Semiconductor Devices

Bipolar Junction Transistors: Part 2

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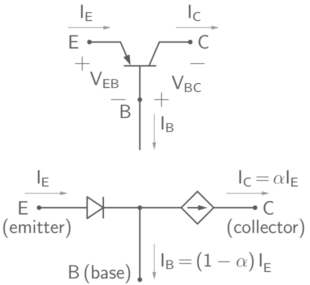

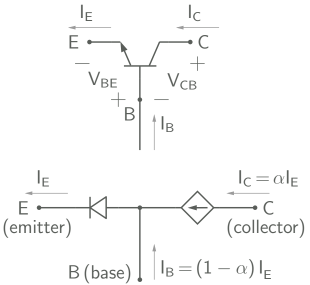

Bipolar junction transistors: Ebers-Moll model

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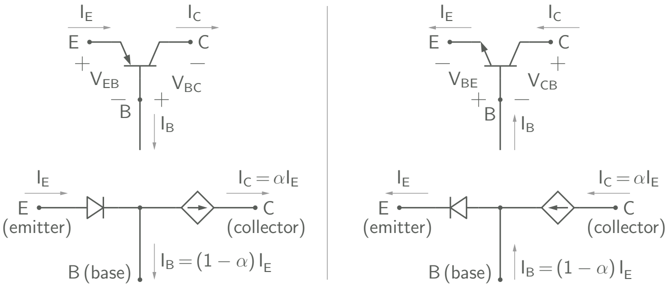
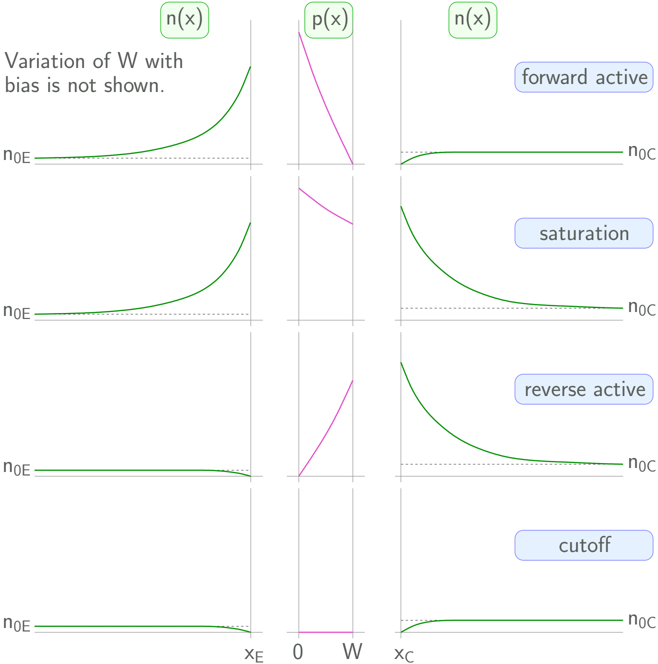


* A generalised model valid in all modes can be obtained by removing the conditions of a forward bias across the *E-B* junction and a reverse bias across the *C-B* junction $\rightarrow$ Ebers-Moll model.

Ebers-Moll model:

Outline of derivation for a *pnp* BJT



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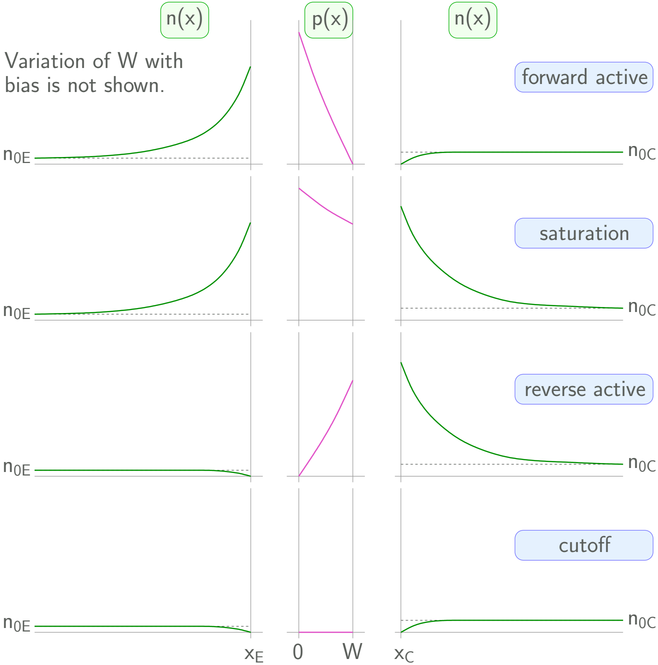

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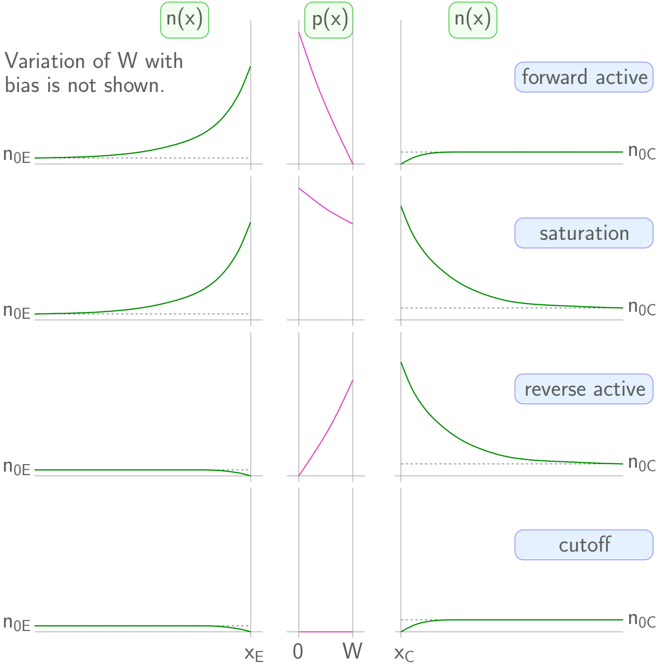

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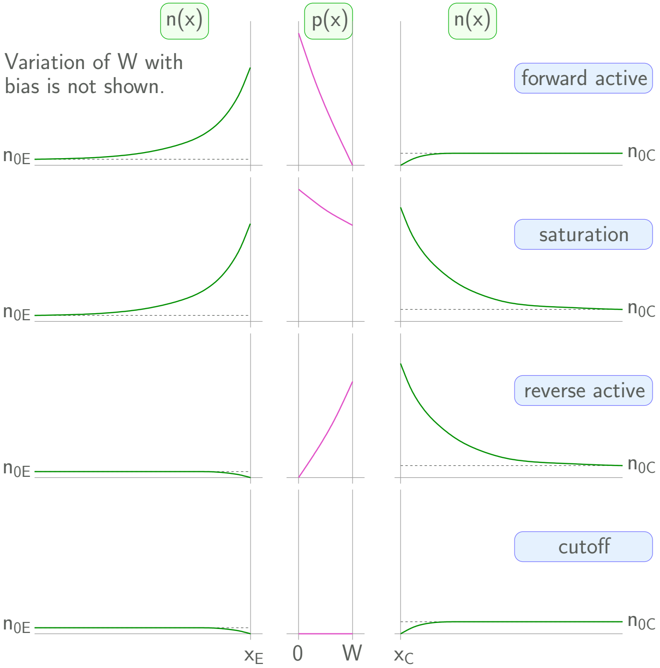

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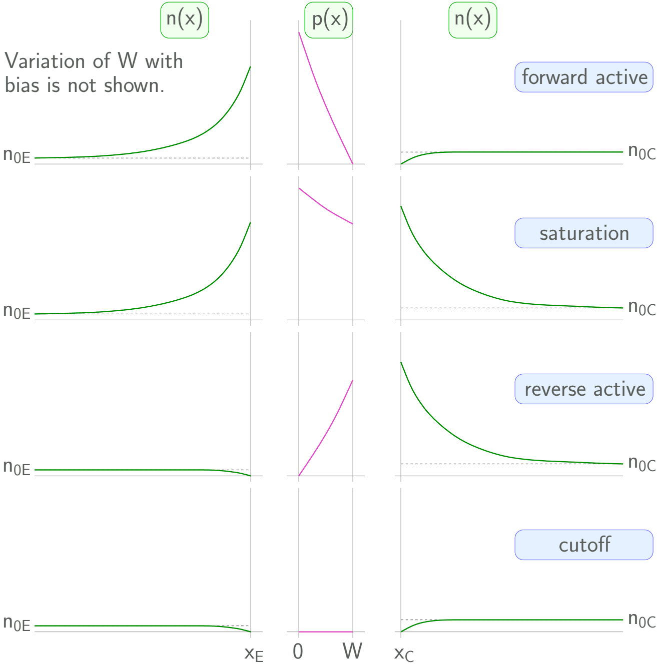

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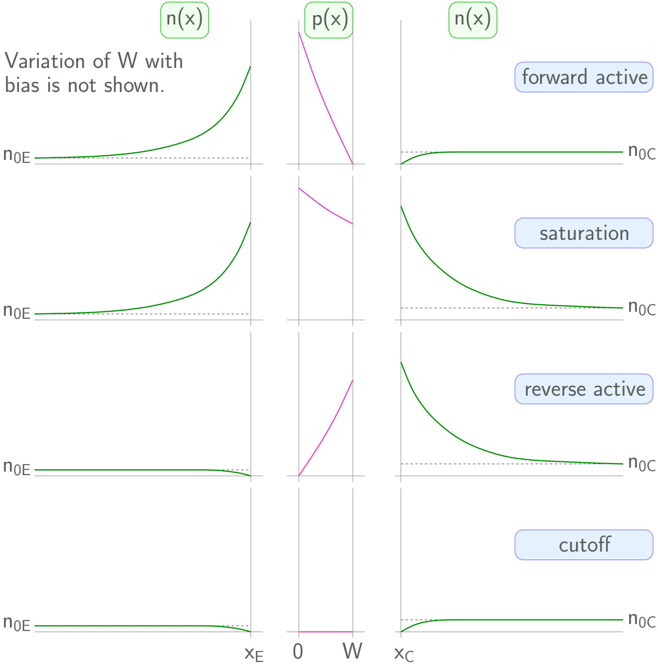

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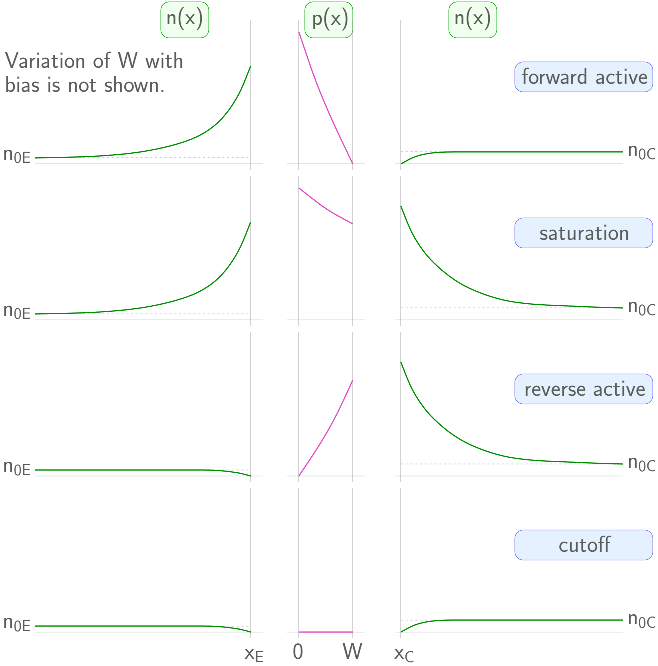
* Solve the minority-carrier continuity equations in the neutral emitter, base, and collector regions.



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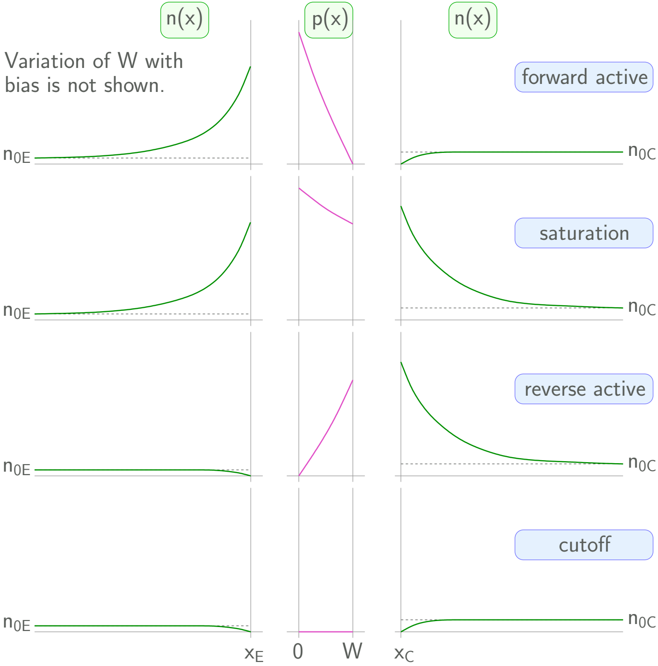
* Solve the minority-carrier continuity equations in the neutral emitter, base, and collector regions.
* From the solutions, obtain the following currents.

$$I_{nE}(x_E) = \quad qAD_{nE}\,\frac{dn}{dx}(x_E).$$

$$I_{pB}(0) \quad = -qAD_{pB}\,\frac{dp}{dx}(0).$$

$$I_{pB}(W) = -qAD_{pB}\,\frac{dp}{dx}(W).$$

$$I_{nC}(x_C) = \quad qAD_{nC}\,\frac{dn}{dx}(x_C).$$



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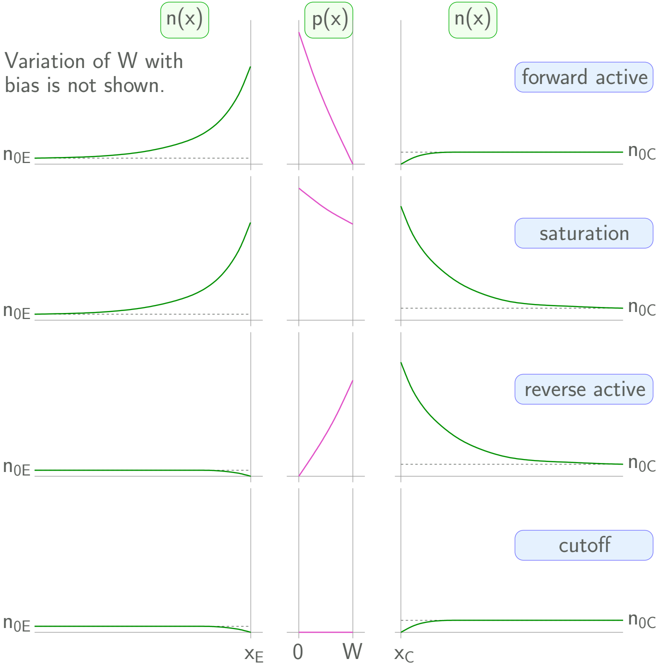

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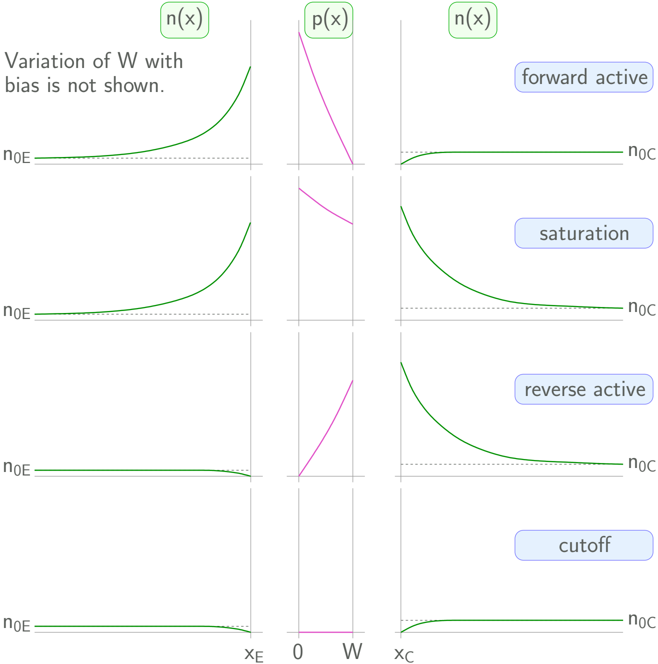
* Obtain the terminal currents, ignoring G-R in the depletion regions.

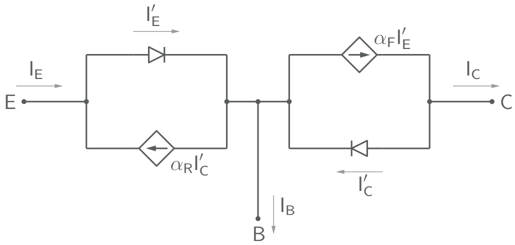
  $I_E = I_{nE}(x_E) + I_{pB}(0)$.

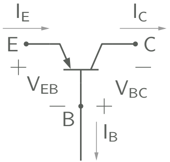
  $I_C = I_{nC}(x_C) + I_{pB}(W)$.

  $I_B = I_E - I_C$.



