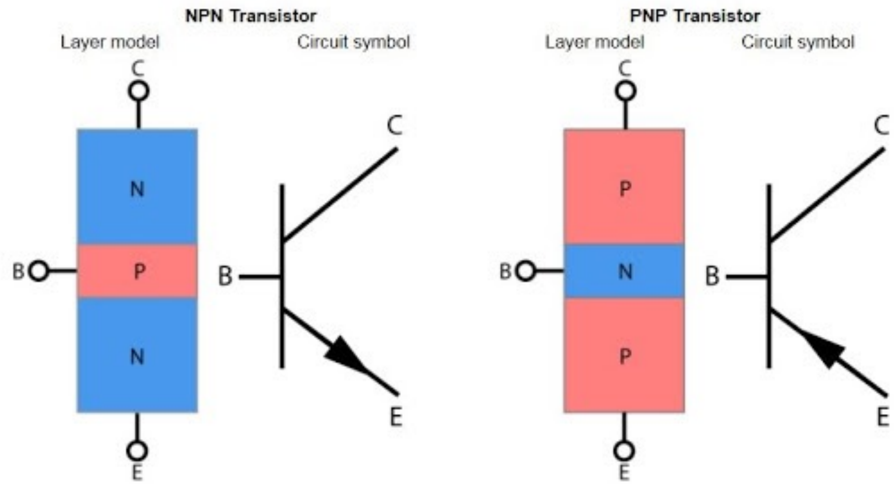
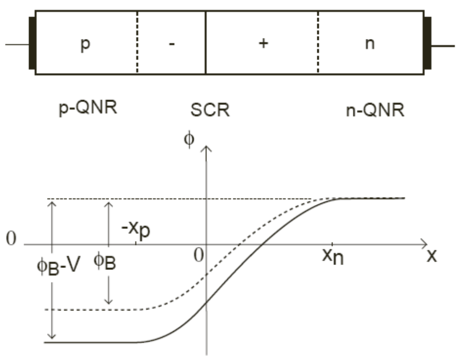
Lecture 6
Microelectronic Devices

Bipolar Junction Transistor (BJT)

- BJT: structure and basic operation
- BJT operation in principle regimes
- Equivalent circuits, signal amplification



Revisiting pn junctions (addition to L4-L5)

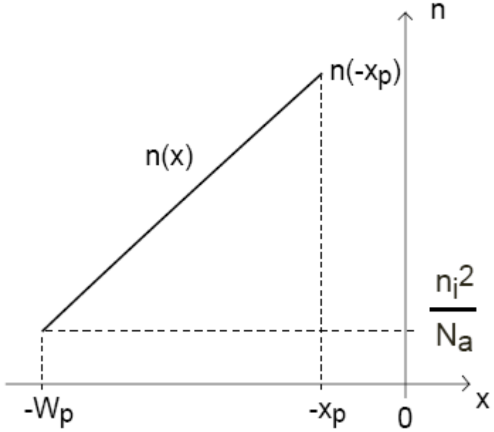


Approximation of "short" QNR:

- Electron/hole recombination is neglected
- Recombination occurs at the interface only

$$J_n = qD_n \frac{dn}{dx}$$

Zoom in to QNR (p-doped)



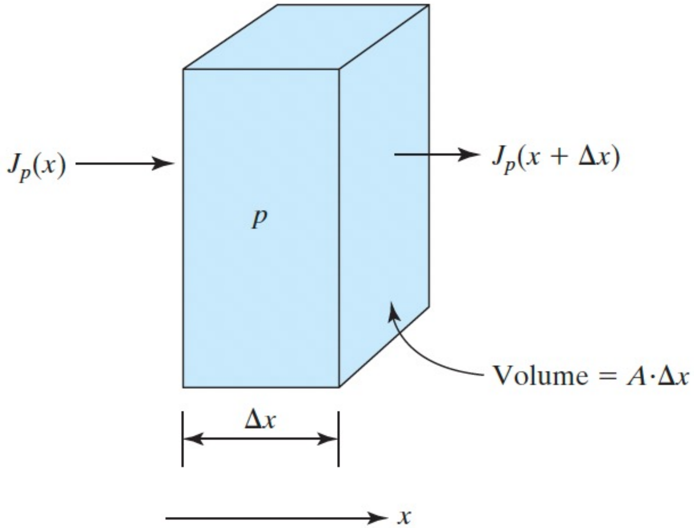
$$n(x = -W_p) = n_o = \frac{n_i^2}{N_a}$$

$$n(-x_p) = \frac{n_i^2}{N_a} \exp \frac{qV}{kT}$$

$$n_p(x) = n_p(-x_p) + \frac{n_p(-x_p) - n_p(-W_p)}{-x_p + W_p}(x + x_p)$$

n(x) is linear! (continuity of diffusion current)

