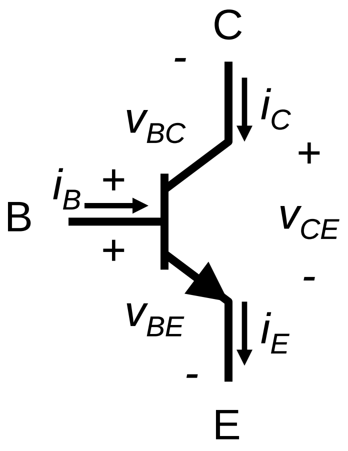
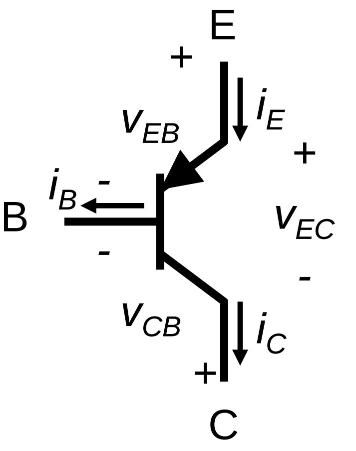
BJTs – Device Structure and Operation

Circuit Symbols



The NPN Circuit Symbol



The PNP Circuit Symbol

$$i_E = i_B + i_C$$

$$v_{BE} = v_{BC} + v_{CE} \qquad \text{(for NPN)}$$

$$v_{EB} = v_{CB} + v_{EC} \qquad \text{(for PNP)}$$

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Note that:

1. The circuit symbols are very similar to MOSFETs, with npn like N-MOS and pnp like P-MOS.
2. Positive current is defined in opposite directions for npn and for pnp (just like N-MOS and PMOS!).
3. The voltages are of opposite polarity for npn and pnp. Specifically, for npn we use v_{BE}, v_{CE} and v_{CB}, whereas for pnp we use v_{EB}, v_{EC} and v_{BC}. This convention typically results in positive voltage values for both npn and pnp (unlike the MOSFET convention!).
4. The base current i_B is not equal to zero (unlike MOSFETS).

BJTs – Device Structure and Operation

- Now that we understand the physical behavior of a BJT—that is, the behavior for each of the three BJT modes (active, saturation, and cutoff)—we need to determine also the mathematical description of BJT behavior.
- We will find that BJT behavior is in many was similar to MOSFET behavior!

<u>ACTIVE MODE</u>

- We found earlier that forward biasing the emitter-base junction results in collector (drift) current. The junction voltage for the emitter-base junction is v_{BE} (for npn).
- Thus, in active mode, the voltage base-to-emitter v_{BE} controls the collector current iC.
- We know the current-voltage relationship for this base-emitter (p-n) junction from our study of diodes:

$$i_C = I_S e^{v_{BE}/V_T} \quad \text{for NPN}$$

$$i_C = I_S e^{v_{EB}/V_T} \quad \text{for PNP}$$

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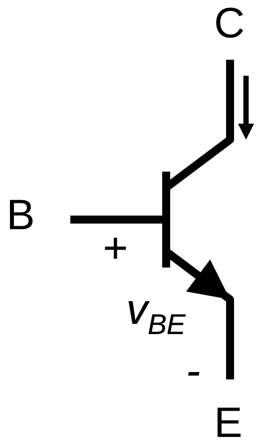
A BJT in ACTIVE mode is analogous to a MOSFET in SATURATION mode.

1. Recall that for a MOSFET in SATURATION, the drain current i_D is "controlled" by the gate-to-source voltage v_{GS}.
2. Likewise, for a BJT in ACTIVE mode, the collector current i_C is "controlled" by the base-to-emitter voltage v_{BE}.

Note the analogies!