Bipolar junction transistors: Ebers-Moll model





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$$I'_E = I_{ES}\left[\exp\left(\frac{V_{EB}}{V_T}\right) - 1\right]$$

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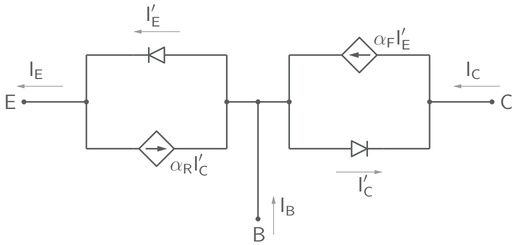

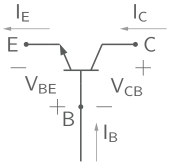

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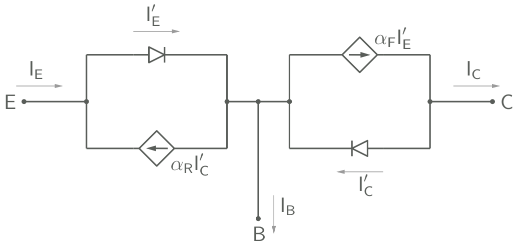

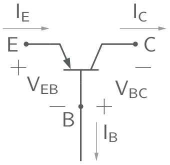

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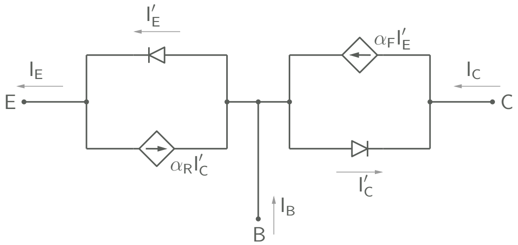

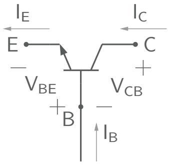

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* Current directions are assigned such that I_C, I_E, I_B are all positive if the BJT operates in the active mode.

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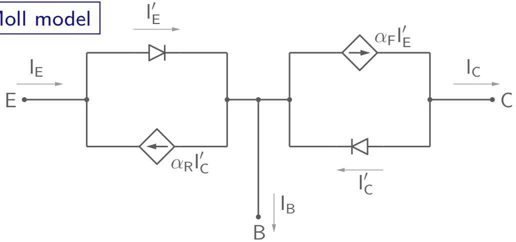

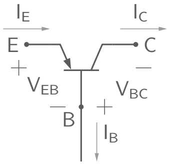

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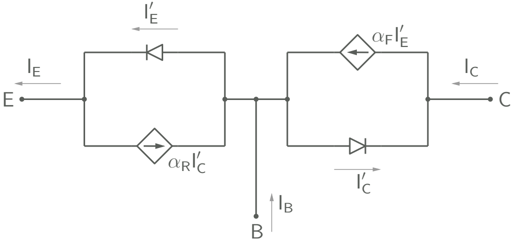

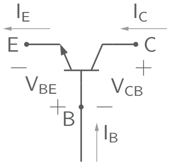

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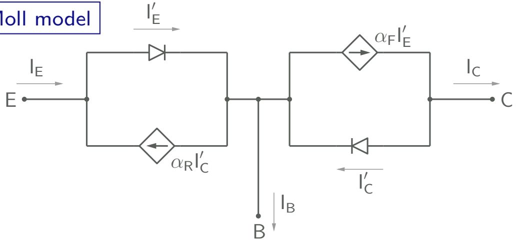

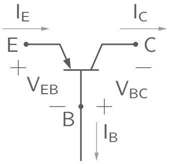

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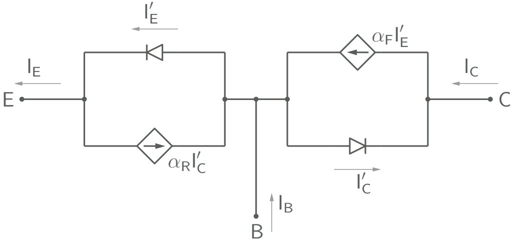

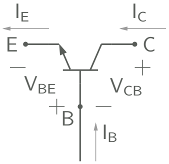

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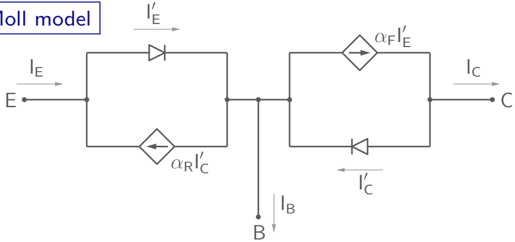

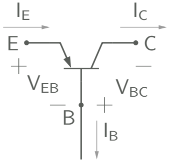

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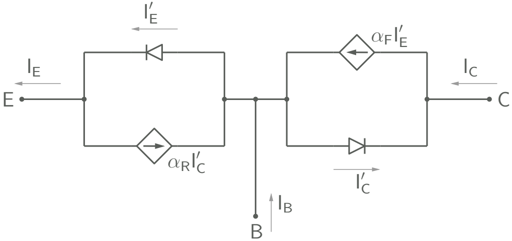

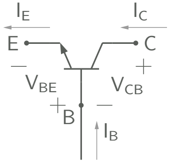

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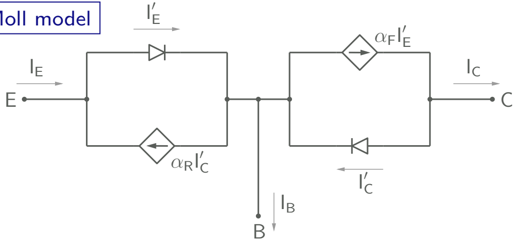
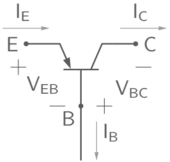
* To construct the Ebers-Moll model, we draw two transistor models: one in the forward active mode, the other in the reverse active mode, and connect them in parallel.
* The forward transistor is represented by the *E*-*B* diode and the corresponding dependent source (the upper branches), and the reverse transistor by the *C*-*B* diode and the corresponding dependent source (the lower branches).

Ebers-Moll model





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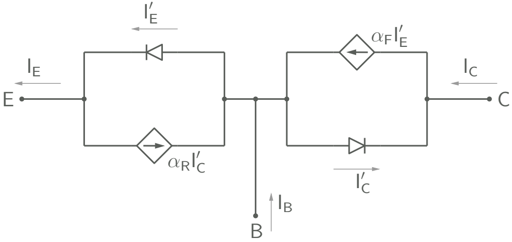

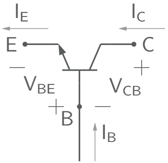

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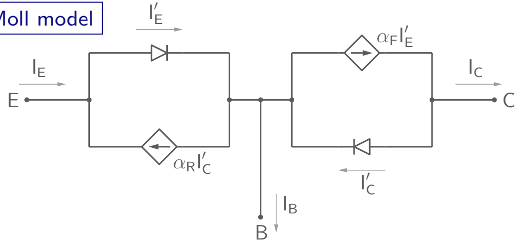

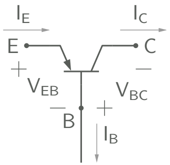

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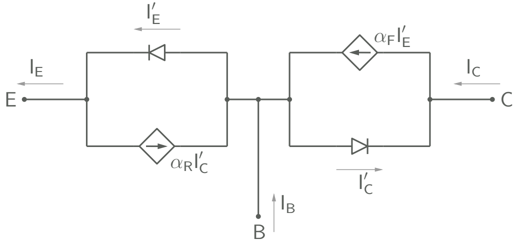

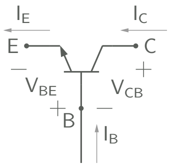

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* The model has four parameters: I_{ES}, I_{CS}, α_F, α_R (F for forward, R for reverse) which can be related to the geometry (base width, device area) and material parameters (doping densities, diffusion coefficients, lifetimes) of the transistor.[1]

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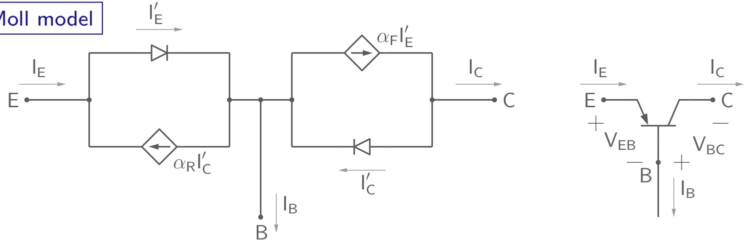
pnp transistor



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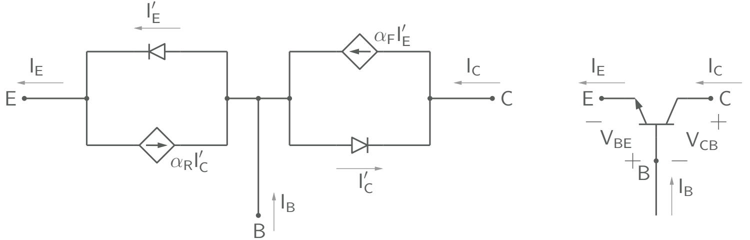

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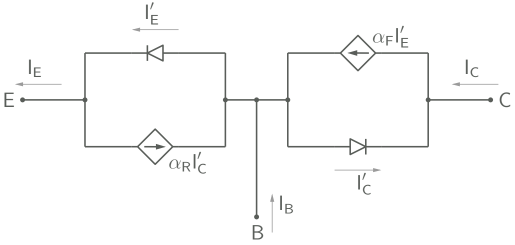
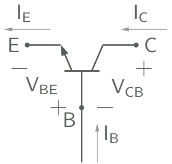
* The Ebers-Moll model can still be used as a "phenomenological" description of the device if model parameters are suitably extracted using measured data.
* More advanced BJT models are available (e.g., the SPICE model[2]) and are used for circuit simulation.

[2] P. Antognetti and G. Massobrio, *Semiconductor Device Modeling with SPICE*. New York: McGraw-Hill, 1988.

Ebers-Moll model: special cases





npn transistor

$$I'_E = I_{ES}\left[\exp\left(\frac{V_{BE}}{V_T}\right) - 1\right]$$

$$I'_C = I_{CS}\left[\exp\left(\frac{V_{BC}}{V_T}\right) - 1\right]$$

* $I_E = 0$, i.e., emitter open-circuited.

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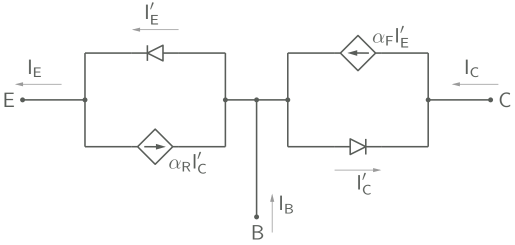

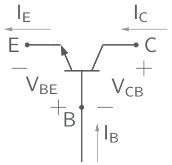

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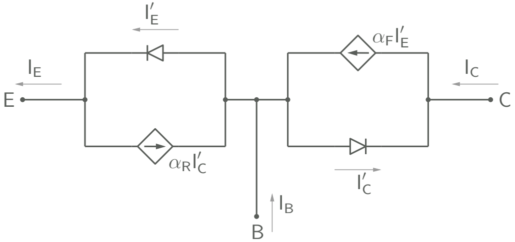

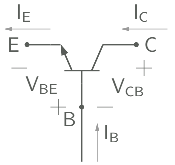

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When the C-B junction is under reverse bias, $I'_C \approx -I_{CS}$, and with $I_E = 0$, we get

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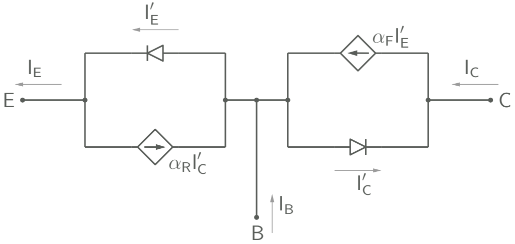

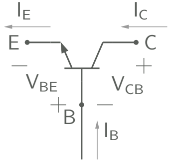

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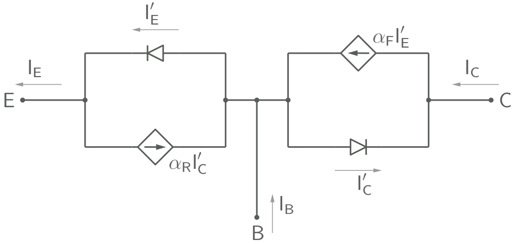
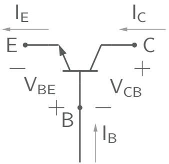
Ebers-Moll model: special cases





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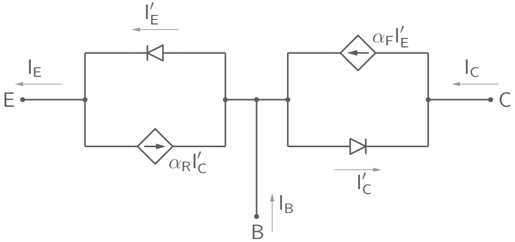

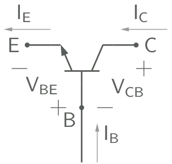

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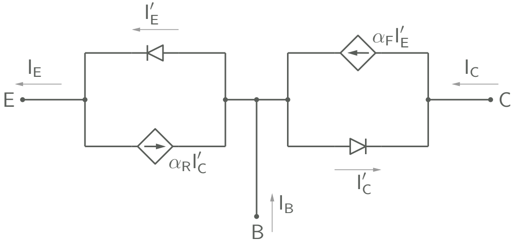
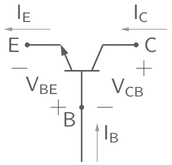
Ebers-Moll model: special cases





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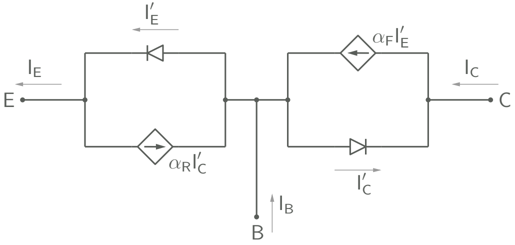
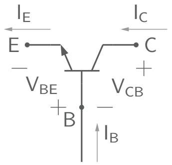
Ebers-Moll model: special cases





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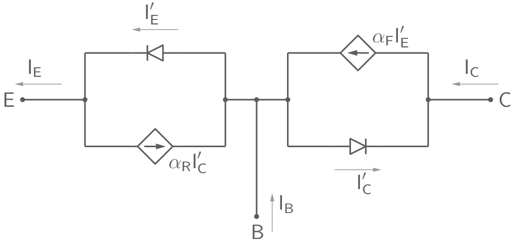
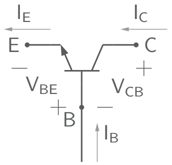
When the C-B junction is under reverse bias, $I'_C \approx -I_{CS}$, and with $I_B = 0$, we get

$$I_C \equiv I_{CEO} = \frac{I_{CS}(1-\alpha_F\alpha_R)}{(1-\alpha_F)} = \frac{I_{CBO}}{(1-\alpha_F)},$$

Ebers-Moll model: special cases





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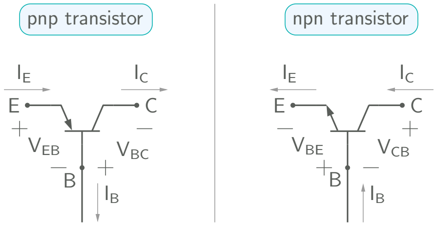
$$I_C \equiv I_{CEO} = \frac{I_{CS}(1-\alpha_F\alpha_R)}{(1-\alpha_F)} = \frac{I_{CBO}}{(1-\alpha_F)},$$

which is much larger than I_{CBO} since α_F is close to 1.

BJT I-V description



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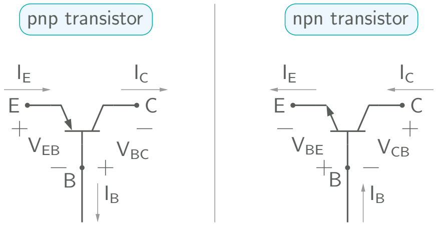
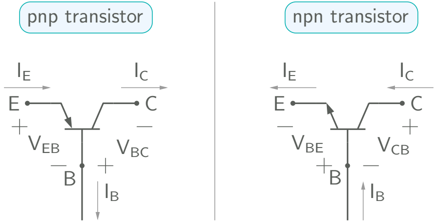
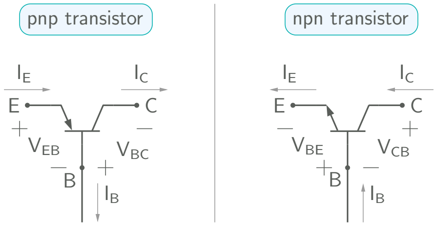


* Unlike the diode (where there is only one current and one voltage), the BJT has three currents and three voltages.



* Unlike the diode (where there is only one current and one voltage), the BJT has three currents and three voltages.
* The current-voltage relationship is described in the form of a "family" of curves, with a current selected as the y variable, a voltage as the x variable, and a third variable as a quantity to be held constant for each I-V curve.

BJT I-V description



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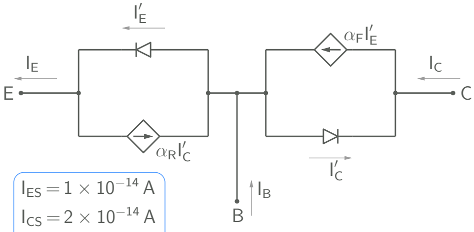
* The current-voltage relationship is described in the form of a "family" of curves, with a current selected as the y variable, a voltage as the x variable, and a third variable as a quantity to be held constant for each I-V curve.
* Two descriptions, which are related to the "common-base" and "common-emitter" configurations, are commonly used.

