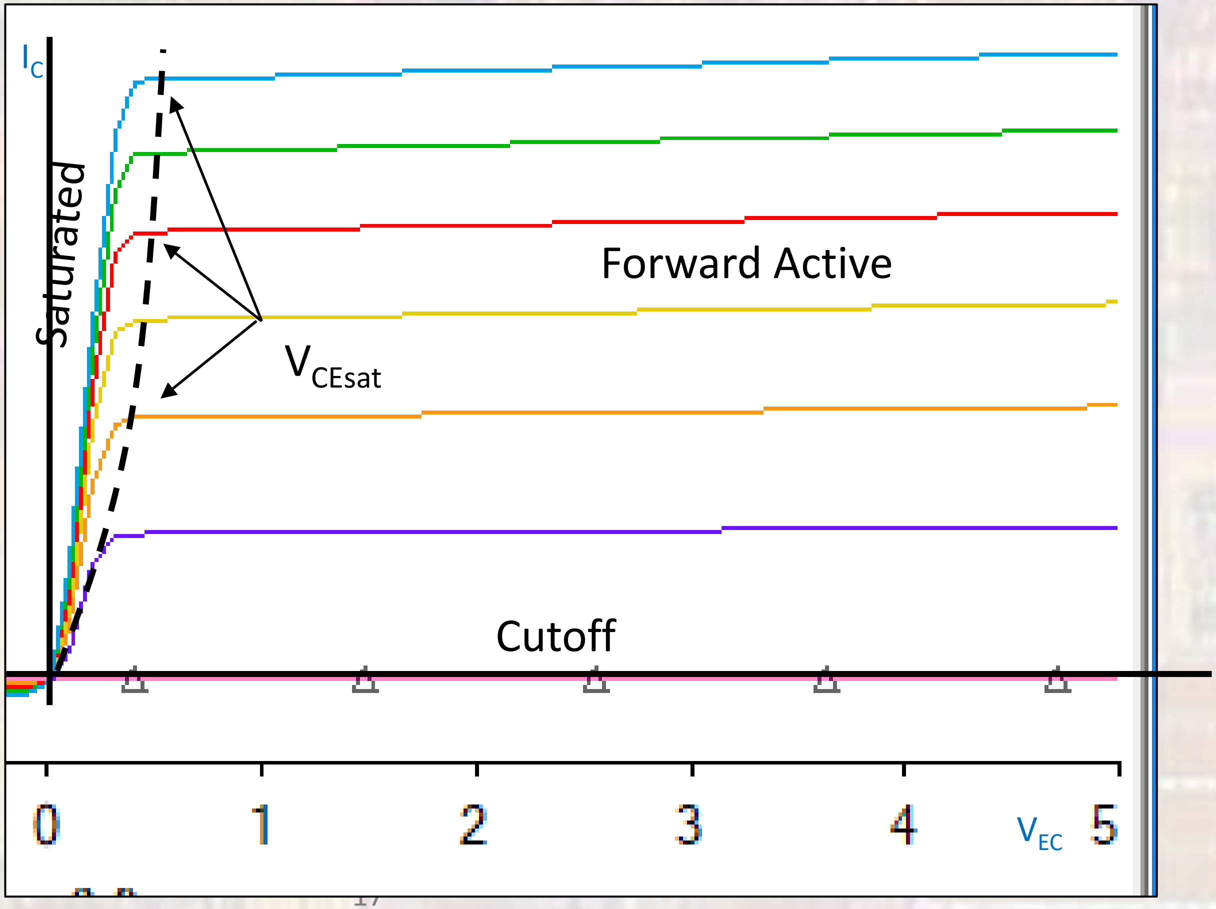
→ IC = 65mA → β = 130



β constant for moderate current levels

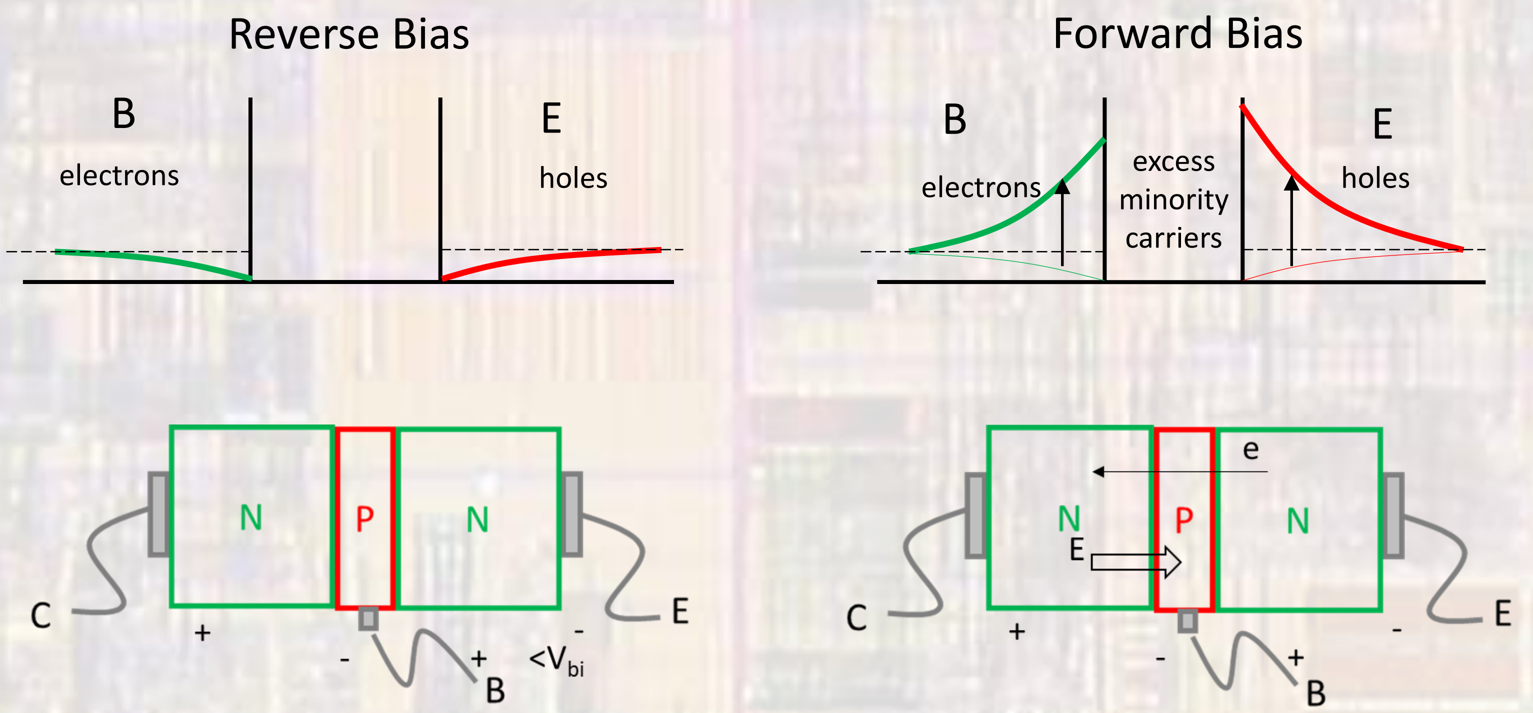
BJT IV Characteristics

- PNP - V_{CEsat}
  - Saturation voltage
  - Highest the collector will "pull up" while still providing current