Revisiting pn junctions (addition to L4-L5)



Approximation of “long” QNR:

- Recombination occurs within the QNR
- Recombination is characterized by the lifetime of carriers τ

Continuity of the flux of holes:

the number of holes flowing into the box per second = number of holes flowing out of the box per second + number of holes recombining in the box per second

$$A \cdot \frac{J_p(x)}{q} = A \cdot \frac{J_p(x+\Delta x)}{q} + A \cdot \Delta x \cdot \frac{p'}{\tau}$$

$$-\frac{J_p(x+\Delta x) - J_p(x)}{\Delta x} = q\frac{p'}{\tau}$$

$$-\frac{dJ_p}{dx} = q\frac{p'}{\tau}$$

The differential equation describing ***p(x)***

$$qD_p\frac{d^2p}{dx^2} = q\frac{p'}{\tau_p}$$

Revisiting pn junctions (addition to L4-L5)

"long" QNR: constant lifetime approximation

- Recombination occurs within the QNR
- Recombination is characterized by the lifetime of carriers τ

$$qD_p \frac{d^2 p}{dx^2} = q\frac{p'}{\tau_p}$$

$$\frac{d^2 p'}{dx^2} = \frac{p'}{D_p \tau_p} = \frac{p'}{L_p^2}$$

$$L_p \equiv \sqrt{D_p \tau_p}$$

$$\frac{d^2 n'}{dx^2} = \frac{n'}{L_n^2}$$

$$L_n \equiv \sqrt{D_n \tau_n}$$

$$p'(x) = p_{N0}(e^{qV/kT} - 1)e^{-(x-x_N)/L_p}$$

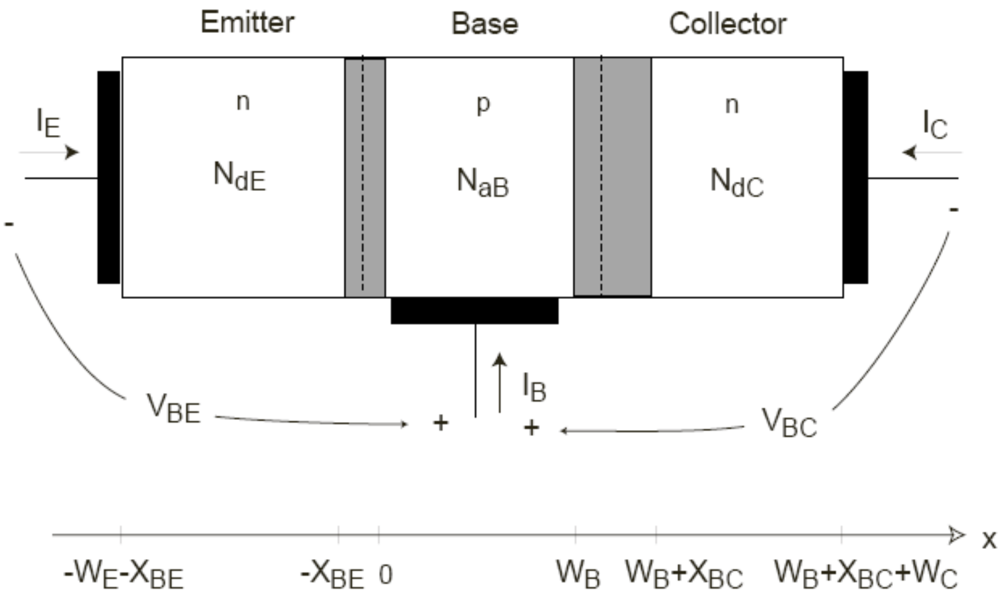
$$n'(x) = n_{P0}(e^{qV/kT} - 1)e^{(x-x_P)/L_n}$$

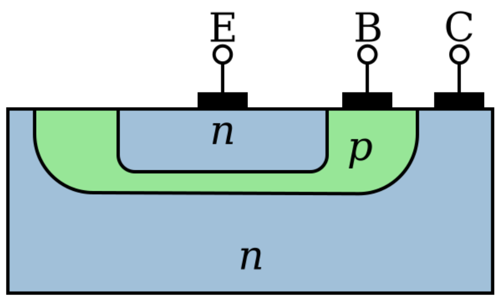
The constant lifetime approximation results in an exponential decrease of the minority carriers with the characteristic lengths L_n, L_p