Common-base configuration

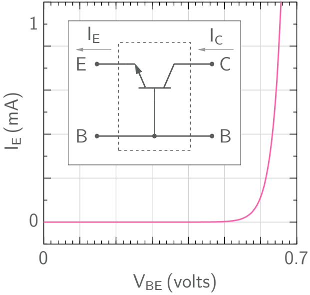


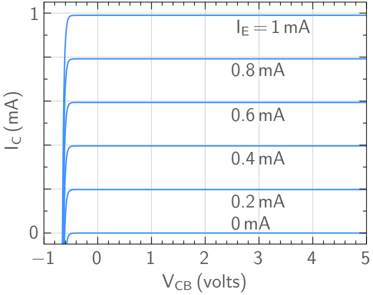
$I_{ES} = 1 \times 10^{-14}$ A

$I_{CS} = 2 \times 10^{-14}$ A

$\alpha_F = 0.99$

$\alpha_R = 0.5$





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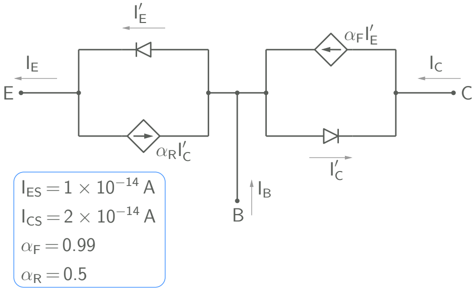
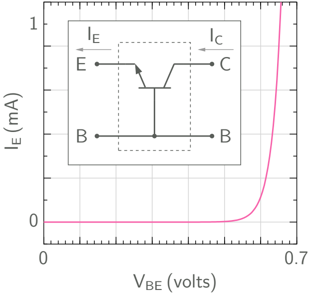
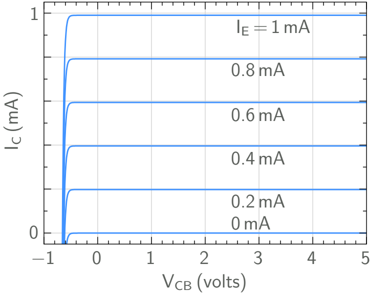
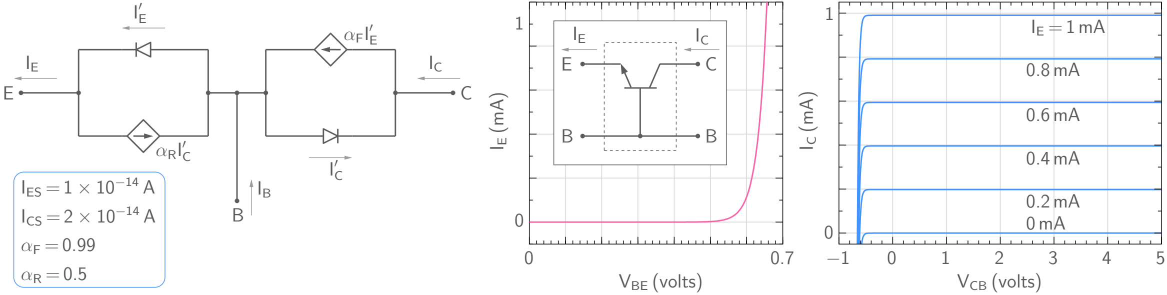






* $V_{CB} > 0\,\text{V}$:
  C-B junction is reverse biased, $I'_C \approx -I_{CS}$, which is negligibly small.



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  $I_E \approx I'_E$, $I_C \approx \alpha_F I_E$ $\rightarrow$ for a given I_E, I_C is a constant.

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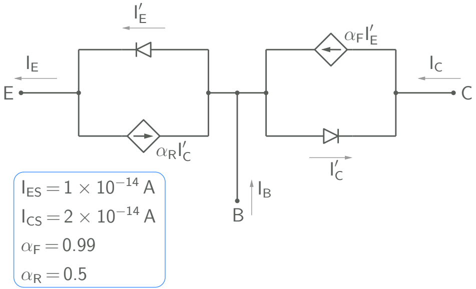

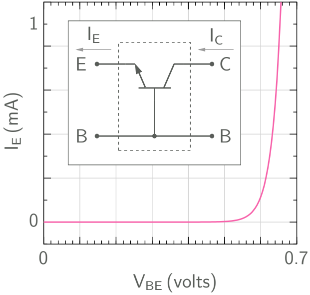

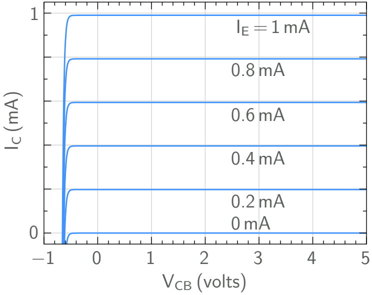

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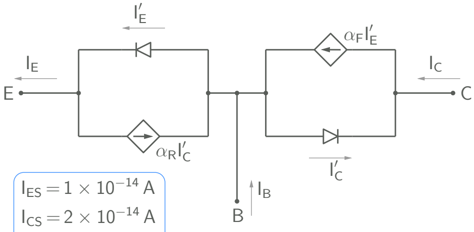
  On the input side, the I_C versus V_{BE} curve (for a positive V_{CB} value) is like a diode I-V relationship.

Common-base configuration



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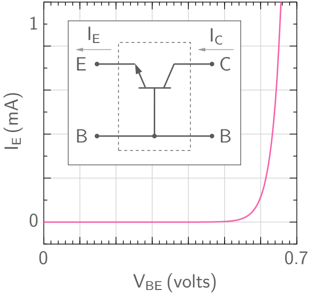

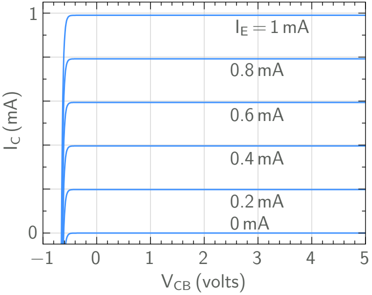

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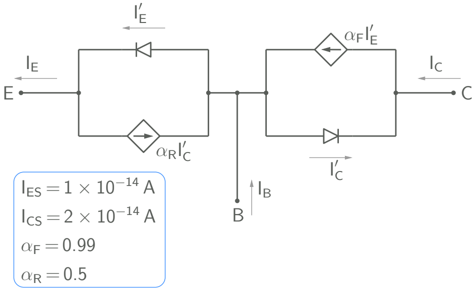

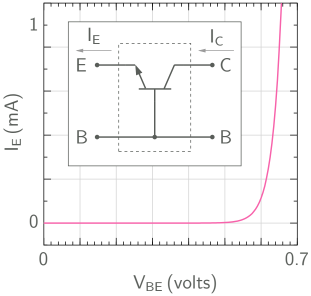

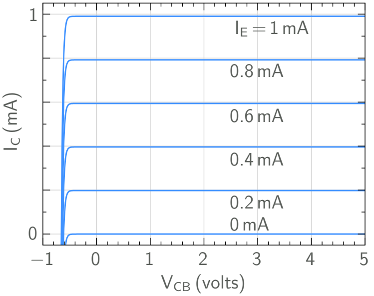

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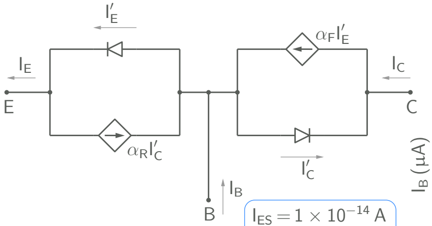
* $V_{CB} < 0$ V:
  C-B junction is forward biased, but I'_C becomes substantial only when $V_{CB} \approx -0.5$ V.
  Beyond this point, I_C drops sharply since $I_C = \alpha_F I'_E - I'_C \rightarrow$ saturation mode.

Common-emitter configuration



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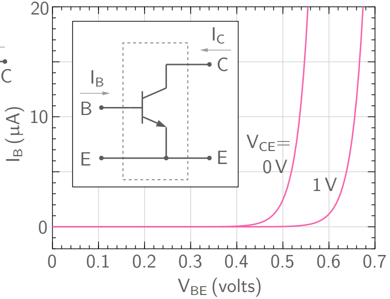

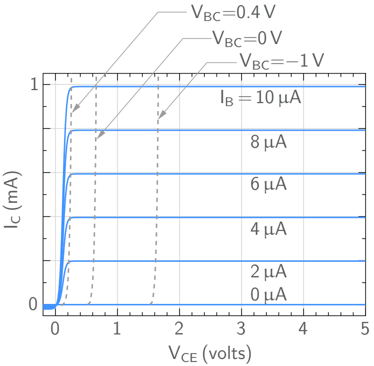

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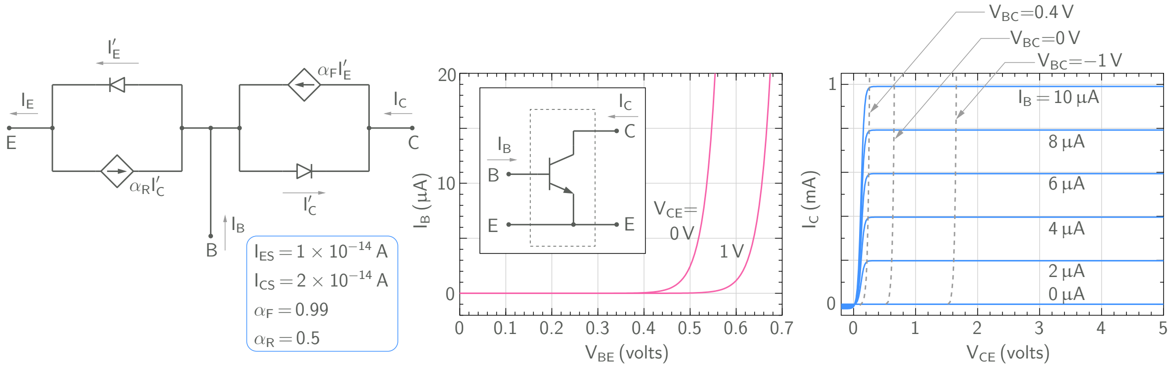

* In the active region (where I_C is constant for a given I_B), the B-C junction is reverse biased.
  $\rightarrow I'_C \approx 0 \rightarrow I_C = \alpha_F I_E = \beta I_B$, irrespective of V_{CE}.

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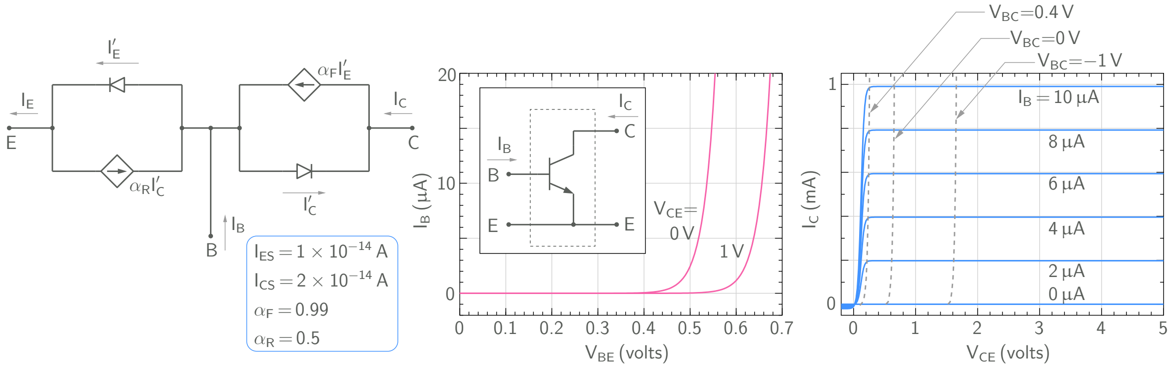

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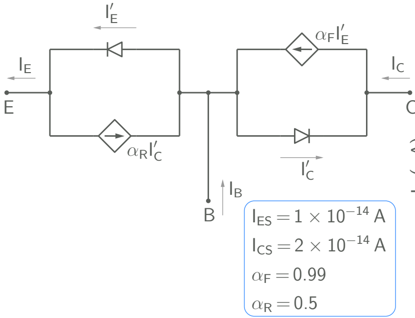
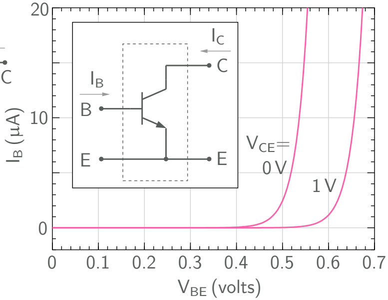
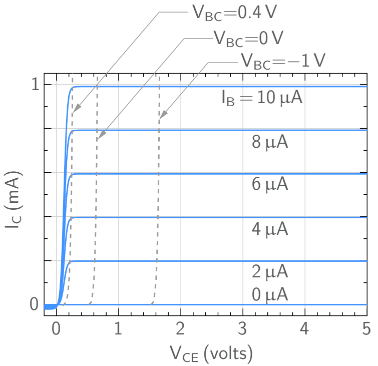
* When V_{BC} becomes greater than about 0.4 V, I'_C becomes significant, and $I_C = \alpha_F I'_E - I'_C$ decreases $\rightarrow I_C < \beta I_B$.

Common-emitter configuration







- ∗ In the active region (where I_C is constant for a given I_B), the B-C junction is reverse biased.
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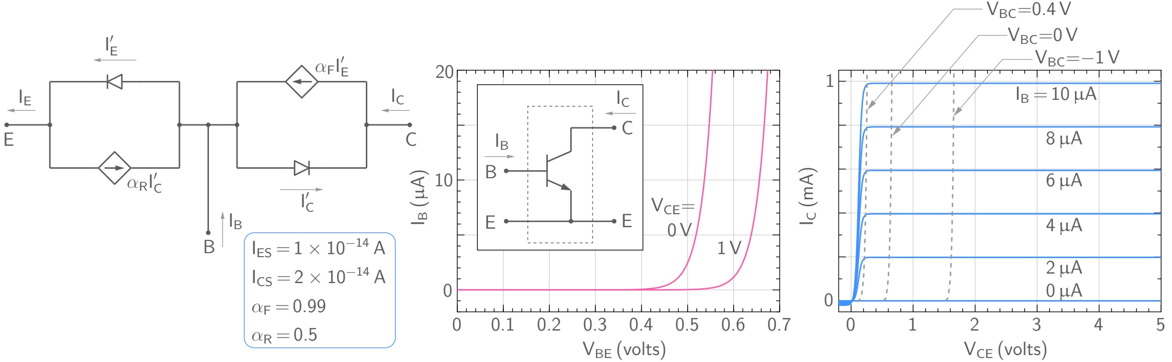
- ∗ When V_{BC} becomes greater than about 0.4 V, I'_C becomes significant, and $I_C = \alpha_F I'_E - I'_C$ decreases $\rightarrow I_C < \beta I_B$.
- ∗ In the active region (e.g., $V_{CE} = 1\,\text{V}$), V_{BE} is nearly constant ($\sim 0.65\,\text{V}$).

Common-emitter configuration



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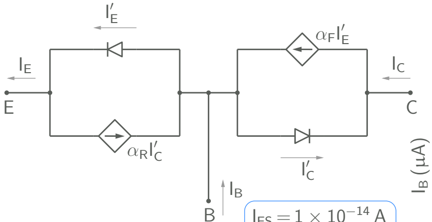
* In the saturtion region, V_{CE} is 0.2 V or smaller. This is generally true for all low-power BJTs.

Common-emitter configuration



$I_{ES} = 1 \times 10^{-14}$ A
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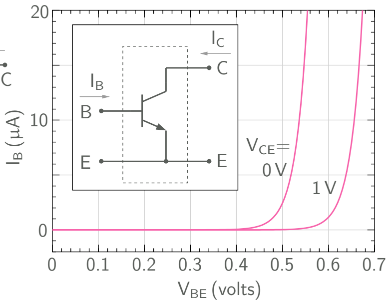
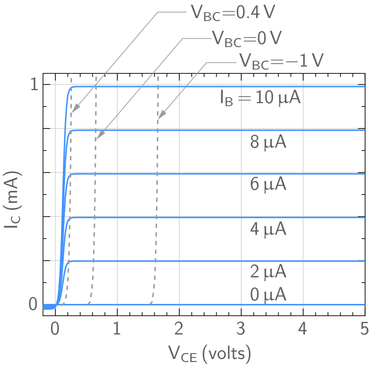
$\alpha_R = 0.5$





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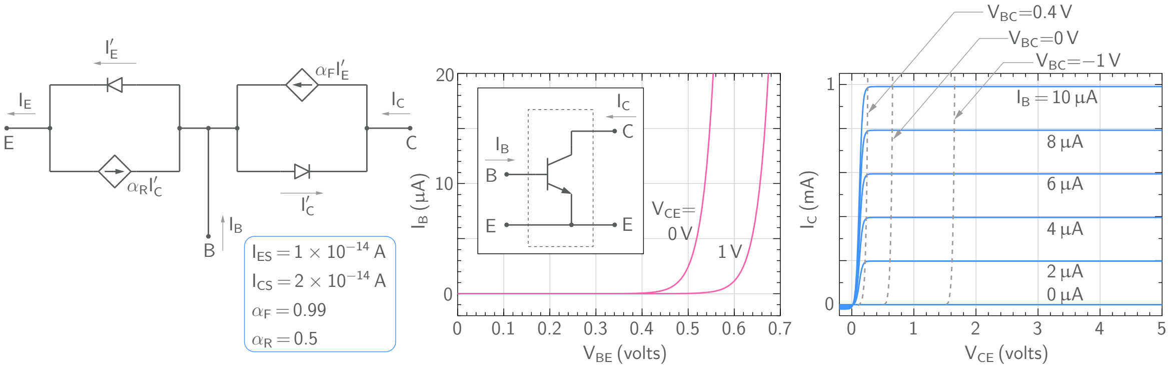

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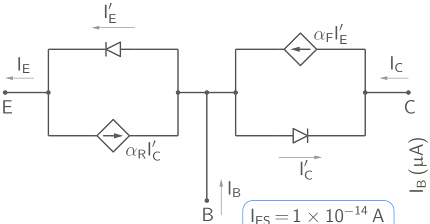

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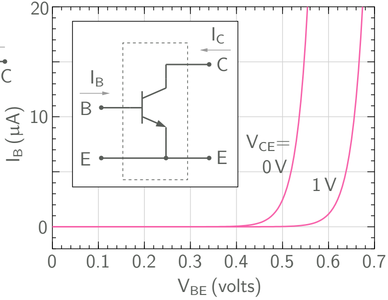

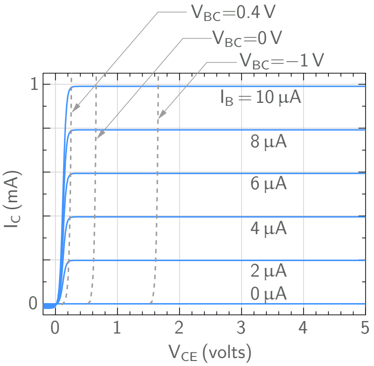

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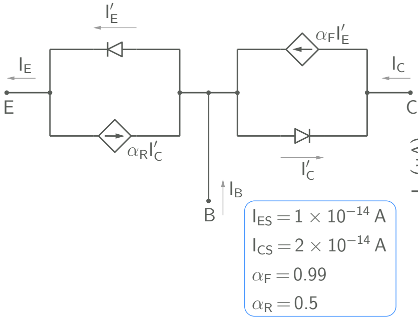