BJT Switching

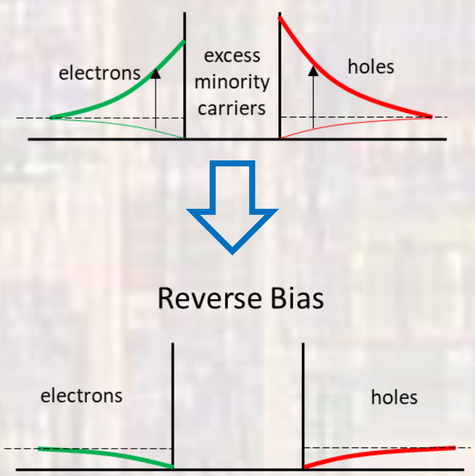
- In forward bias(B-E), carriers are traversing the depletion region and create an excess of minority carriers in the N and P regions



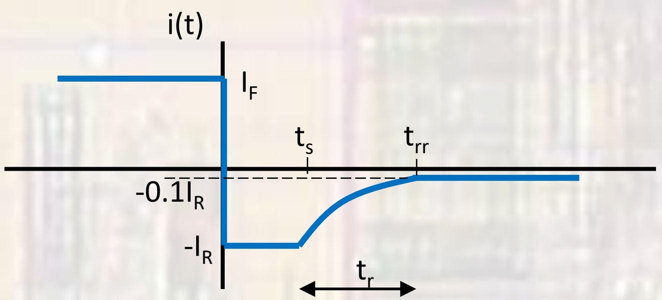
BJT Switching

- 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

Forward Bias

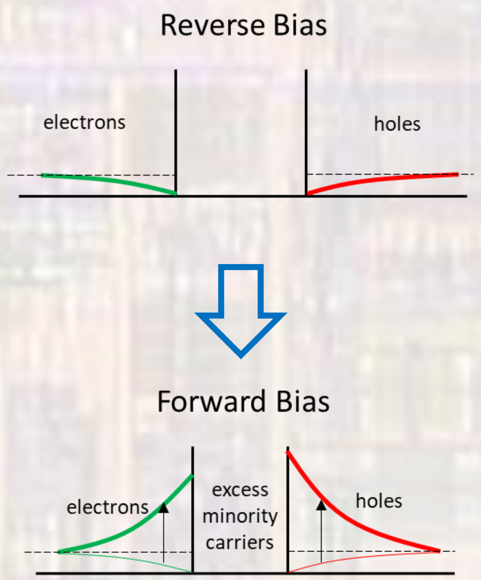


Turn Off



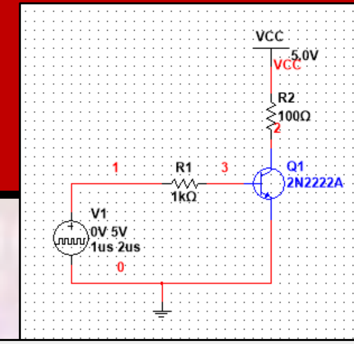
BJT Switching

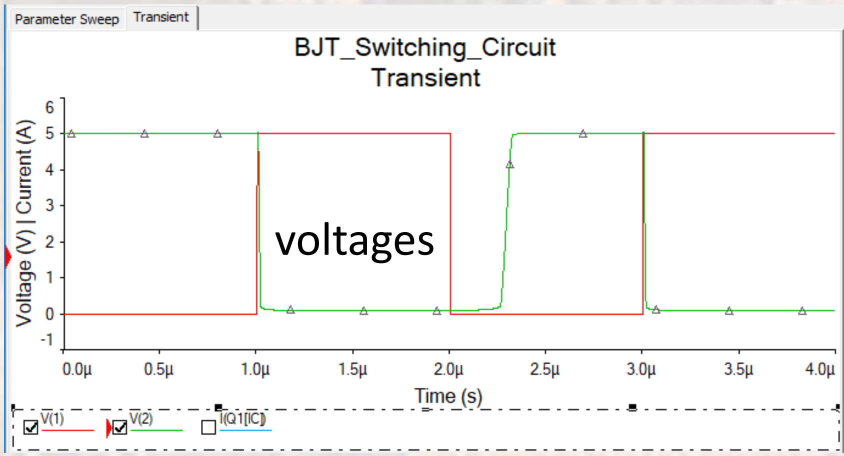
- Switching from reverse bias to forward bias
  - No excess minority carriers to be removed
  - → No storage time
    - Fast transitions