Bipolar junction transistors: key questions

- What does a bipolar junction transistor look like?
- How does a bipolar junction transistor operate?
- What are the leading dependencies of the terminal currents of a BJT in the forward active regime?
- Equivalent circuits, small signal amplification

BJT: 1D simplified model





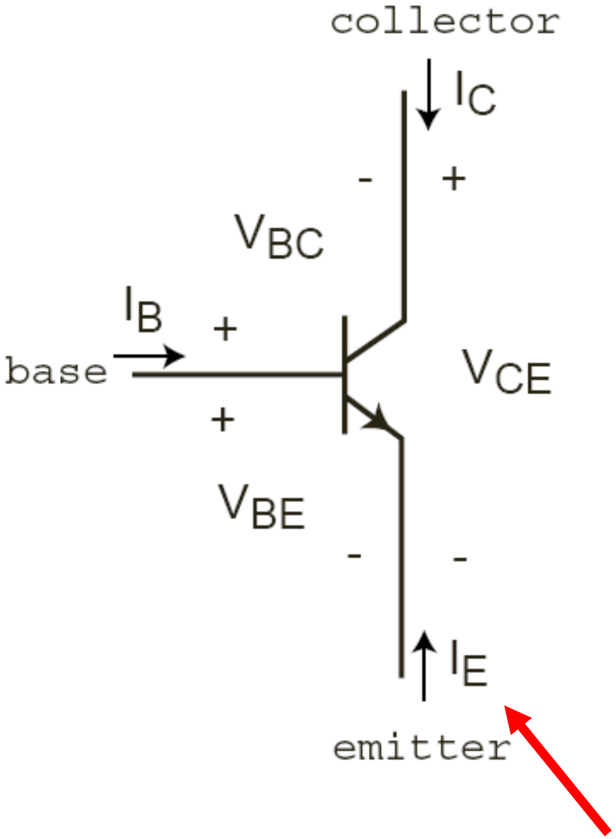
Simplified cross section of a planar *NPN* bipolar junction transistor

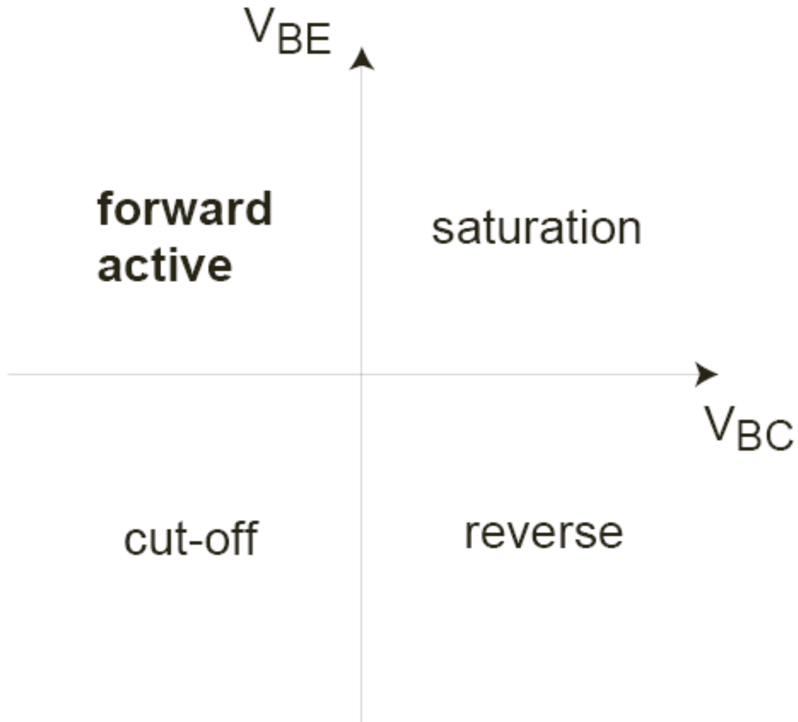
BJT = two neighbouring pn junctions back-to-back:

- close enough for minority carriers to interact (can diffuse quickly through base)
- far apart enough for depletion regions not to interact (prevent ”punchthrough”)

IN ANY CASE: **NOT EQUIVALENT TO TWO BACK-TO-BACK CONNECTED DIODE CIRCUIT**!