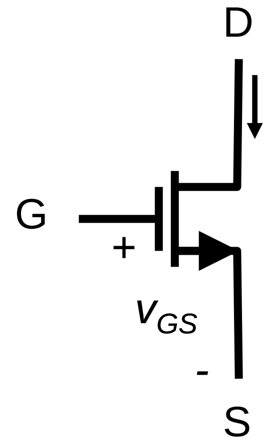
1. i_D is analogous to i_C.
2. v_{BE} is analogous to v_{GS}.
3. ACTIVE is analogous to SATURATION.

BJTs – Device Structure and Operation



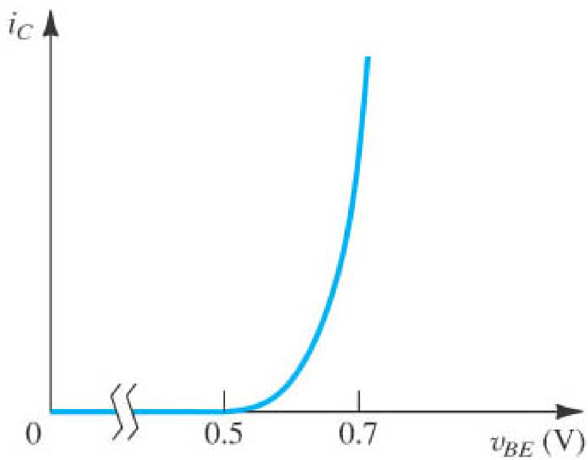
$$i_C = I_S e^{v_{BE}/V_T}$$

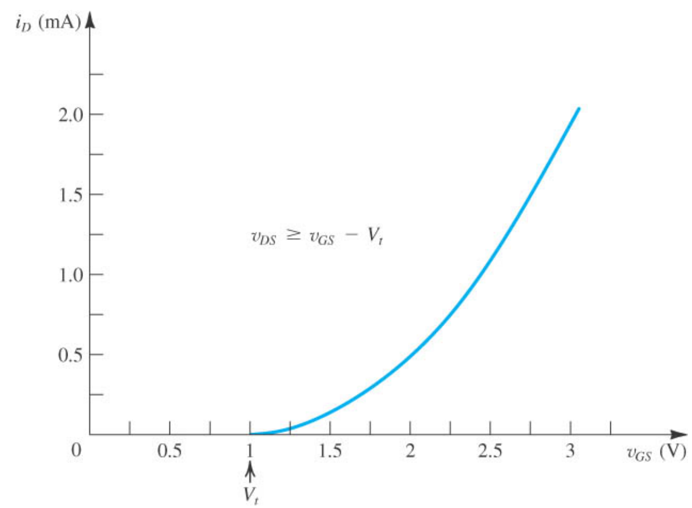
The NPN in ACTIVE MODE



$$i_D = \frac{1}{2} k_n (v_{GS} - V_{tn})^2$$

The NMOS in SATURATION



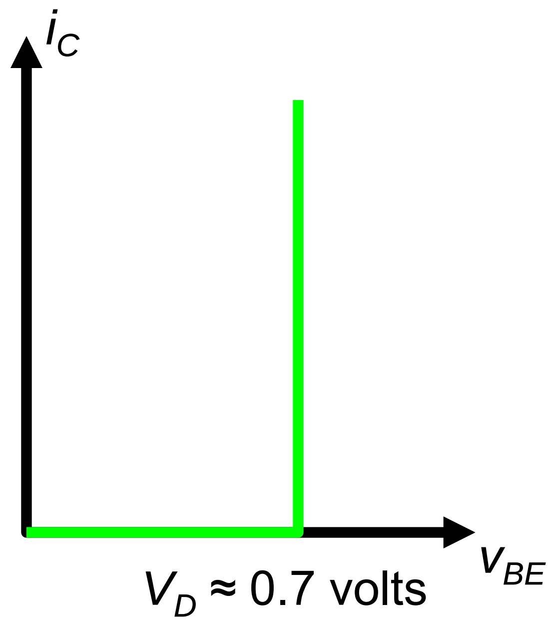


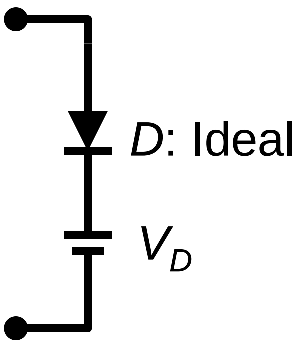
BJTs – Device Structure and Operation

Conditions for a npn BJT to be in the active mode.