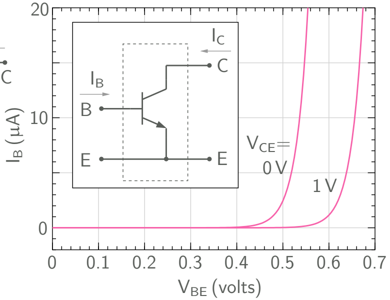

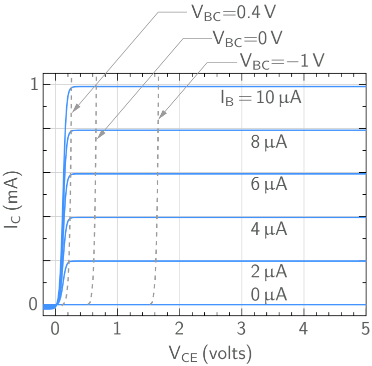

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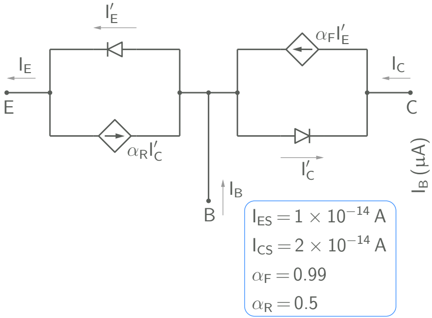
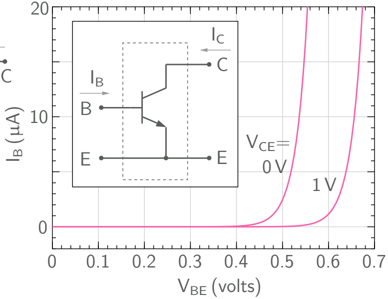
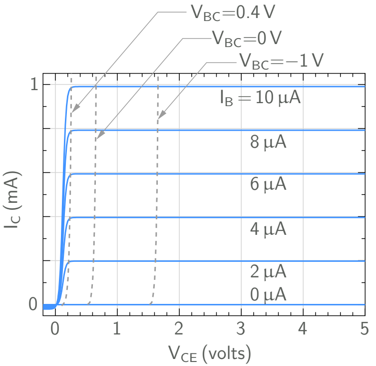
Common-emitter configuration







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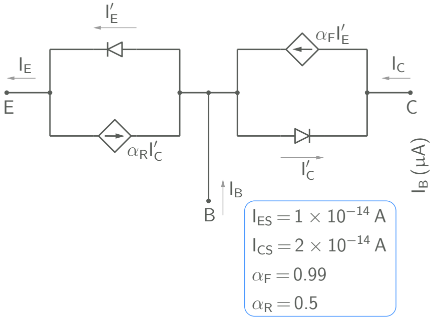

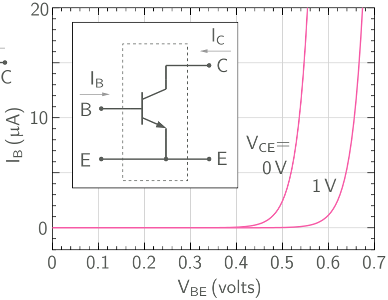

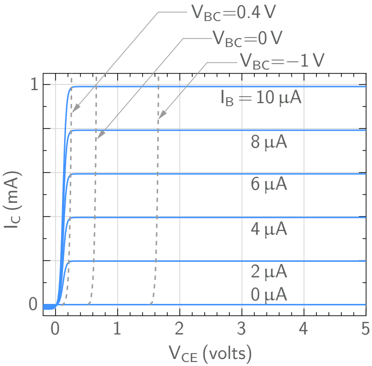

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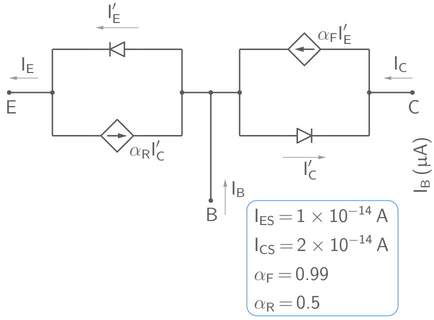
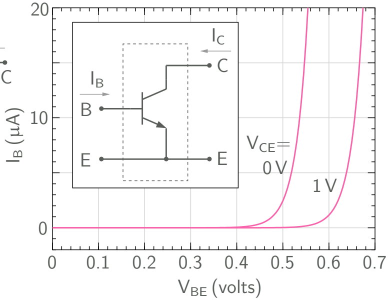
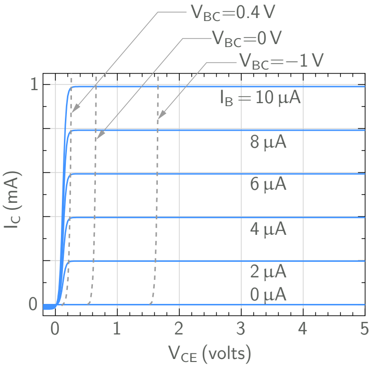
Common-emitter configuration







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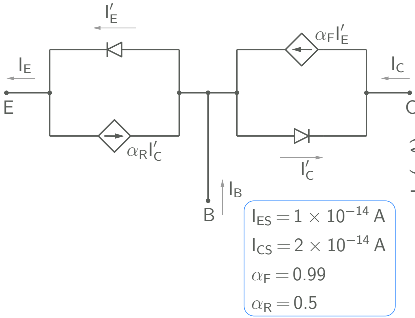

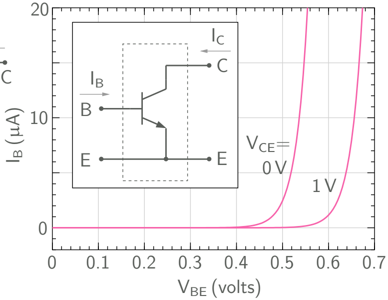

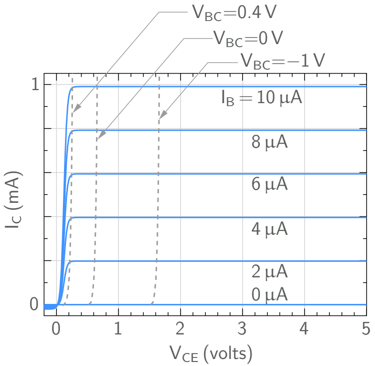

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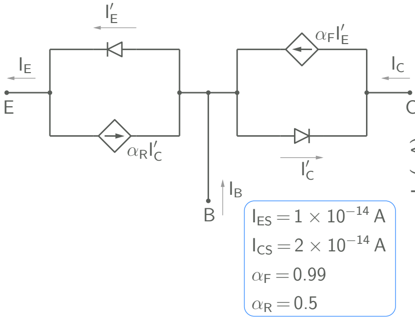
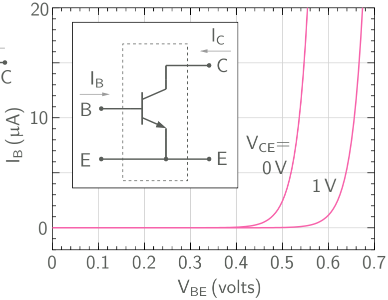
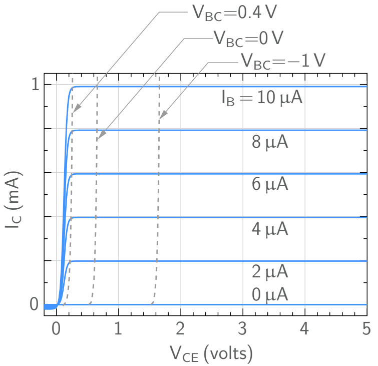
Common-emitter configuration







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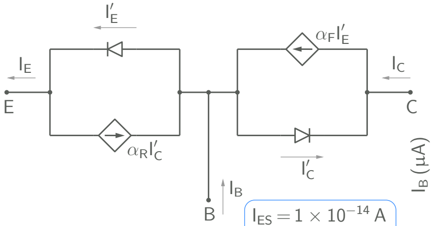

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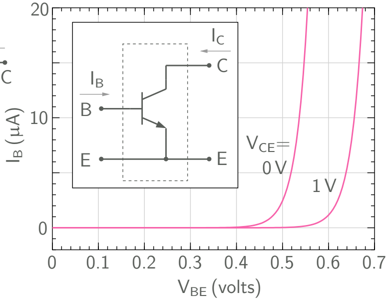

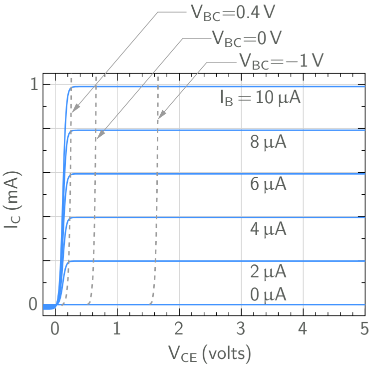

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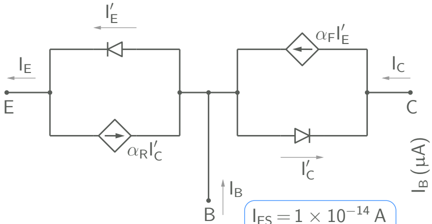
Common-emitter configuration



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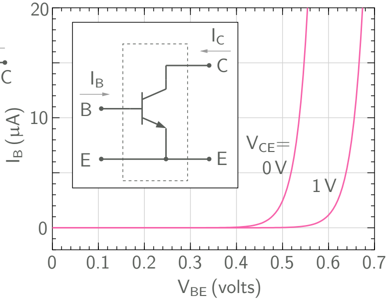

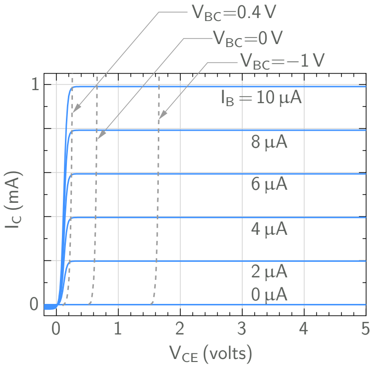

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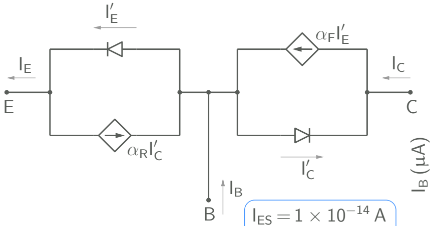

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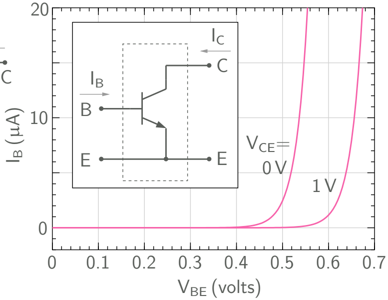

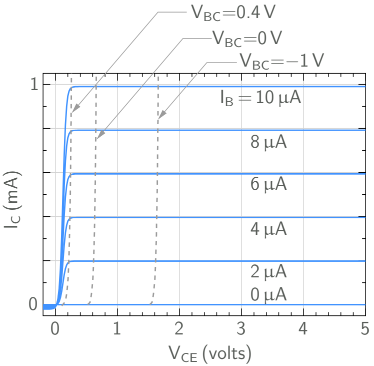

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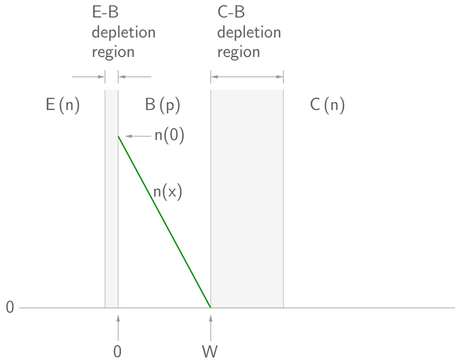
* We will consider
  - base width modulation
  - breakdown phenomena

Base width modulation

We have assumed so far that the width of the neutral base region (in the active mode) is independent of V_{BE} and V_{BC}.
This is a reasonable assumption for the following reasons.



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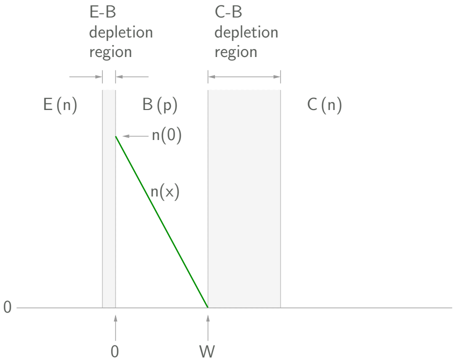

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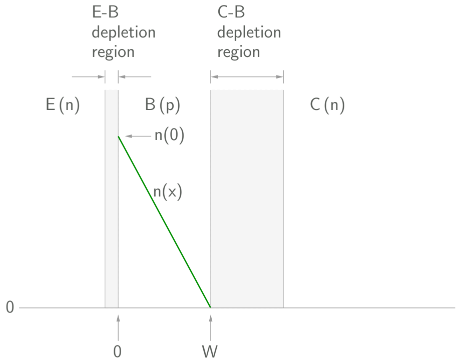
  However, the change occurs mostly on the collector side since $N_a(\mathrm{B}) \gg N_d(\mathrm{C})$.



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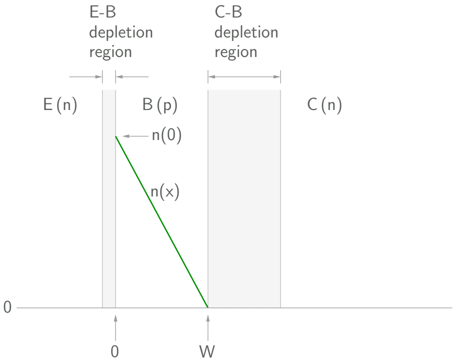
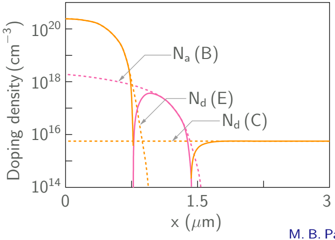
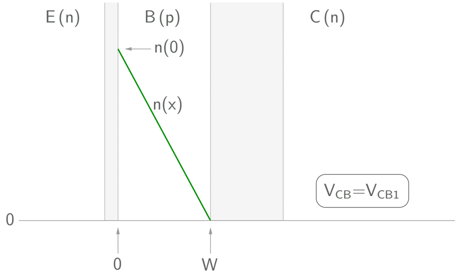
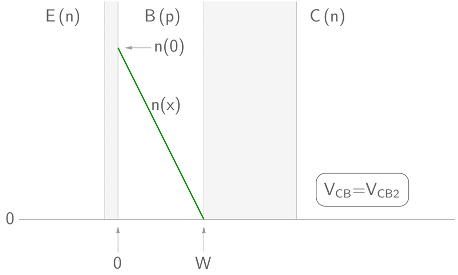




Base width modulation

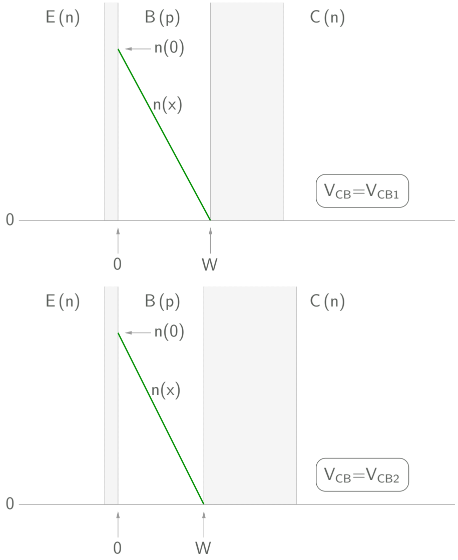




Base width modulation

- As $V_{CB}\uparrow$, the B-C depletion region expands, $W\downarrow$

$$\rightarrow\ I_C \propto \frac{dn}{dx}(W)\uparrow$$



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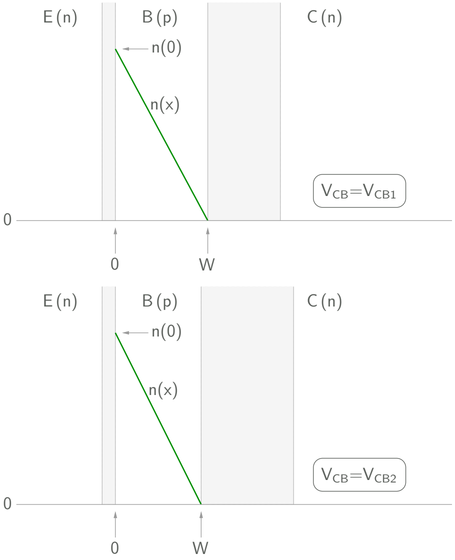
  $(V_{CE} \uparrow \ \rightarrow\ V_{CB}\,(= V_{CE} - V_{BE}) \uparrow \ \rightarrow\ W \downarrow \ \rightarrow\ I_C \uparrow)$