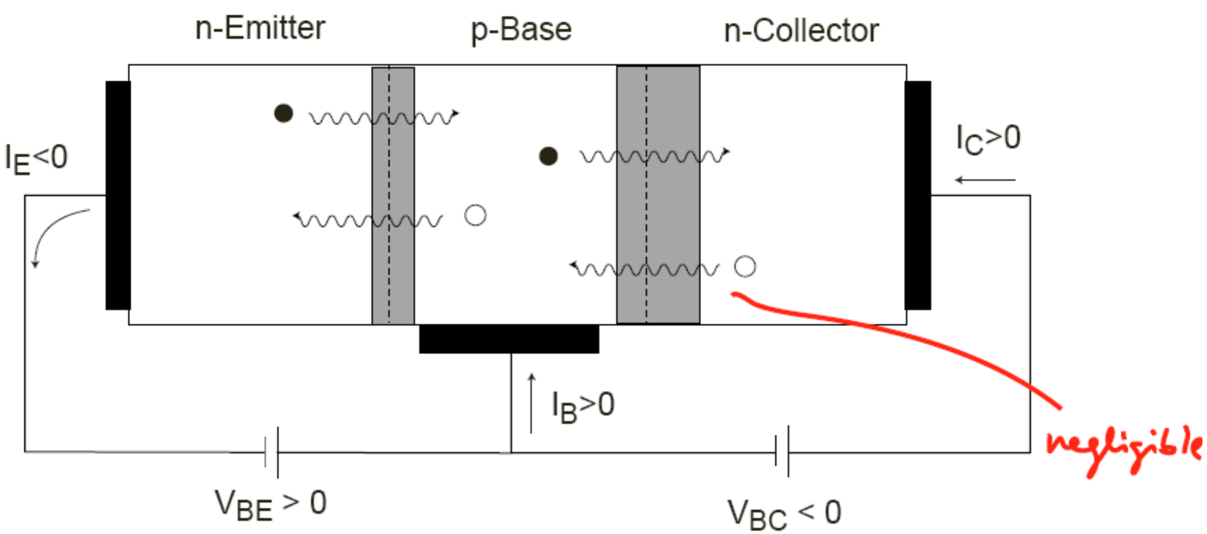
BJT operation (NPN): symbol & the regime chart

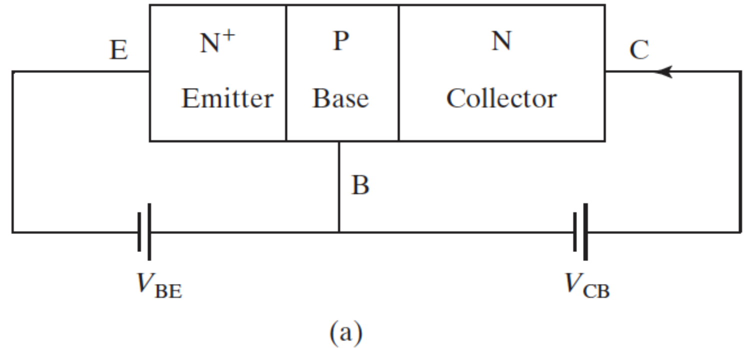


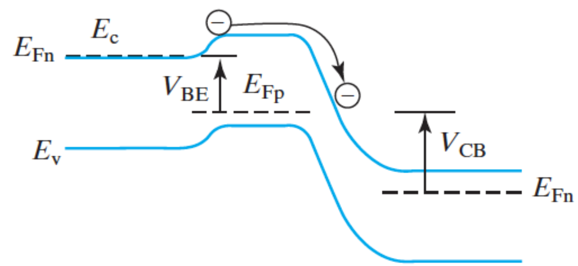


Physical I_E is opposite (shown by arrow)