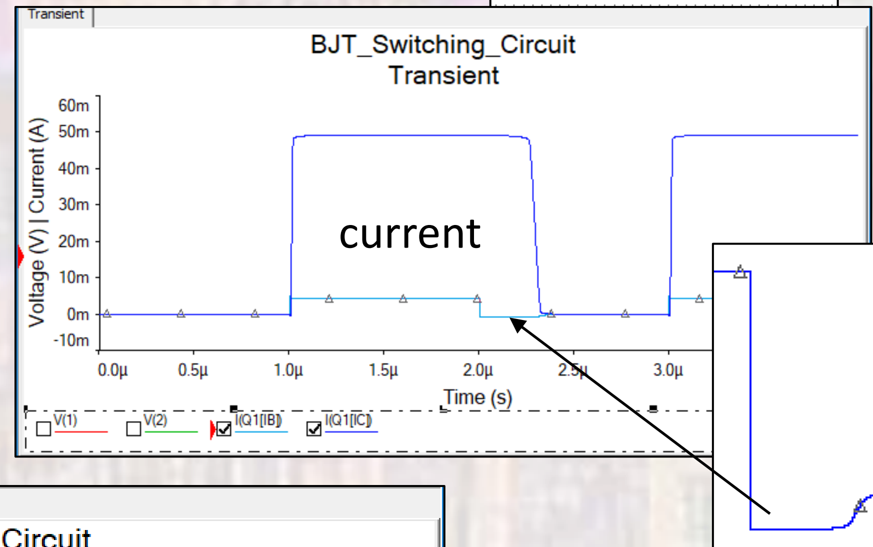


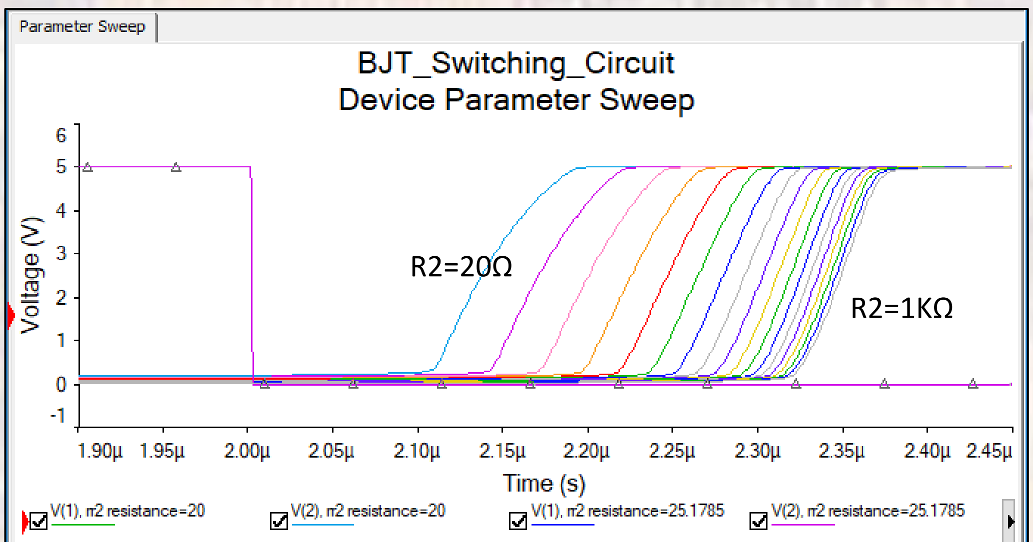
BJT Switching

- Simulation Example









R2 swept from
20Ω to 1K Ω

The larger R2
the deeper Q1
goes into saturation
→
longer base recovery
times

Other BJTs

- Schottky Transistor
  - Combine BJT with Schottky diode
  - Used to prevent the BJT from going into saturation
    - Improved switching time
  - Can be built very efficiently on an integrated circuit