V_{BE}

- Note that a necessary (but not sufficient) condition for a npn BJT to be in ACTIVE mode is that $v_{BE} \approx 0.7$ volts ($v_{BE} \approx V_D$) (i.e., the EBJ is forward biased).
- This is analogous to an NMOS in SATURATION, where a necessary (but not sufficient) condition is that $v_{GS} > V_t$ (i.e., the channel is conducting).
- We are simply modeling the base-emitter junction as a diode (thus the arrow in the circuit symbol) … specifically the constant voltage drop model.
- If the v_{BE} is less than V_D then the transistor is in cuttor.
- If the v_{BE} is equal to V_D then the transistor is in either in active or saturation.





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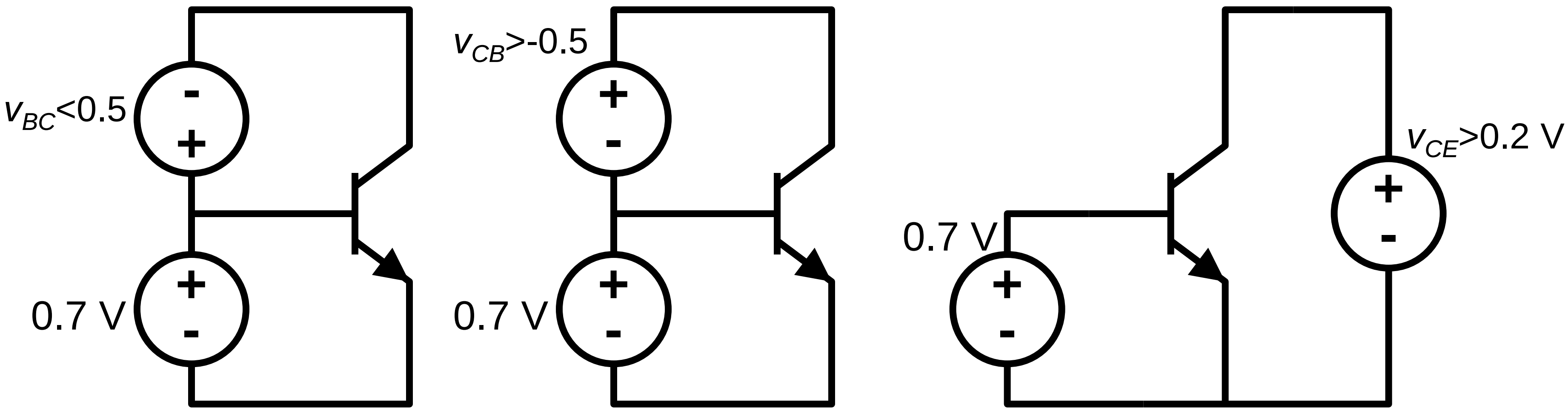
v_{CE}

- Likewise, for a BJT to be in the ACTIVE mode, the collector-base junction must be in reverse bias (i.e, $v_{BC} < 0$).
- Assuming that the forward biased EBJ results in $v_{BE} = 0.7$ volts, we can use KVL to determine that the CBJ will be reverse biased only when:

$$v_{CE} > 0.2 \text{ volts} \quad \text{(for NPN)}$$

$$v_{EC} > 0.2 \text{ volts} \quad \text{(for PNP)}$$

- These statements above are **analogous** to the MOSFET inequality $v_{DS} > v_{GS} - V_t$ for MOSFET SAT.



BJTs – Device Structure and Operation

The similarities between NPN and NMOS end here … the base current is not zero!