BJT basic operation in forward mode





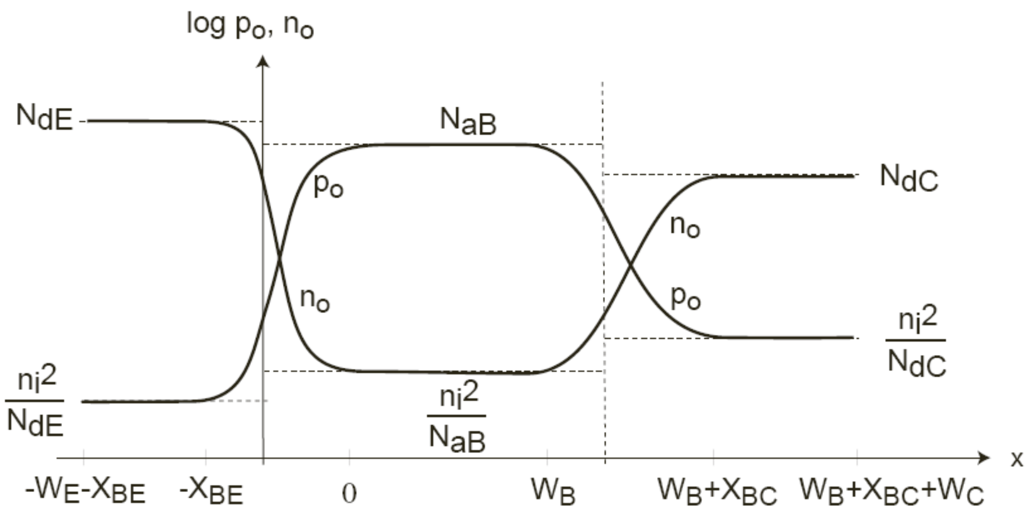


- VBE > 0 ⇒ injection of electrons from E to B
  injection of holes from B to E
- VBC < 0 ⇒ extraction of electrons from B to C
  extraction of holes from C to B

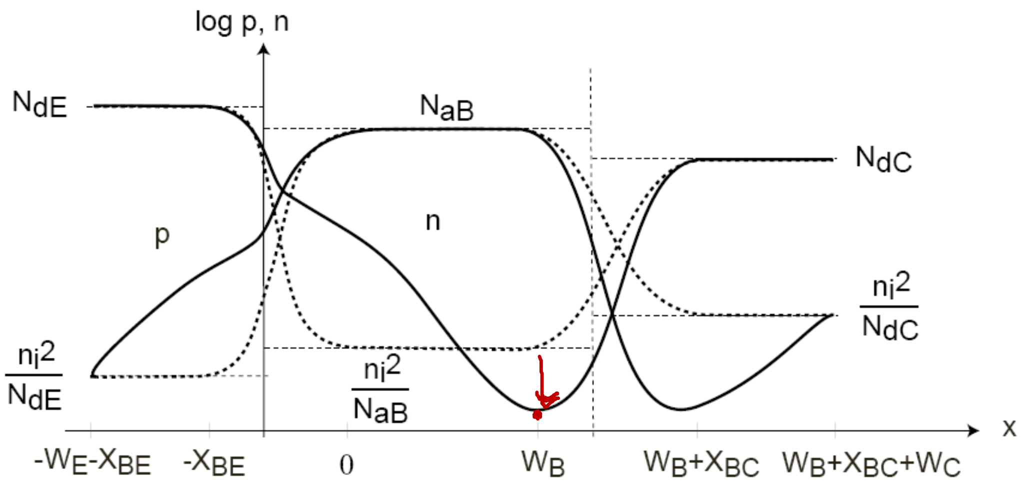
Transistor effect: electrons injected from E to B, extracted by C!

Transistor: nearly same current in the emitter and collector junctions, resistance (higher in BC): power amplification!

Carrier profiles

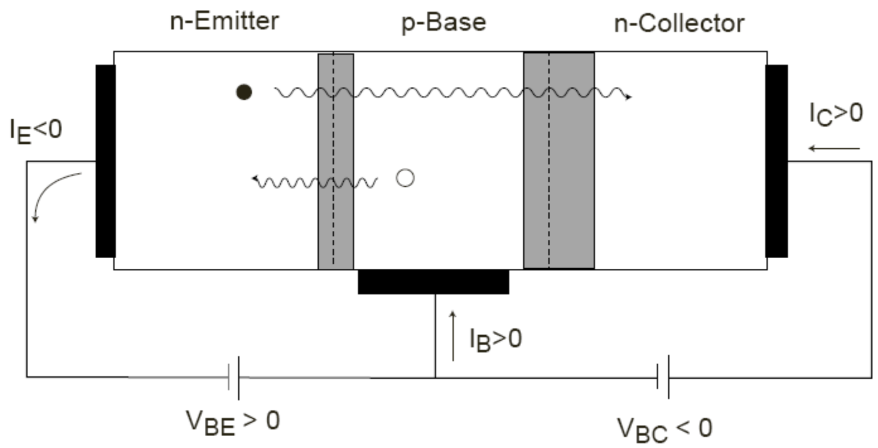


Thermal equilibrium



Forward operation

Dominant current in forward BJT operation



I_C : electron injection from E to B and collection into C

I_B : hole injection from B to E

$I_E = -I_C - I_B$

Key dependencies:

I_C on V_{BE} :	$\exp(qV_{BE}/kT)$
I_C on V_{BC} :	none
I_B on V_{BE} :	$\exp(qV_{BE}/kT)$
I_B on V_{BC} :	none
I_C on I_B :	LINEAR (β factor)!