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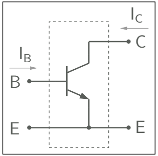
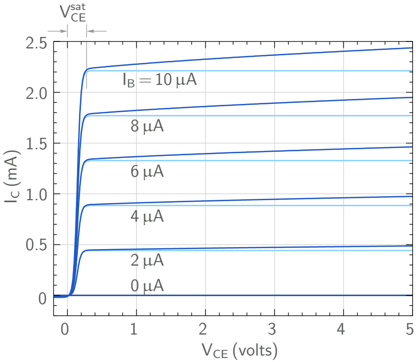
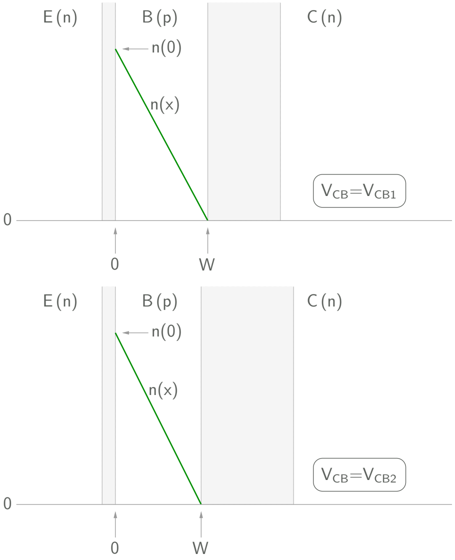
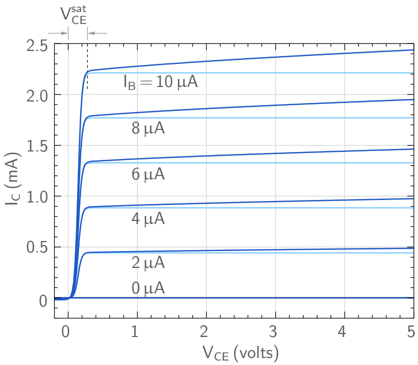
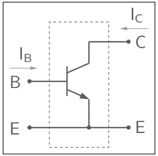


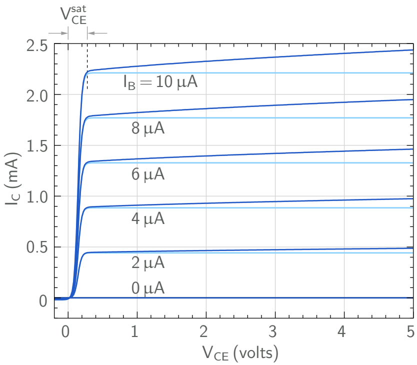


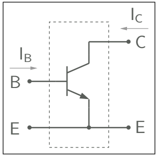


Base width modulation

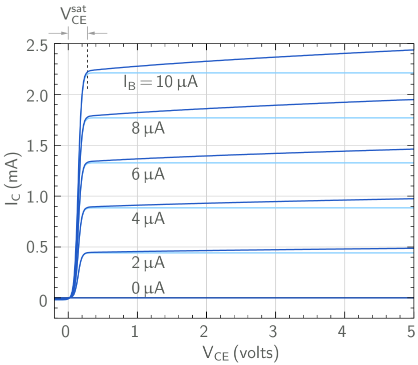


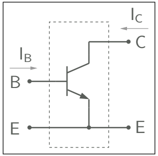


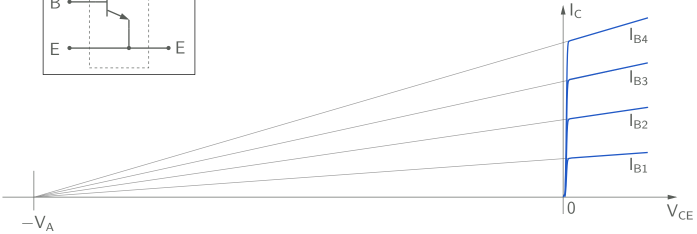




* When the active region parts of the I_C-V_{CE} curves are extended backwards, they intersect the V_{CE} axis approximately at the same point, $-V_A$.







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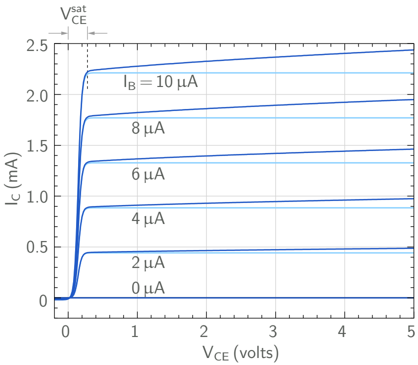

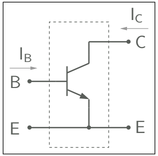

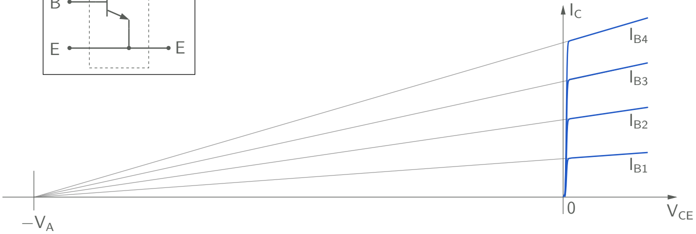

* When the active region parts of the I_C-V_{CE} curves are extended backwards, they intersect the V_{CE} axis approximately at the same point, $-V_A$.

* V_A is called the Early voltage.

* We have seen that a *pn* junction diode cannot withstand arbitrarily large reverse voltages, it breaks down at some point.

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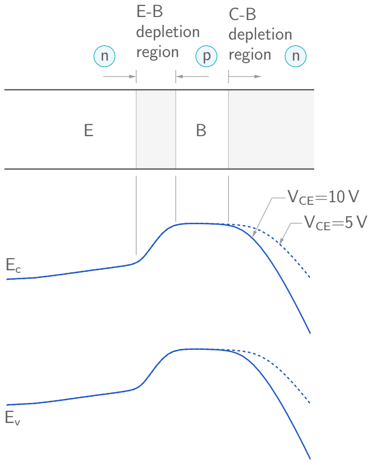
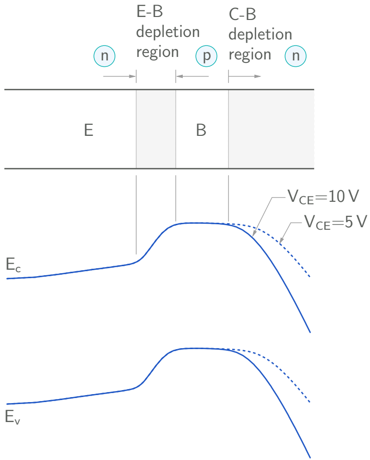
* Similarly, if the reverse bias across the B-C junction of a BJT is increased, it breaks down at some point, i.e., the collector current becomes very large.
* We will look at two breakdown mechanisms:
  - punchthrough
  - avalanche breakdown

Punchthrough



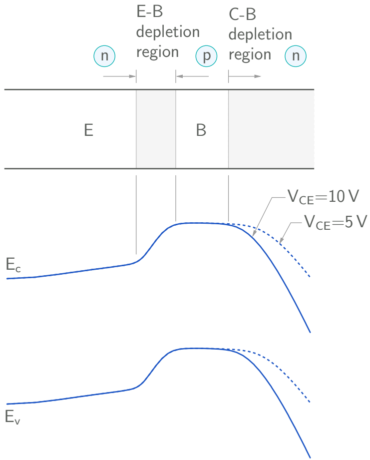
Punchthrough

* As the reverse bias V_{CB} is increased, the C-B depletion region expands $\rightarrow$ the neutral base region shrinks.



Punchthrough

* As the reverse bias V_{CB} is increased, the C-B depletion region expands $\rightarrow$ the neutral base region shrinks.
* At some point, the E-B and C-B depletion regions consume the entire base region. This condition is called punchthrough.



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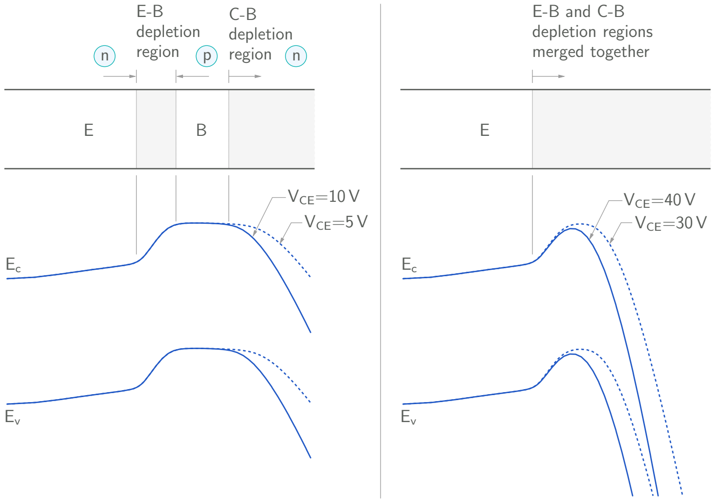

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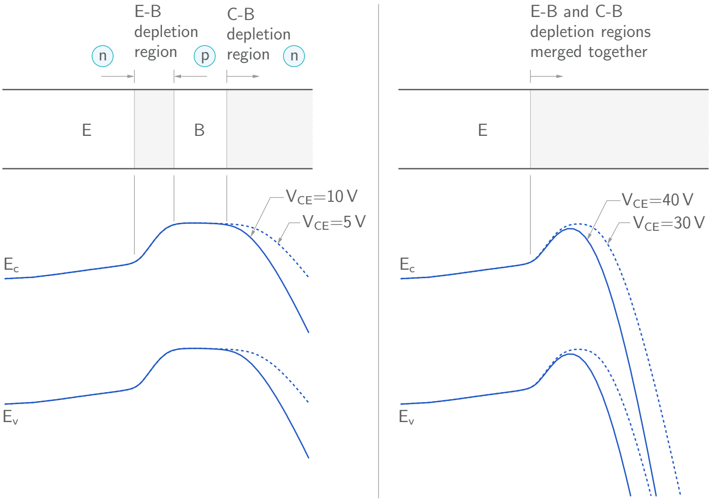
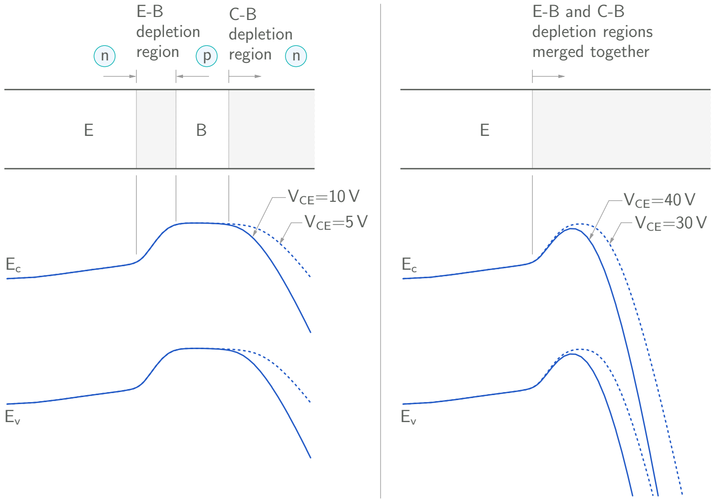
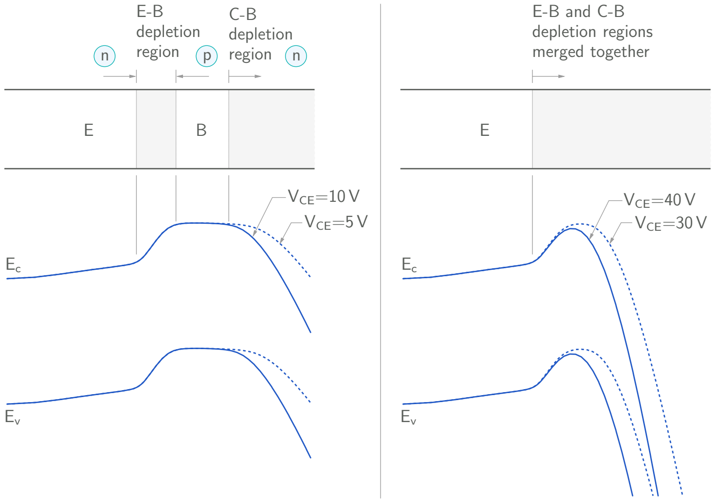
  (The band bending in the emitter region is due to non-uniform doping in the simulated structure.)



Punchthrough

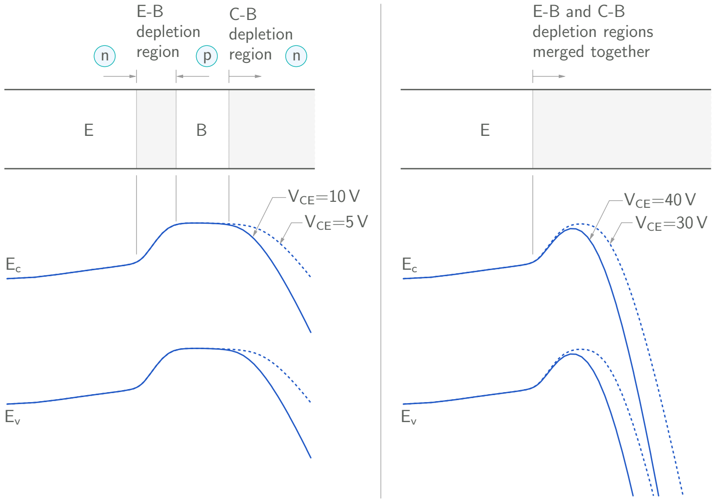


* Prior to punchthrough, an increase in the C-B reverse bias only affects the bands in the base and collector regions, leaving the E-B barrier (for electron flow) unchanged.

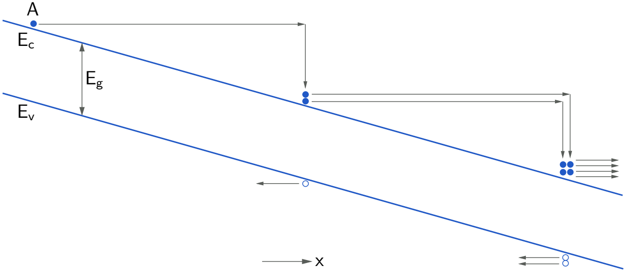


Punchthrough

* Prior to punchthrough, an increase in the C-B reverse bias only affects the bands in the base and collector regions, leaving the E-B barrier (for electron flow) unchanged.
* After punchthrough, any further increase in V_{CB} lowers the E-B potential barrier. The number of electrons injected from the emitter increases dramatically. They get swept away toward the collector, resulting in a large collector current.

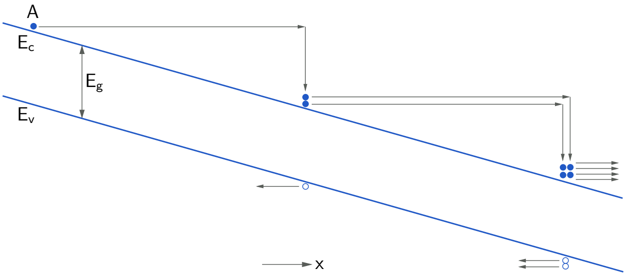


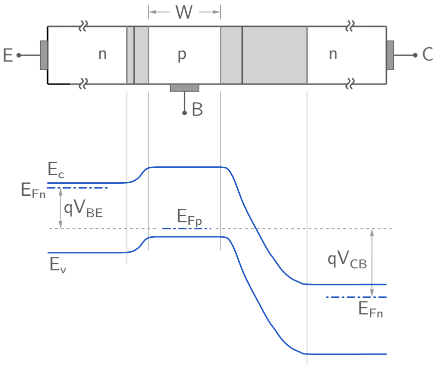
Avalanche breakdown



* Avalanche multiplication because of impact ionisation can take place in a semiconductor if the electric field is high ($\sim$ critical field $\mathcal{E}_c$).

Avalanche breakdown





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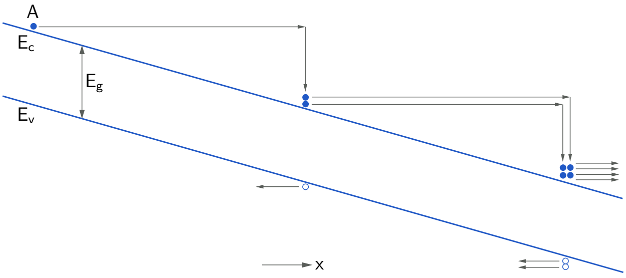
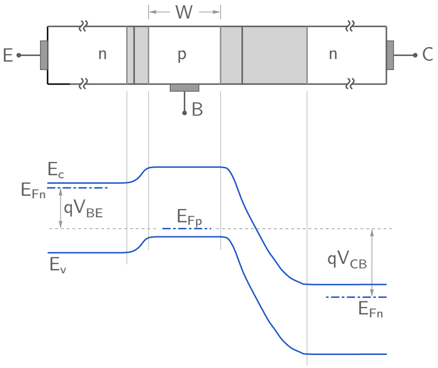
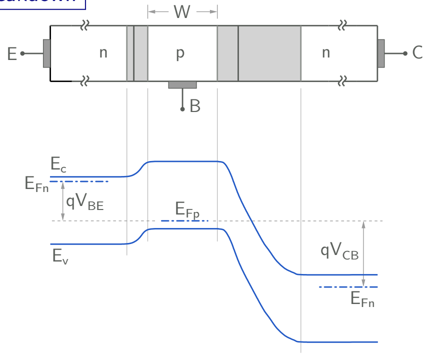




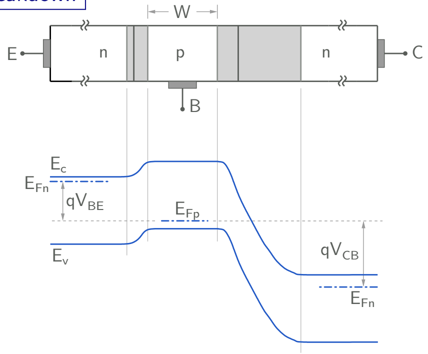
* Avalanche multiplication because of impact ionisation can take place in a semiconductor if the electric field is high ($\sim$ critical field $\mathcal{E}_c$).
* In a BJT operating in the active mode, the C-B junction is under reverse bias. If the reverse voltage is sufficiently large, avalanche breakdown can take place.

Avalanche breakdown



* The avalanche multiplication process is characterised by a multiplication factor *M*.