- Recall i_G=0 always, but for BJTs we find that i_B is not always equal to zero.
- Instead, we found that although most of the charge carriers (e.g., holes or free electrons) diffusing across the EBJ end up “drifting” across the CBJ into the collector, some charge carriers do “exit” the base terminal.
- For every one charge carrier that leaves the base terminal, there are typically 50 to 250 charge carriers that drift into the collector.
- As a result, the collector current for ACTIVE mode is typically 50 to 250 times larger than the base current! I.E.:

$$50 < \frac{i_C}{i_B} < 250$$

- This ratio is a device parameter for a specific transistor type and is defined as beta:

$$\beta = \frac{i_C}{i_B}$$

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- Thus, we find that the **base current** can be expressed as:

$$i_B = \frac{i_C}{\beta} = \frac{I_S}{\beta} e^{v_{BE}/V_T} \quad \text{for (NPN)}$$

$$i_B = \frac{i_C}{\beta} = \frac{I_S}{\beta} e^{v_{EB}/V_T} \quad \text{for (PNP)}$$

- Likewise, from **KCL**, we can determine the **emitter current** for a BJT in the ACTIVE mode:

$$\begin{aligned} i_E &= i_C + i_B \\ &= \beta i_B + i_B \\ &= (\beta + 1) i_B \end{aligned}$$

$$\begin{aligned} i_E &= i_C + i_B \\ &= i_C + \frac{i_C}{\beta} \\ &= \left(1 + \frac{1}{\beta}\right) i_C \\ &= \left(\frac{\beta + 1}{\beta}\right) i_C \end{aligned}$$

- Remember, β is a large value so i_E is much larger than i_B and i_E is just slightly larger than i_C.

BJTs – Device Structure and Operation

- An **alternative** to device parameter β is the **device parameter** α, defined as:

$$\alpha = \frac{i_C}{i_E} = \frac{\beta}{\beta + 1}$$

- Note that the value of α will be just slightly less than one.
- We can thus alternatively express the current relationships as:

$$i_E = (\beta + 1) i_B \qquad i_E = \left(\frac{\beta + 1}{\beta} \right) i_C$$

$$i_B = (1 - \alpha) i_E \qquad i_C = \alpha i_E$$

- And therefore:

$$i_E = \frac{i_C}{\alpha} = \frac{I_S}{\alpha} e^{v_{BE}/V_T} \quad \text{for (NPN)}$$

$$i_E = \frac{i_C}{\alpha} = \frac{I_S}{\alpha} e^{v_{EB}/V_T} \quad \text{for (PNP)}$$

BJTs – Device Structure and Operation

- Recall that the exponential expression for a pn junction turned out to be of limited use, as it typically led to unsolvable equations.
- The same is true for these exponential equations! We will thus generally use the equations below to approximate the behavior of a BJT in the ACTIVE mode:

$$\boxed{\begin{array}{llll} i_C = \beta i_B & v_{BE} \approx 0.7 & v_{CE} > 0.2 & \text{(NPN in Active)} \\[2ex] i_C = \beta i_B & v_{EB} \approx 0.7 & v_{EC} > 0.2 & \text{(PNP in Active)} \end{array}}$$

BJTs – Device Structure and Operation

SATURATION MODE

- Recall for BJT SATURATION mode that both the CBJ and the EBJ are forward biased.
- Thus, the collector current is due to two physical mechanisms, the first being charge carriers (holes or free-electrons) that drift across the CBJ (just like ACTIVE mode), and the second being charge carriers that diffuse across the forward biased CBJ!
- As a result, a second term appears in our mathematical description of collector current (when the BJT is in SATURATION):
- This second term accounts for the current due to the collector-base pn junction acting like a diode in forward bias.

$$i_C = I_S e^{v_{BE}/V_T} - \frac{I_S}{\alpha_R} e^{v_{BC}/V_T} \quad \text{(NPN)}$$

$$i_C = I_S e^{v_{EB}/V_T} - \frac{I_S}{\alpha_R} e^{v_{CB}/V_T} \quad \text{(PNP)}$$