Forward mode BJT operation

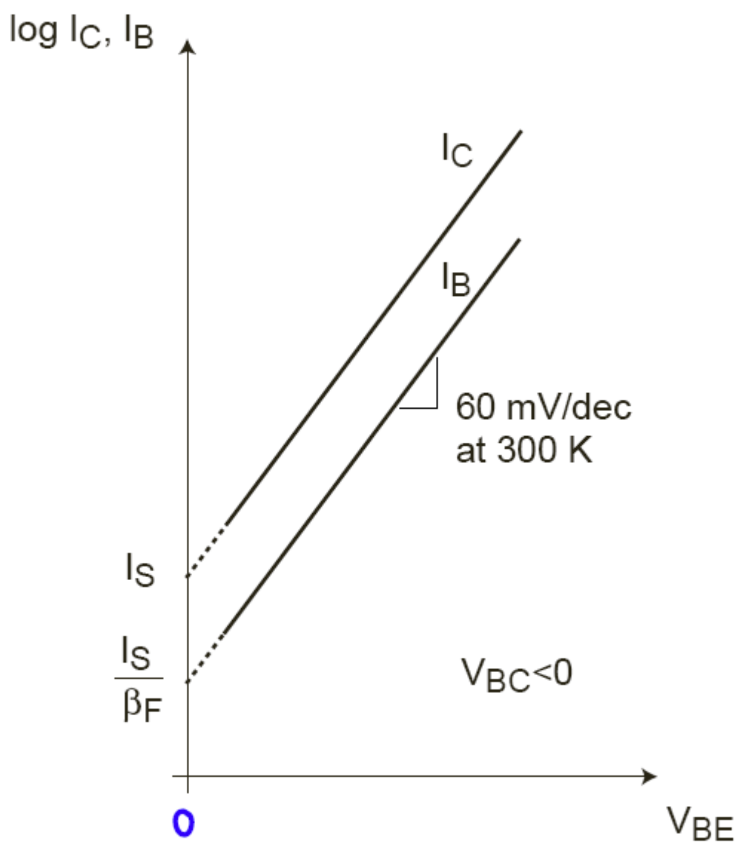
In forward-active regime:

- V_{BE} controls IC: ”transistor effect”
- I_C independent of V_{BC}: ”isolation”
- price to pay for control: I_B#0

BJT figure of merit:
current gain

$$\beta_F = \frac{I_C}{I_B}$$

BJT: Current gain, I_c, I_B vs V_{BE} , general discussion



Current gain

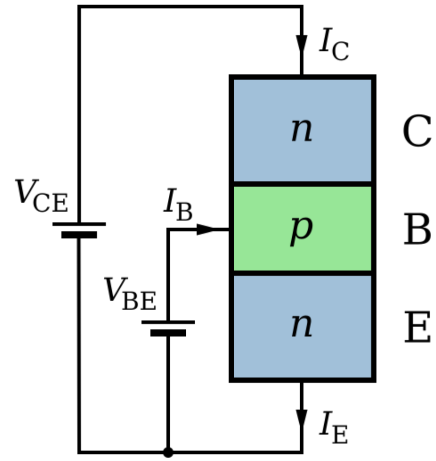
$$\beta_F = \frac{I_C}{I_B} = \frac{n_{pBo}\frac{D_n}{W_B}}{p_{nEo}\frac{D_p}{W_E}} = \frac{N_{dE} D_n W_E}{N_{aB} D_p W_B}$$

To maximize β_F :

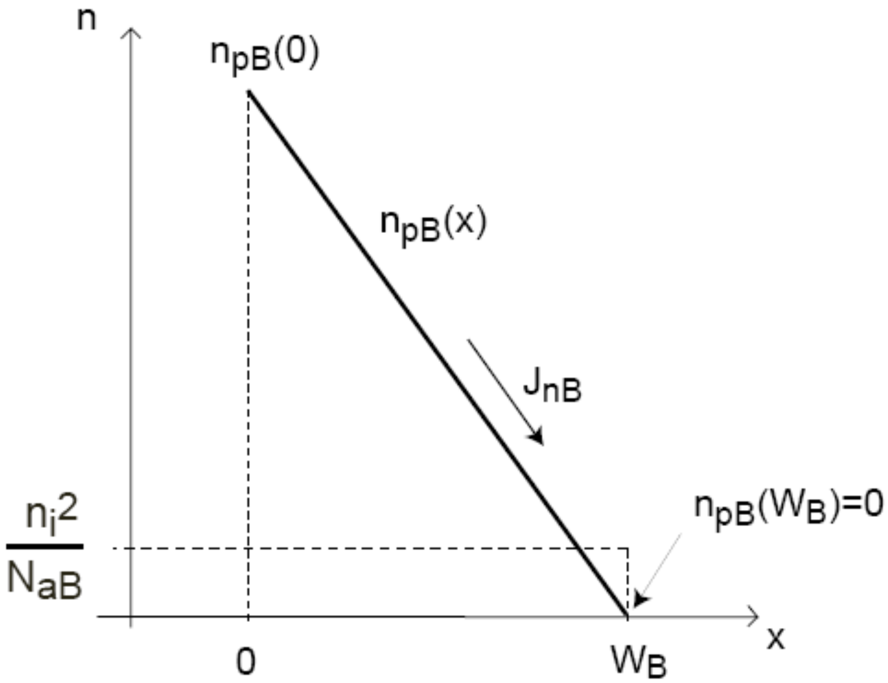
- $Nd_E >> Na_B$
- $W_E >> W_B$
- in most of cases preferred is npn, rather than pnp design because D_n >Dp