Avalanche breakdown

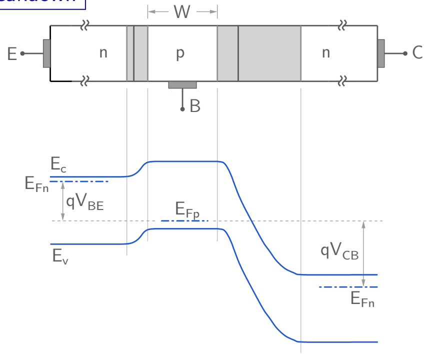


* The avalanche multiplication process is characterised by a multiplication factor M.

* Let I_0 = current through the high-field region without multiplication
  I = current through the high-field region with multiplication

  Then, $M = \dfrac{I}{I_0}$.

Avalanche breakdown



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* Let $I_0 =$ current through the high-field region without multiplication
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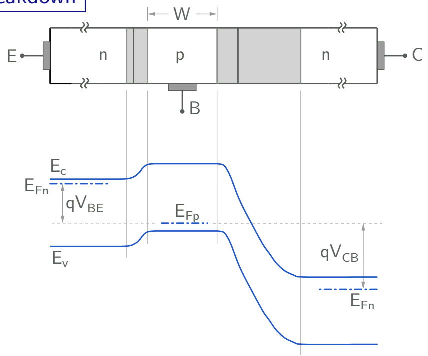
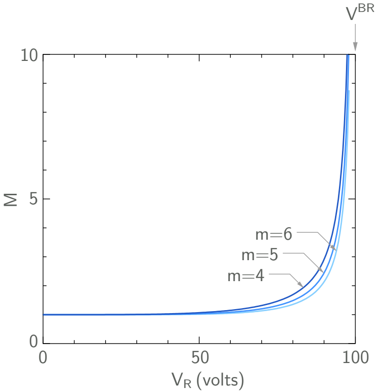
* Empirically, it is observed that $M = \dfrac{1}{1 - \left(\dfrac{V_R}{V^{\mathrm{BR}}}\right)^m}$, where $3 < m < 6$ (depending on the semiconductor),

  V_R is the reverse bias, and V^{BR} is the breakdown voltage.

Avalanche breakdown





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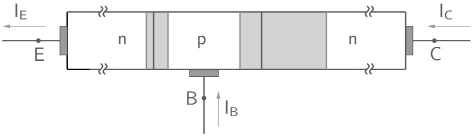
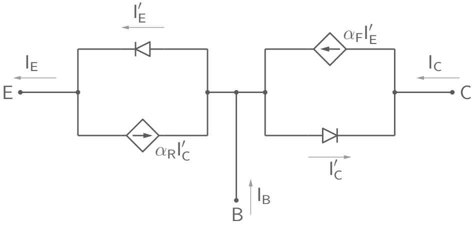
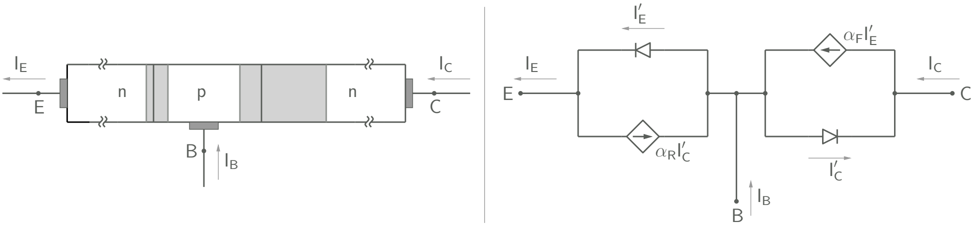
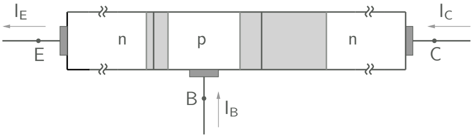


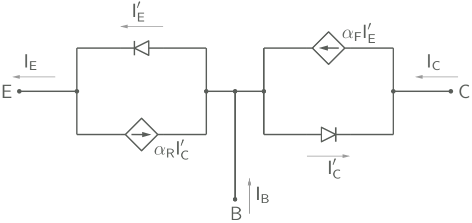


Avalanche breakdown



* Collector current without multiplication is $\alpha_F I'_E - I'_C$.

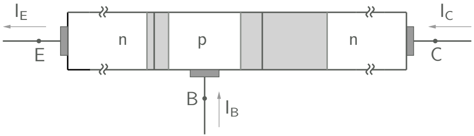


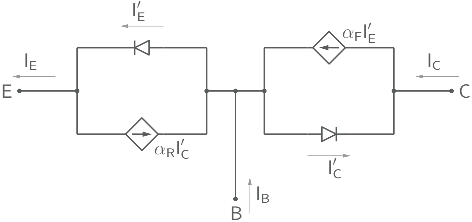


* Collector current without multiplication is $\alpha_F I'_E - I'_C$.
* Collector current with multiplication is $M\left(\alpha_F I'_E - I'_C\right)$, i.e.,

$$
\begin{aligned}
I_C &= M\left(\alpha_F I'_E + I_{CS}\right) \qquad \because I'_C \approx -I_{CS} \\
&= M\left[\alpha_F\left(I_E + \alpha_R I'_C\right) + I_{CS}\right] \\
&= M\,\alpha_F I_E + M\,I_{CS}\left(1 - \alpha_F \alpha_R\right) \\
&= M\,\alpha_F I_E + M\,I_{CBO}.
\end{aligned}
$$

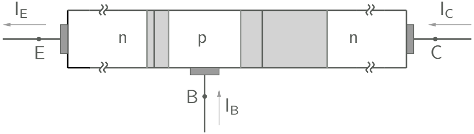
Avalanche breakdown

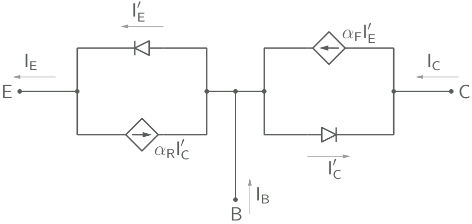




$$I_C = M\,\alpha_F\,I_E + M\,I_{CBO}.$$

Avalanche breakdown





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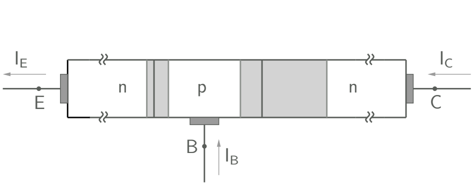
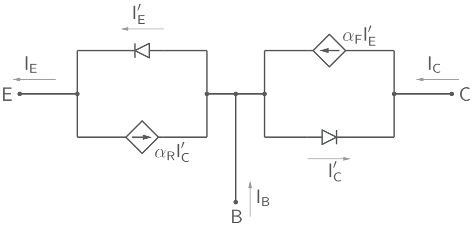
* Emitter open:

Avalanche breakdown





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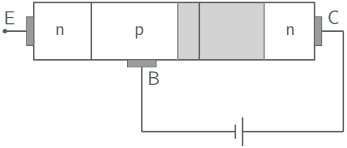
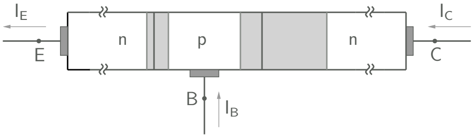
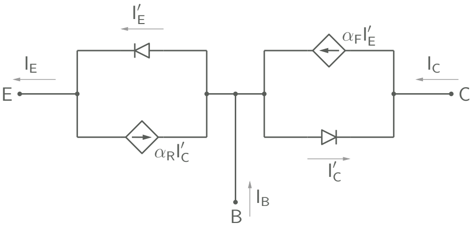


Avalanche breakdown

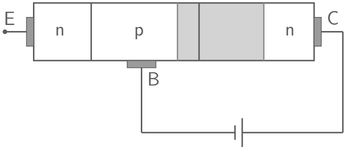




$$I_C = M\,\alpha_F\,I_E + M\,I_{CBO}.$$

* Emitter open:

$$I_C = MI_{CBO} = I_{CBO} \times \frac{1}{1 - \left(\dfrac{V_R}{V_{BC}^{\mathrm{BR}}}\right)^m}.$$



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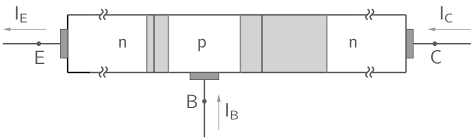
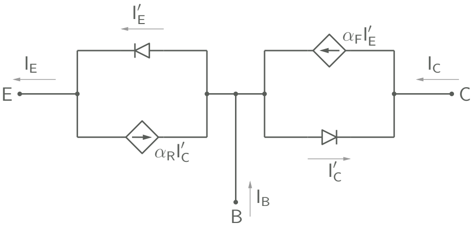


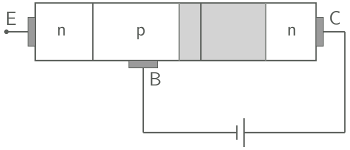


$I_C = M\,\alpha_F\,I_E + M\,I_{CBO}$.

- Emitter open:

$$I_C = M I_{CBO} = I_{CBO} \times \frac{1}{1-\left(\dfrac{V_R}{V_{BC}^{BR}}\right)^m}.$$

Breakdown voltage: As $V_R \rightarrow V_{BC}^{BR}$, $I_C \rightarrow \infty$, and therefore the breakdown voltage with the emitter open (denoted by V_{CBO}) is simply $V_{CBO} = V_{BC}^{BR}$.



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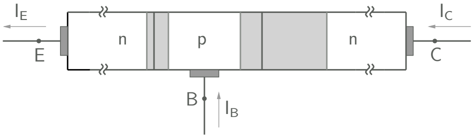

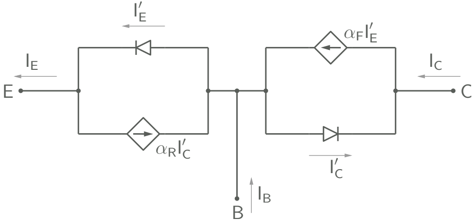

$$I_C = M\,\alpha_F\,I_E + M\,I_{CBO}.$$

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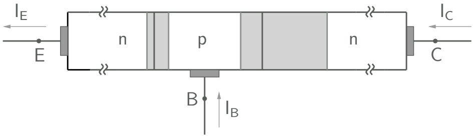
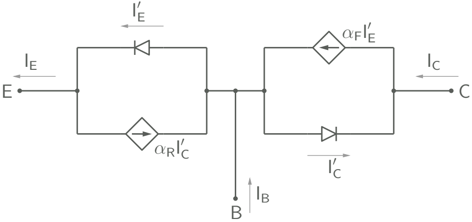
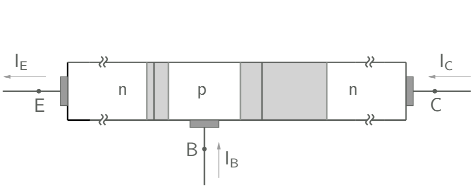


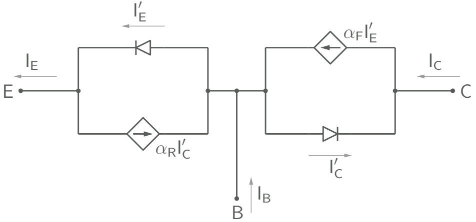


$I_C = M\,\alpha_F\,I_E + M\,I_{CBO}$.

- * Base open:

Avalanche breakdown





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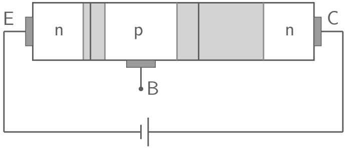
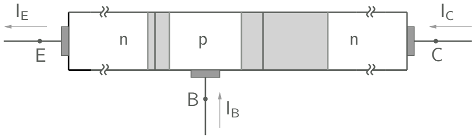
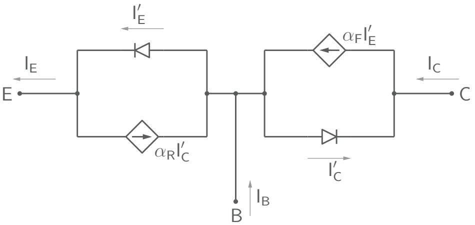


Avalanche breakdown

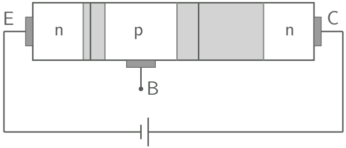


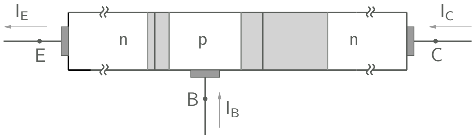


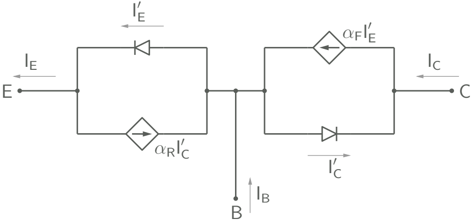
$$I_C = M\,\alpha_F I_E + M\,I_{CBO}.$$

- Base open:

$$I_C = M\,\alpha_F (I_C + I_B) + M\,I_{CBO}$$
$$= M\,\alpha_F I_C + M\,I_{CBO}$$







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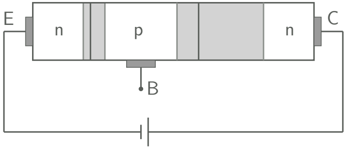
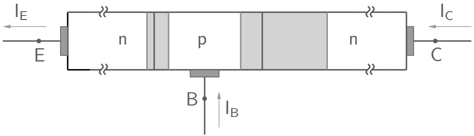
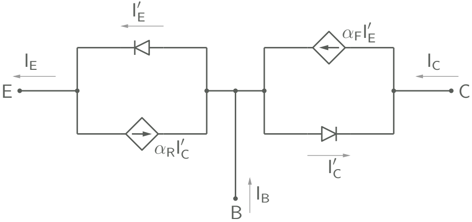
$$I_C = M\,\alpha_F\,(I_C + I_B) + M\,I_{CBO}$$
$$= M\,\alpha_F\,I_C + M\,I_{CBO}$$
$$\rightarrow\ I_C(1 - M\alpha_F) = M\,I_{CBO} \rightarrow\ I_C = \frac{M\,I_{CBO}}{1 - M\alpha_F}.$$



Avalanche breakdown





$I_C = M\,\alpha_F I_E + M\,I_{CBO}$.

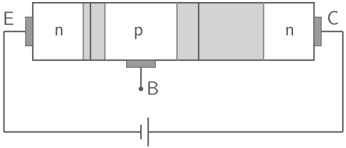
* Base open:

$$I_C = M\,\alpha_F (I_C + I_B) + M\,I_{CBO}$$

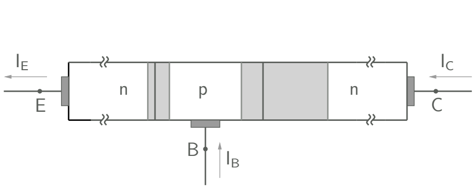
$$= M\,\alpha_F I_C + M\,I_{CBO}$$

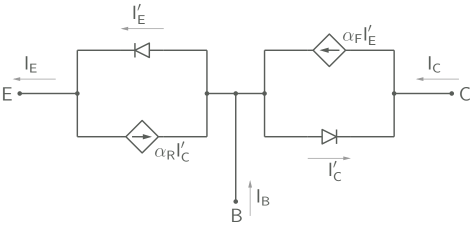
$$\rightarrow \ I_C(1 - M\alpha_F) = M\,I_{CBO} \rightarrow \ I_C = \frac{M\,I_{CBO}}{1 - M\alpha_F}.$$

Breakdown condition: $M\alpha_F \rightarrow 1$ or $M \rightarrow \dfrac{1}{\alpha_F}$.



Avalanche breakdown





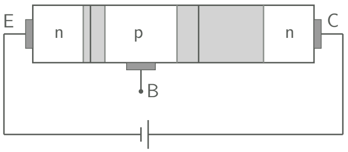
$I_C = M\,\alpha_F I_E + M\,I_{CBO}$.

* Base open:

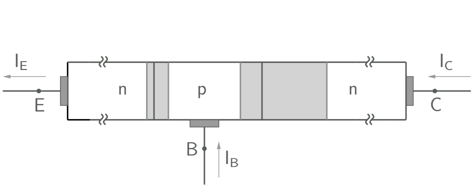
$$I_C = M\,\alpha_F (I_C + I_B) + M\,I_{CBO}$$
$$= M\,\alpha_F I_C + M\,I_{CBO}$$
$$\rightarrow\ I_C(1 - M\alpha_F) = M\,I_{CBO} \rightarrow\ I_C = \frac{M\,I_{CBO}}{1 - M\alpha_F}.$$

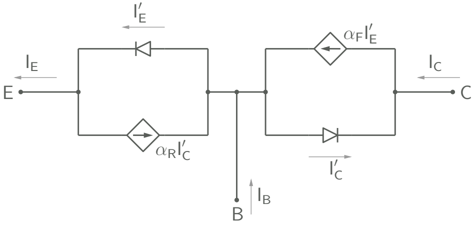
Breakdown condition: $M\alpha_F \rightarrow 1$ or $M \rightarrow \dfrac{1}{\alpha_F}$.

$$\rightarrow\ \frac{1}{1 - \left(\dfrac{V_R}{V_{BC}^{\mathrm{BR}}}\right)^m} = \frac{1}{\alpha_F} = \frac{\beta_F + 1}{\beta_F}$$



Avalanche breakdown





$I_C = M\,\alpha_F I_E + M\,I_{CBO}.$

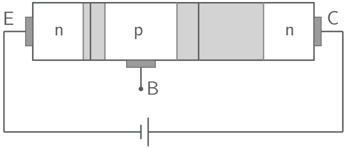
* Base open:

$$I_C = M\,\alpha_F (I_C + I_B) + M\,I_{CBO}$$
$$= M\,\alpha_F I_C + M\,I_{CBO}$$
$$\rightarrow\ I_C(1 - M\alpha_F) = M\,I_{CBO}\ \rightarrow\ I_C = \frac{M\,I_{CBO}}{1 - M\alpha_F}.$$

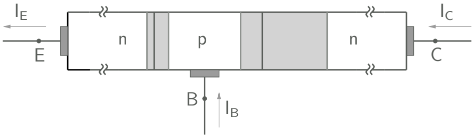
Breakdown condition: $M\alpha_F \rightarrow 1$ or $M \rightarrow \dfrac{1}{\alpha_F}$.