BJTs – Device Structure and Operation

SATURATION MODE

- This second term describes the current due to **diffusion** across the CBJ. Note that this current is in the **opposite** direction of the drift current (the first term), hence the **minus** sign in the second term.
- We can express this in terms of v_{BE} and v_{CE}.

$$i_C = I_S e^{v_{BE}/V_T} - \frac{I_S}{\alpha_R} e^{(v_{BE}-v_{CE})/V_T}$$

$$= I_S e^{v_{BE}/V_T}\left(1-\frac{e^{-v_{CE}/V_T}}{\alpha_R}\right)$$

- It is thus clear that for a BJT in SATURATION, the collector current iC is dependent on both v_{BE} and v_{CE}.
- This is precisely analogous to the TRIODE mode for MOSFETS!

$$i_C = I_S e^{v_{BE}/V_T}\left(1-\frac{e^{-v_{CE}/V_T}}{\alpha_R}\right) \quad \text{(NPN)} \qquad i_C = I_S e^{v_{EB}/V_T}\left(1-\frac{e^{-v_{EC}/V_T}}{\alpha_R}\right) \quad \text{(PNP)}$$

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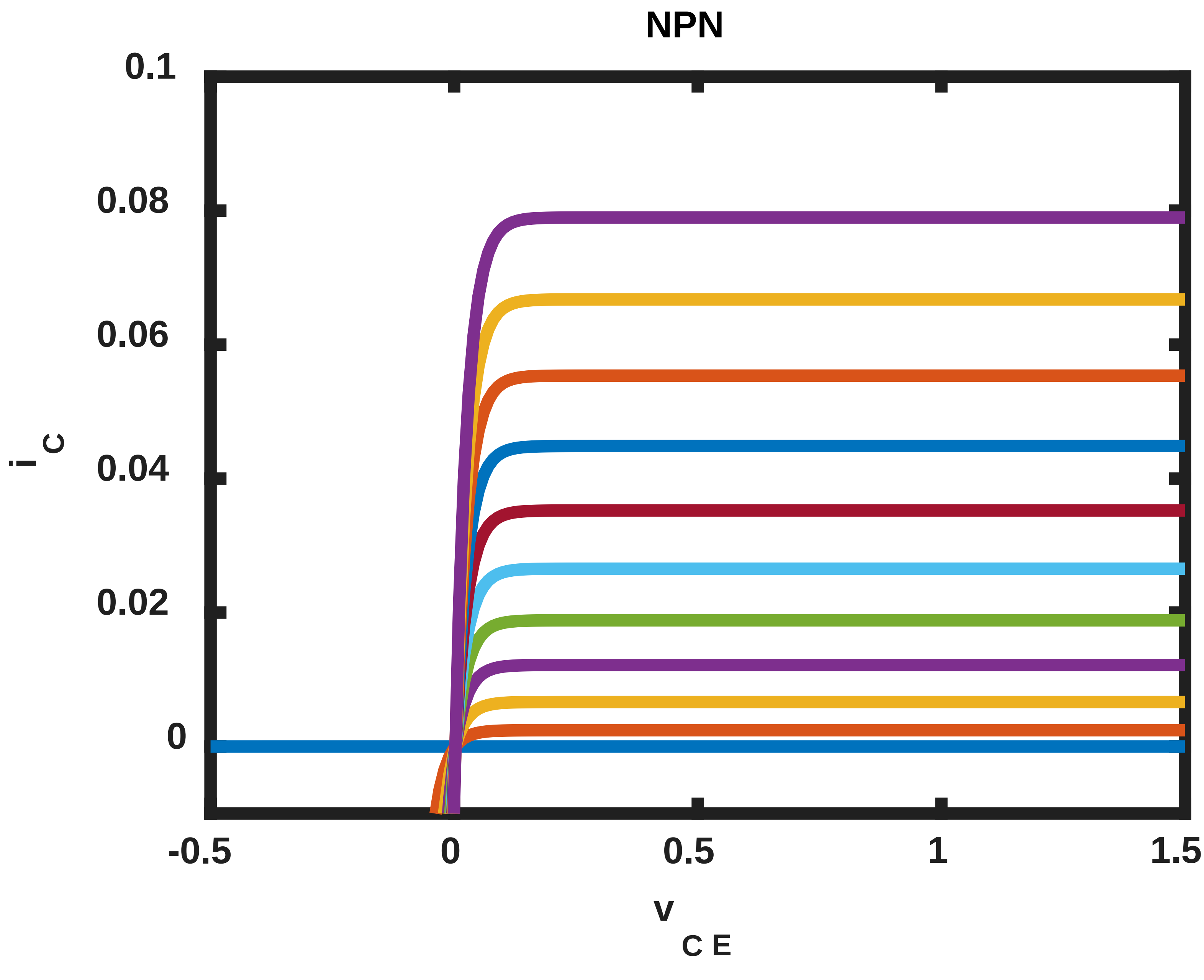