State-of-the-art IC BJT's today:
IC ~ 0.1−1 mA, β_F ~ 50 − 300

Calculation of collector current, I_C (1)



Forward bias mode: focus on electron diffusion in base



Boundary conditions:

$$n_{pB}(0) = n_{pBo} \exp \frac{qV_{BE}}{kT}, \qquad n_{pB}(W_B) = 0$$

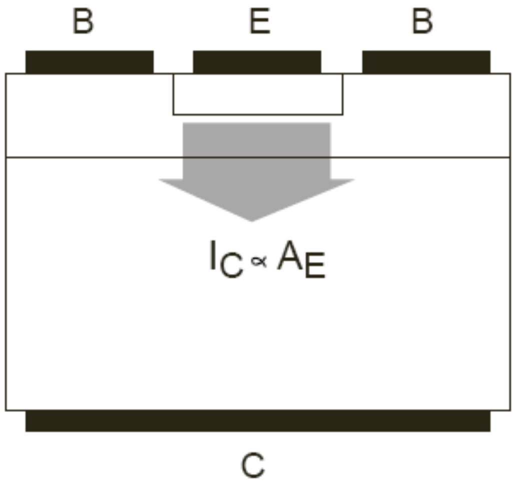
Electron profile:

$$n_{pB}(x) = n_{pB}(0)(1 - \frac{x}{W_B})$$

Calculation of collector current, I_C (2)

$$J_{nB} = qD_n \frac{dn_{pB}}{dx} = -qD_n \frac{n_{pB}(0)}{W_B}$$

Electron current density



For the current calculation:
• consider the collector area - collector current scales with the base-emitter junction area, A_E, so that:

$$I_C = I_S \exp \frac{qV_{BE}}{kT}$$

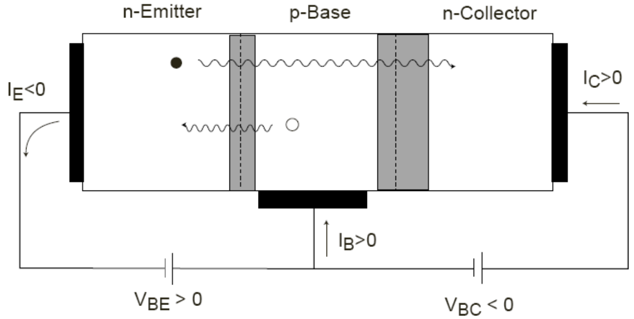
$$I_C = -J_{nB}A_E = qA_E \frac{D_n}{W_B} n_{pBo} \exp \frac{qV_{BE}}{kT}$$

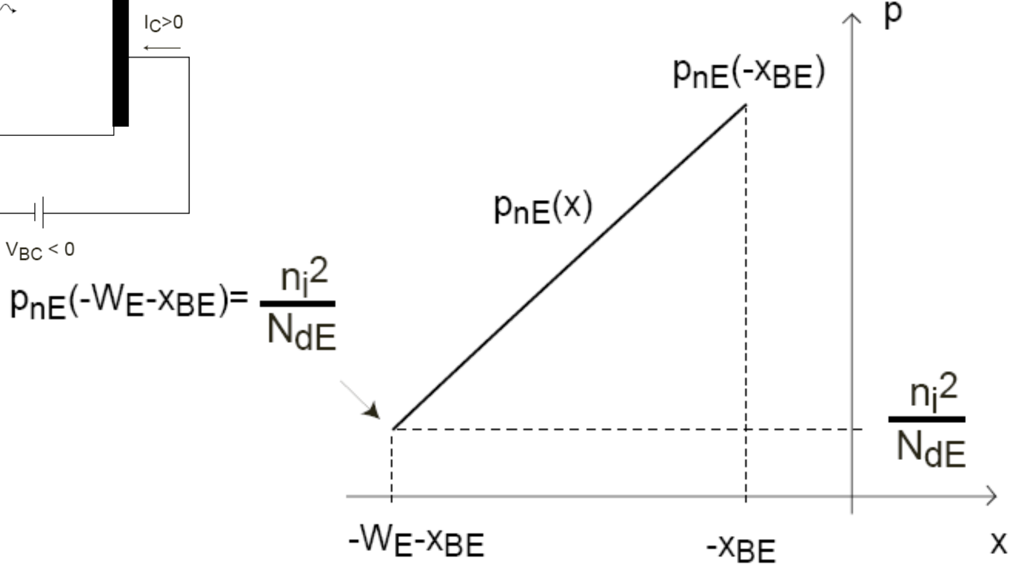
Where I_S is called collector saturation current