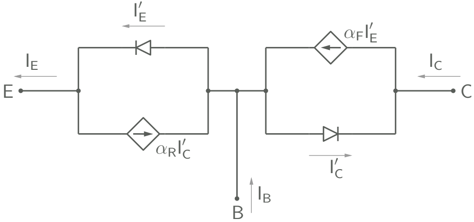
$$\rightarrow\ \frac{1}{1 - \left(\dfrac{V_R}{V_{BC}^{\text{BR}}}\right)^m} = \frac{1}{\alpha_F} = \frac{\beta_F + 1}{\beta_F}$$

$$\rightarrow V_R \equiv V_{CEO} = \frac{V_{BC}^{\text{BR}}}{(\beta_F + 1)^{1/m}} \approx \frac{V_{CBO}}{\beta_F^{1/m}}.$$

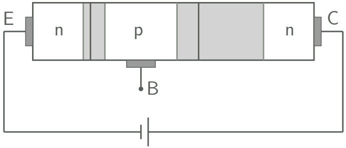


Avalanche breakdown

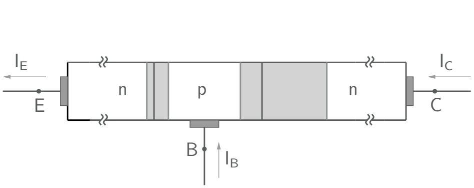


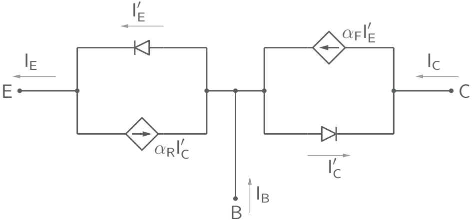


* Base open: $V_{CEO} = \dfrac{V_{BC}^{\mathrm{BR}}}{(\beta_F + 1)^{1/m}} \approx \dfrac{V_{CBO}}{\beta_F^{1/m}}$.



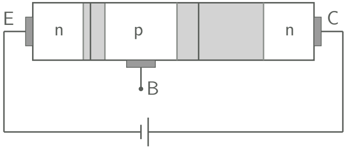
Avalanche breakdown

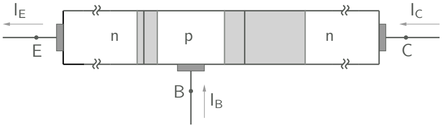




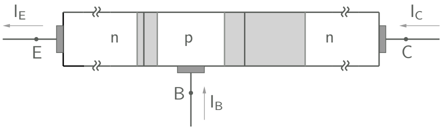
* Base open: $V_{CEO} = \dfrac{V_{BC}^{\mathrm{BR}}}{(\beta_F + 1)^{1/m}} \approx \dfrac{V_{CBO}}{\beta_F^{1/m}}$.

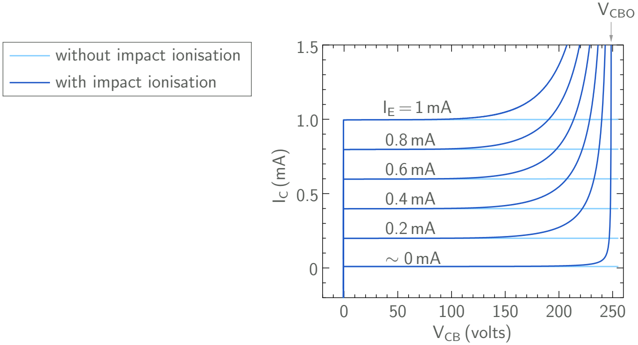
  As an example, for $\beta_F = 200$ and $m = 4$, $V_{CEO} = V_{CBO}/3.8$, which is significantly smaller than V_{CBO}.



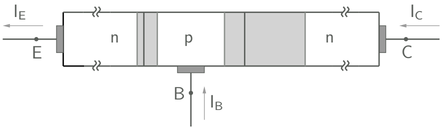


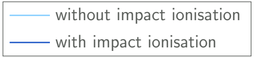
Significance of V_{CBO} and V_{CEO}:

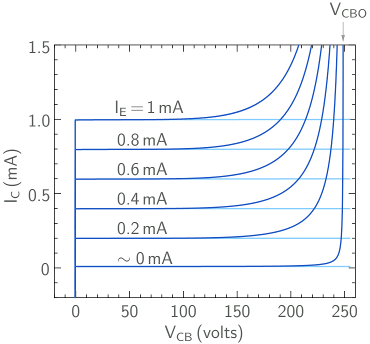




Significance of V_{CBO} and V_{CEO}:

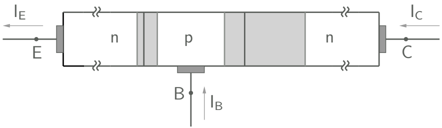


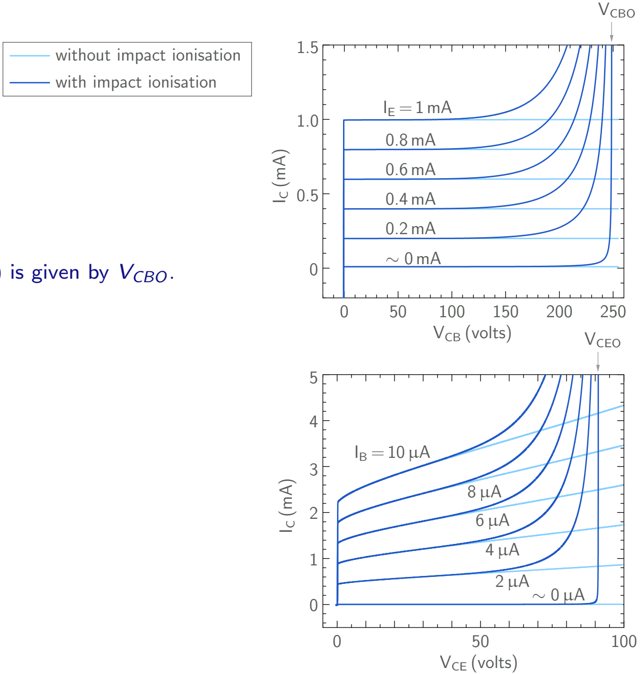




Significance of V_{CBO} and V_{CEO}:

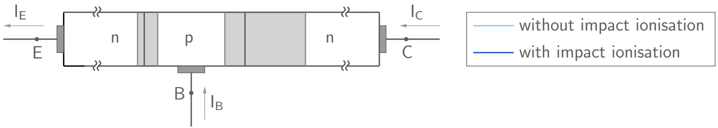
* When $I_E = 0$, the breakdown voltage (V_{CB}) is given by V_{CBO}. In the above example, it is $\sim 230\,\text{V}$.

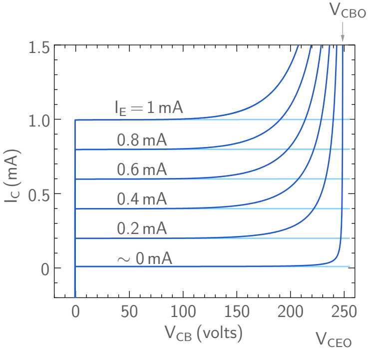


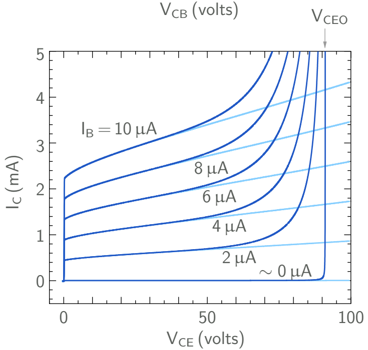


Significance of V_{CBO} and V_{CEO}:

* When $I_E = 0$, the breakdown voltage (V_{CB}) is given by V_{CBO}.
  In the above example, it is ~ 230 V.

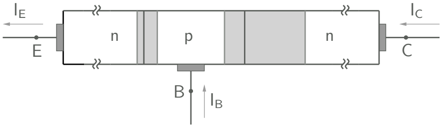


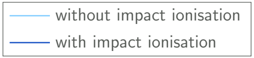


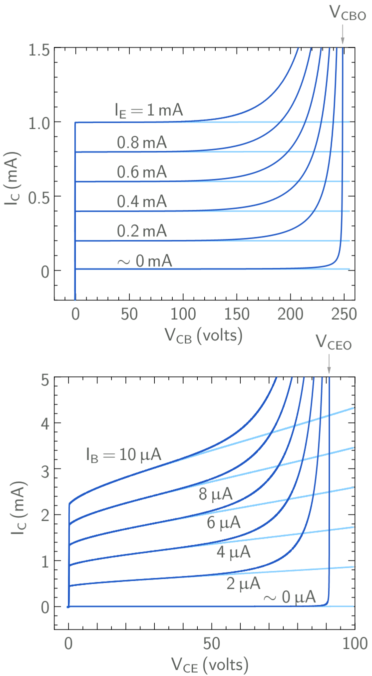


Significance of V_{CBO} and V_{CEO}:

* When $I_E = 0$, the breakdown voltage (V_{CB}) is given by V_{CBO}. In the above example, it is $\sim 230\,$V.
* When $I_B = 0$, the breakdown voltage (V_{CE}) is given by V_{CEO}. In the above example, it is $\sim 90\,$V, which is significantly lower, as we would expect.

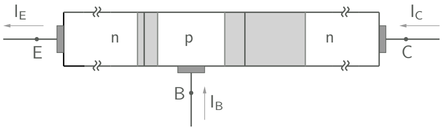


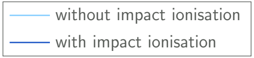




Significance of V_{CBO} and V_{CEO}:

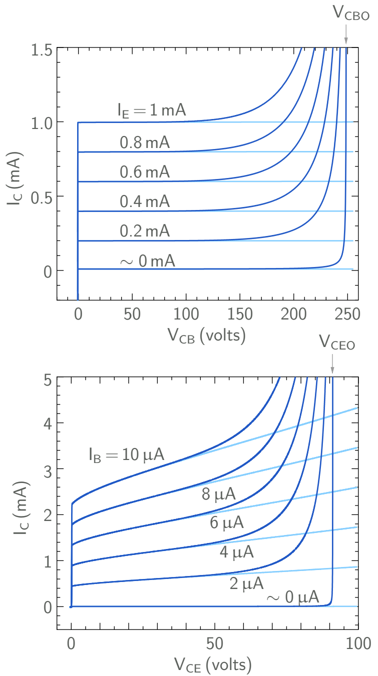
* When $I_E = 0$, the breakdown voltage (V_{CB}) is given by V_{CBO}. In the above example, it is $\sim$ 230 V.
* When $I_B = 0$, the breakdown voltage (V_{CE}) is given by V_{CEO}. In the above example, it is $\sim$ 90 V, which is significantly lower, as we would expect.
* Note that the slope of the I_C-V_{CE} curves in the linear region without impact ionisation is because of base width modulation.

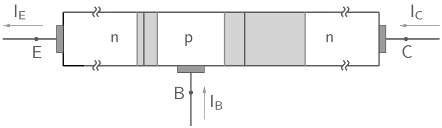


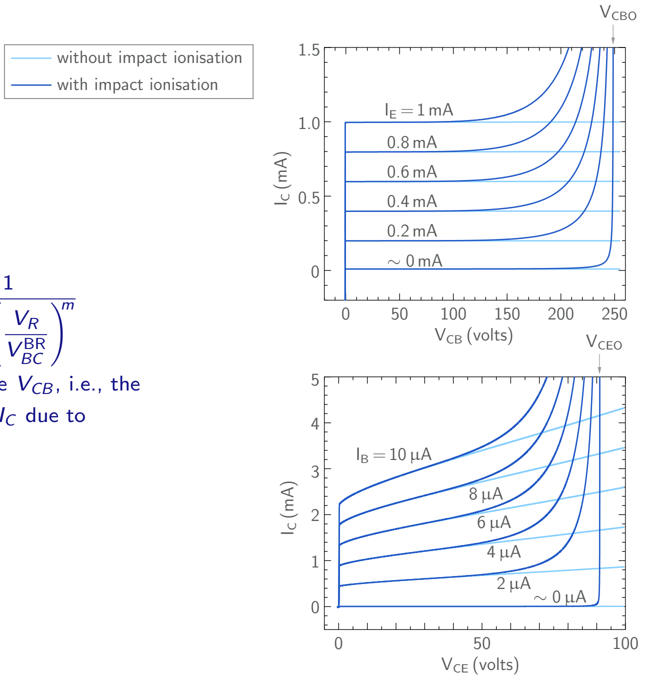


$$I_C = M\,\alpha_F I_E + M\,I_{CBO}$$

$$= \frac{M\alpha_F I_B}{1 - M\alpha_F} + \frac{M I_{CBO}}{1 - M\alpha_F}, \quad \text{with} \quad M = \frac{1}{1 - \left(\dfrac{V_R}{V_{BC}^{BR}}\right)^m}$$



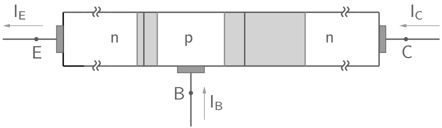


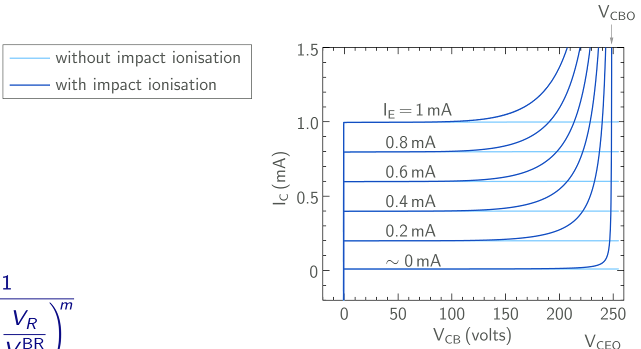


$$I_C = M\,\alpha_F I_E + M\,I_{CBO}$$

$$= \frac{M\alpha_F I_B}{1 - M\alpha_F} + \frac{M I_{CBO}}{1 - M\alpha_F}, \quad \text{with} \quad M = \frac{1}{1 - \left(\dfrac{V_R}{V_{BC}^{BR}}\right)^m}$$

* Common-base characteristics: For the same V_{CB}, i.e., the same multiplication factor, the increase in I_C due to multiplication is larger for larger I_E.

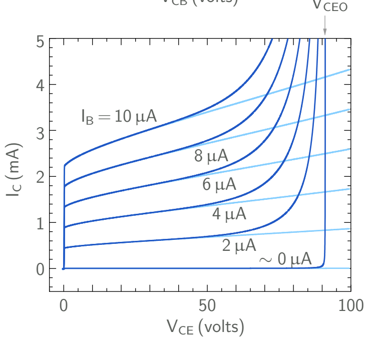




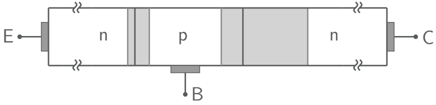
$$I_C = M\,\alpha_F\,I_E + M\,I_{CBO}$$

$$= \frac{M\alpha_F I_B}{1-M\alpha_F} + \frac{M I_{CBO}}{1-M\alpha_F}, \quad \text{with} \quad M = \frac{1}{1-\left(\dfrac{V_R}{V_{BC}^{BR}}\right)^m}$$

- * Common-base characteristics: For the same V_{CB}, i.e., the same multiplication factor, the increase in I_C due to multiplication is larger for larger I_E.
- * Common-emitter characteristics: For the same V_{CE} ($\sim V_{CB}$), i.e., the same multiplication factor, the increase in I_C due to multiplication is larger for larger I_B.

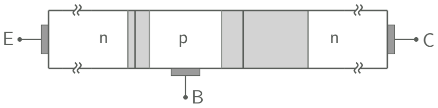


$V_{CEO} < V_{CBO}$: qualitative exaplnation



* V_{CEO} is sbustantially smaller than V_{CBO} although, in both cases, the breakdown is related to the *same* junction (the C-B junction). Why?

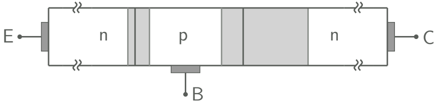
$V_{CEO} < V_{CBO}$: qualitative exaplnation



* V_{CEO} is sbustantially smaller than V_{CBO} although, in both cases, the breakdown is related to the *same* junction (the C-B junction). Why?

* With the emitter open, the breakdown process is really no different than an isolated C-B junction.

$V_{CEO} < V_{CBO}$: qualitative exaplnation



* V_{CEO} is sbustantially smaller than V_{CBO} although, in both cases, the breakdown is related to the *same* junction (the C-B junction). Why?
* With the emitter open, the breakdown process is really no different than an isolated C-B junction.
* With the base open, the situation is different.

$\boxed{V_{CEO} < V_{CBO}\text{: qualitative exaplnation}}$

Consider an electron undergoing impact ionisation with the base open.

$V_{CEO} < V_{CBO}$: qualitative exaplnation

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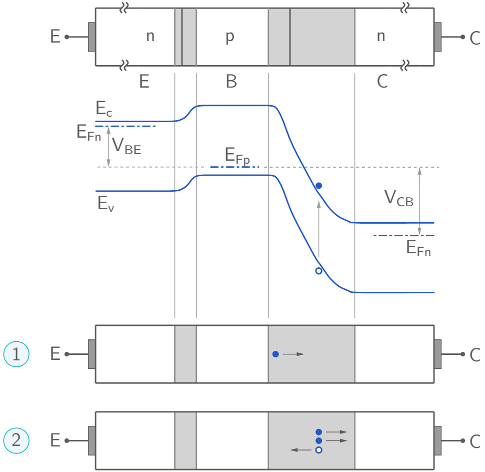
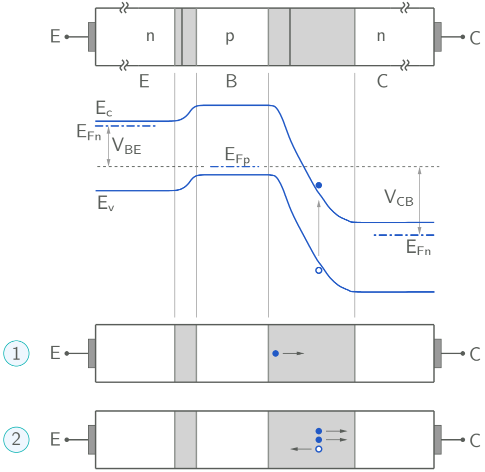


$V_{CEO} < V_{CBO}$: qualitative exaplnation

Consider an electron undergoing impact ionisation with the base open.