BJTs – Device Structure and Operation

Conditions for SATURATION MODE

- Now, a BJT is in SATURATION mode if both the CBJ and the EBJ are forward biased. Assuming that v_{BE}≈0.7 V if the EBJ is forward biased, the CBJ voltage v_{BC} will be positive only if:

$$v_{BC} = 0.5$$

$$v_{BE} - v_{CE} = 0.5$$

$$v_{BE} - v_{CE} = 0.5$$

$$0.7 - v_{CE} = 0.5$$

$$v_{CE} = 0.2 \qquad \text{for NPN}$$

$$v_{EC} = 0.2 \qquad \text{for PNP}$$

BJTs – Device Structure and Operation

Conditions for SATURATION MODE

- If we model the base-collector pn junction using a constant voltage drop model we find:

$$v_{BC} \approx 0.5\,\text{volts}$$

$$v_{CE} \approx 0.2\,\text{volts}$$

- We also see that the collector current will be less than that for the active mode:

$$i_C = I_S e^{v_{BE}/V_T}\left(1 - \frac{e^{-v_{CE}/V_T}}{\alpha_R}\right) < I_S e^{v_{BE}/V_T} = \beta i_B$$

$$\boxed{\begin{array}{llll} i_C < \beta i_B & v_{BE} \approx 0.7 & v_{CE} \approx 0.2 & \text{(NPN in Active)} \\ i_C < \beta i_B & v_{EB} \approx 0.7 & v_{EC} \approx 0.2 & \text{(PNP in Active)} \end{array}}$$

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<u>NPN</u>

Cutoff: $i_C=i_B=i_E=0$

$v_{BE}<0.7V$, $v_{CE}>v_{BE}-0.5V$ ($v_{BC}<0.5V$)

Active: $v_{BE}=0.7V$, $i_B=i_C/\beta$

$v_{CE}>0.2V$

Saturation: $V_{BE}=0.7$, $v_{CE}=0.2V$

$i_B>i_C/\beta$ ($\beta_{EFF}=i_C/i_B<\beta$)

~~**Reverse**~~ $\cancel{v_{BC}=0.5V,\ i_B=-i_E/\beta_R}$

~~**Active:**~~ $\cancel{v_{BE}<0.7V}$

BJTs – Device Structure and Operation

PNP

Cutoff: $i_C=i_B=i_E=0$

$v_{EB}<0.7V$, $v_{EC}>V_{EB}-0.5V$ ($v_{CB}<0.5$)

Active: $v_{EB}=0.7V$, $i_B=i_C/\beta$

$v_{EC}>0.2V$

Saturation: $V_{EB}=0.7$, $v_{EC}=0.2V$

$i_B>i_C/\beta$ ($\beta_{EFF}=i_C/i_B<\beta$)

~~**Reverse**~~ $\cancel{v_{CB}=0.5V,\ i_B=-i_E/\beta_R}$

~~**Active:**~~ $\cancel{v_{EB}<0.7V}$