* A hole generated by impact ionisation experiences an electric field pointing toward the base, and it enters the neutral base region.



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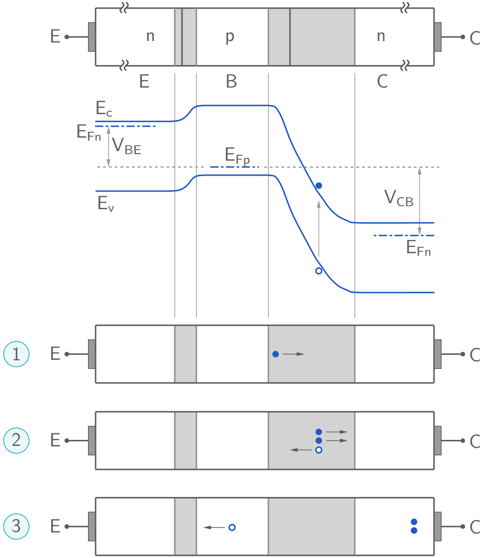
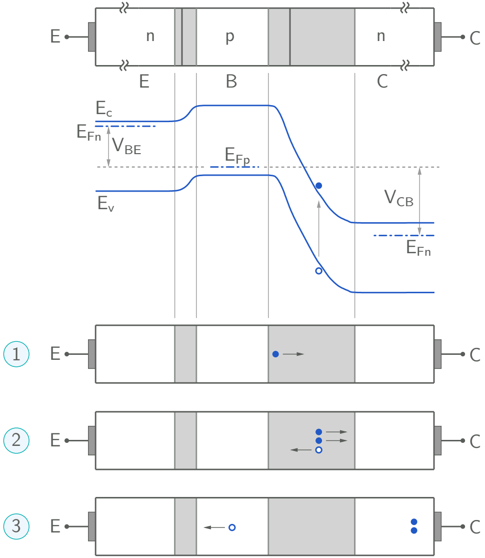


$V_{CEO} < V_{CBO}$: qualitative exaplnation

Consider an electron undergoing impact ionisation with the base open.

* A hole generated by impact ionisation experiences an electric field pointing toward the base, and it enters the neutral base region.
* Since the base is open, the hole gets injected to the emitter side.

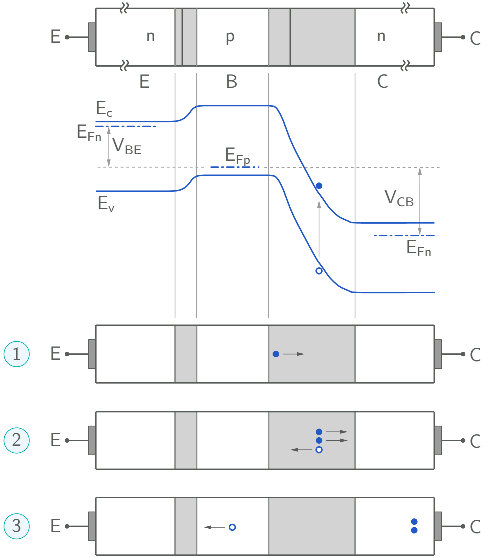


$V_{CEO} < V_{CBO}$: qualitative exaplnation

Consider an electron undergoing impact ionisation with the base open.

* A hole generated by impact ionisation experiences an electric field pointing toward the base, and it enters the neutral base region.
* Since the base is open, the hole gets injected to the emitter side.
* The electron and hole components at the B-E junction are related by

$$\gamma = \frac{I_{nE}}{I_E} = \frac{I_{nE}}{I_{nE} + I_{pE}}$$



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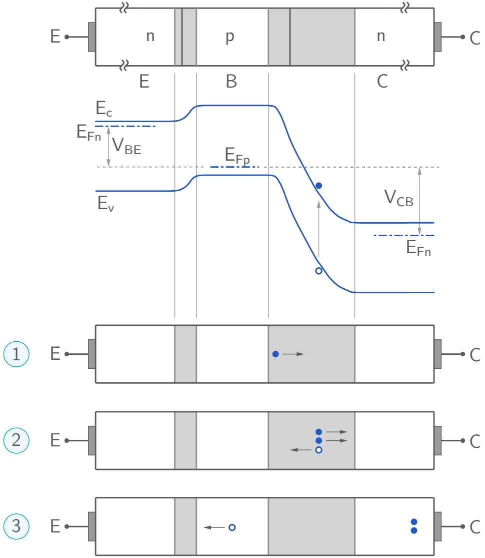

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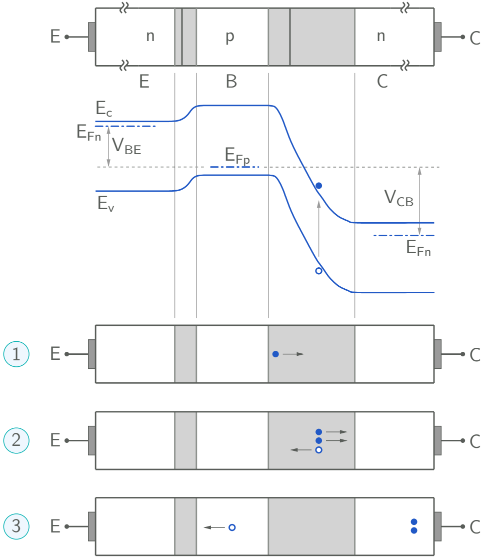
$\rightarrow$ injection of one hole into the emitter region causes injection of $\dfrac{\gamma}{1-\gamma}$ electrons from the emitter into the base region.



$V_{CEO} < V_{CBO}$: qualitative exaplnation

Consider an electron undergoing impact ionisation with the base open.

* A hole generated by impact ionisation experiences an electric field pointing toward the base, and it enters the neutral base region.
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* The electron and hole components at the B-E junction are related by

$$\gamma = \frac{I_{nE}}{I_E} = \frac{I_{nE}}{I_{nE} + I_{pE}} \rightarrow \frac{I_{nE}}{I_{pE}} = \frac{\gamma}{1-\gamma}.$$

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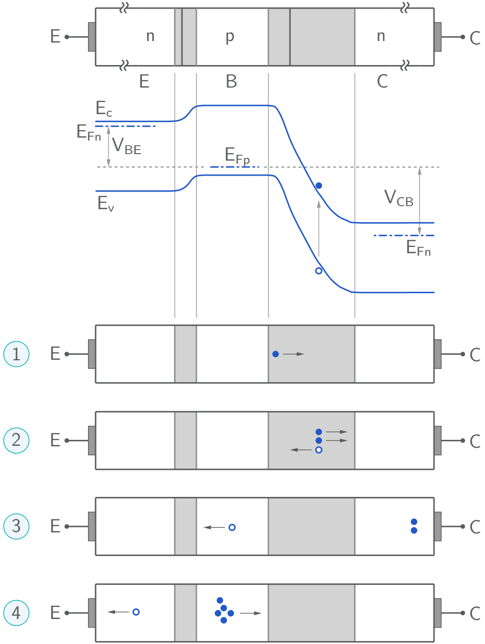

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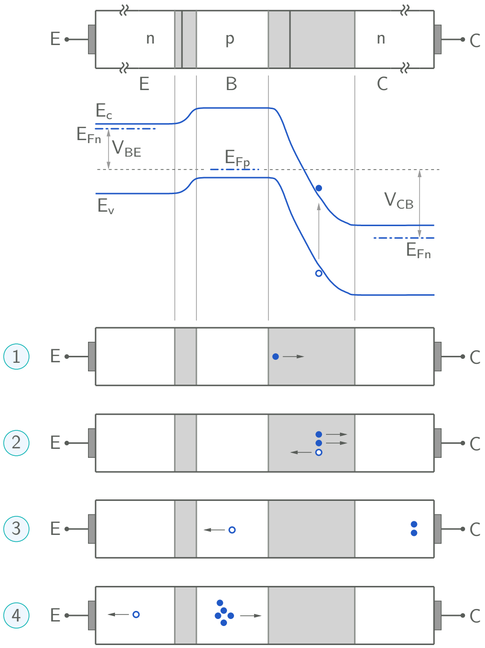
* Since the base is open, the hole gets injected to the emitter side.
* The electron and hole components at the B-E junction are related by

  $$\gamma = \frac{I_{nE}}{I_E} = \frac{I_{nE}}{I_{nE} + I_{pE}} \rightarrow \frac{I_{nE}}{I_{pE}} = \frac{\gamma}{1-\gamma}.$$

  $\rightarrow$ injection of one hole into the emitter region causes injection of $\dfrac{\gamma}{1-\gamma}$ electrons from the emitter into the base region.

  $\rightarrow$ multiplication of carriers is enhanced $\rightarrow$ lower breakdown voltage [Pierret].



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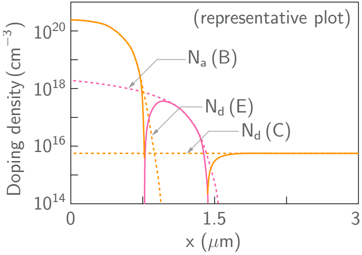

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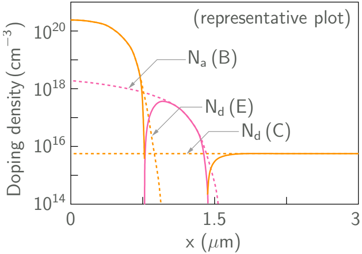

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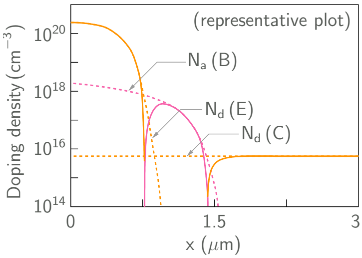

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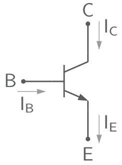

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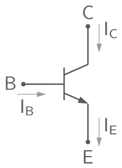

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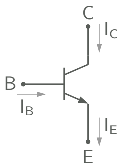

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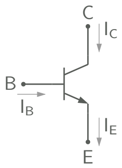

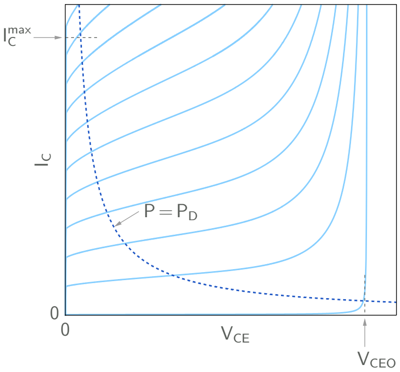

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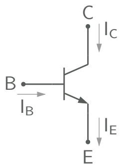
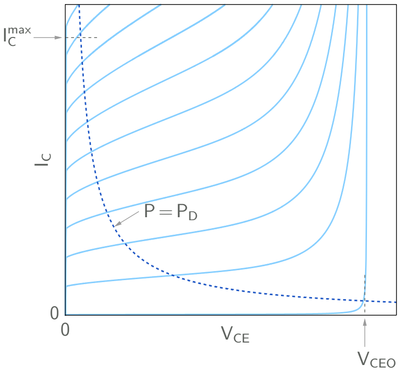
  In designing a BJT amplifier, the DC bias values are subject to the constraints due to I_C^{max}, V_{CEO}, and P_D.





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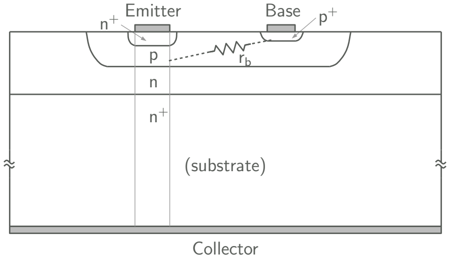

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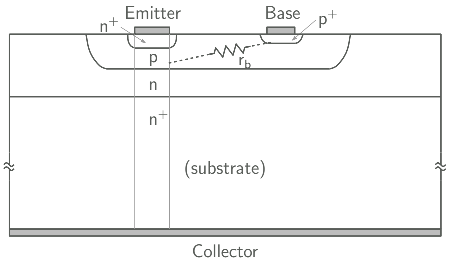

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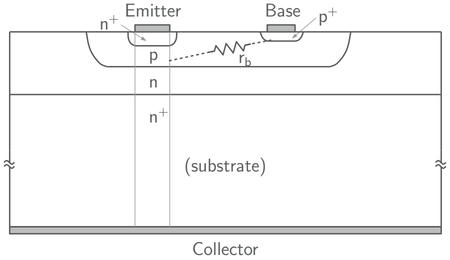

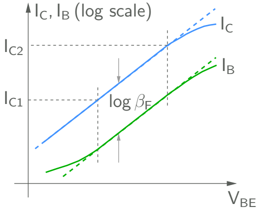

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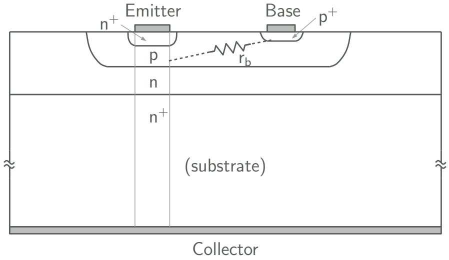

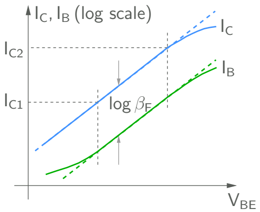

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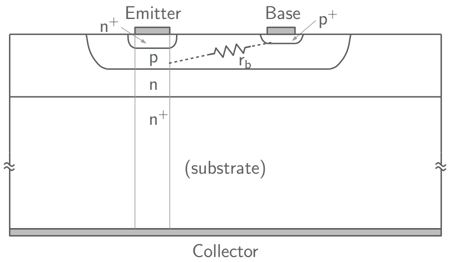

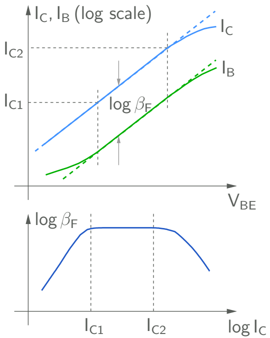

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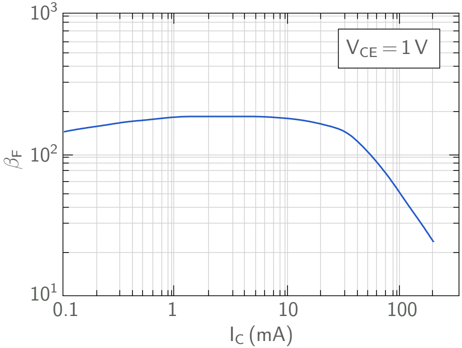

(Note: β_F varies from device to device.)

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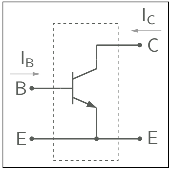
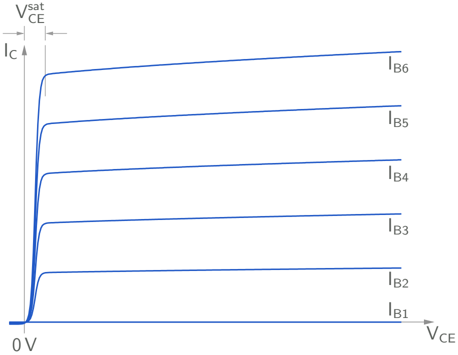
* $V_{CE}^{sat} = 0.2\,\text{V}$ at $I_C = 10\,\text{mA}$, $V_{CE}^{sat} = 0.3\,\text{V}$ at $I_C = 50\,\text{mA}$.





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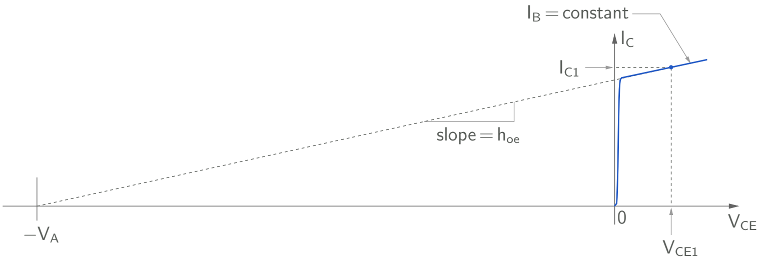

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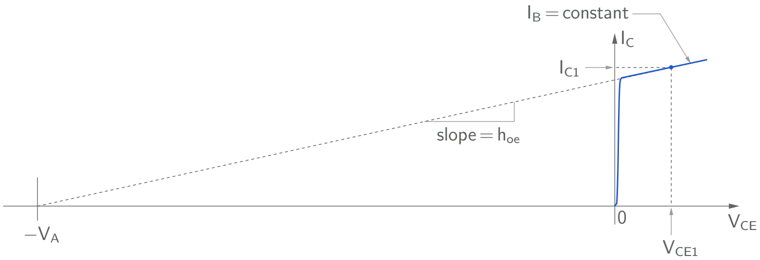

From h_{oe}, we can get an idea of the Early voltage V_A of the device. For example, with $h_{oe} = 10$ μ℧, $I_{C1} = 1\,\text{mA}$, $V_{CE1} = 10\,\text{V}$, we get

$$\frac{I_{c1}}{V_A + V_{CE1}} = h_{oe} \rightarrow V_A = \frac{1 \times 10^{-3}}{10 \times 10^{-6}} - 10 = 90\,\text{V}.$$