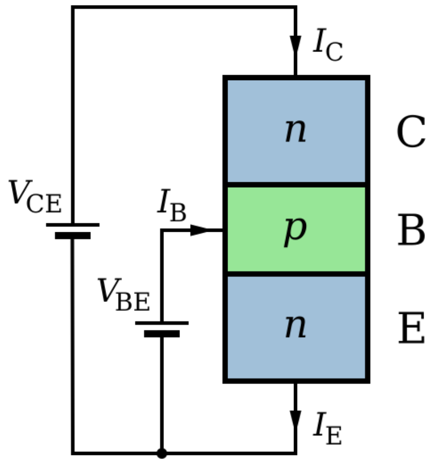
Calculation of base current, I_B (1)

Base current: focus on hole injection and recombination in emitter

Boudary conditions: $p_{nE}(-x_{BE}) = p_{nEo} \exp\frac{qV_{BE}}{kT}, \quad p_{nE}(-W_E - x_{BE}) = p_{nEo}$





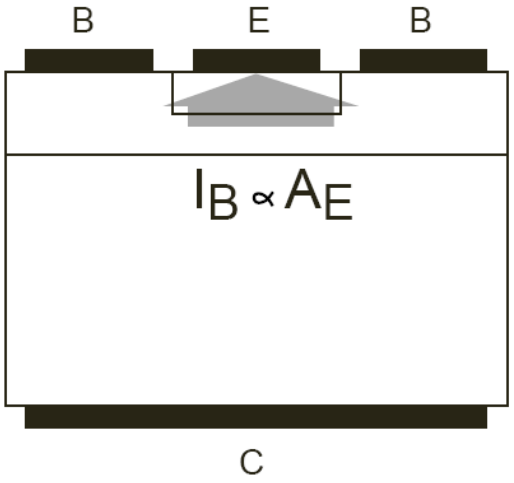


Hole Profile:

$$p_{nE}(x) = [p_{nE}(-x_{BE}) - p_{nEo}](1 + \frac{x + x_{BE}}{W_E}) + p_{nEo}$$

Calculation of base current, I_B (2)

Hole current density: $$J_{pE} = -qD_p \frac{dp_{nE}}{dx} = -qD_p \frac{p_{nE}(-x_{BE}) - p_{nEo}}{W_E}$$



• current scales with base-emitter area, AE

$$I_B = -J_{pE}A_E = qA_E \frac{D_p}{W_E} p_{nEo} (\exp \frac{qV_{BE}}{kT} - 1)$$

Compare with:

$$I_C = -J_{nB}A_E = qA_E \frac{D_n}{W_B} n_{pBo} \exp \frac{qV_{BE}}{kT}$$

For $V_{BE} \gg \frac{kT}{q}$:

$$I_B \simeq \frac{I_C}{\beta_F}$$

$$I_B = \frac{I_S}{\beta_F} (\exp \frac{qV_{BE}}{kT} - 1)$$

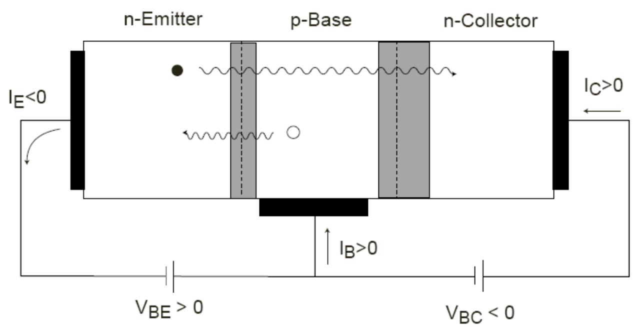
What are the values of β_F in a 'very good' transistor….?

Collector current is nearly identical to the (magnitude) of the emitter current … define

$$I_C = \alpha_F I_E \qquad \alpha_F = .999$$

Kirchhoff:

$$I_E = I_C + I_B$$

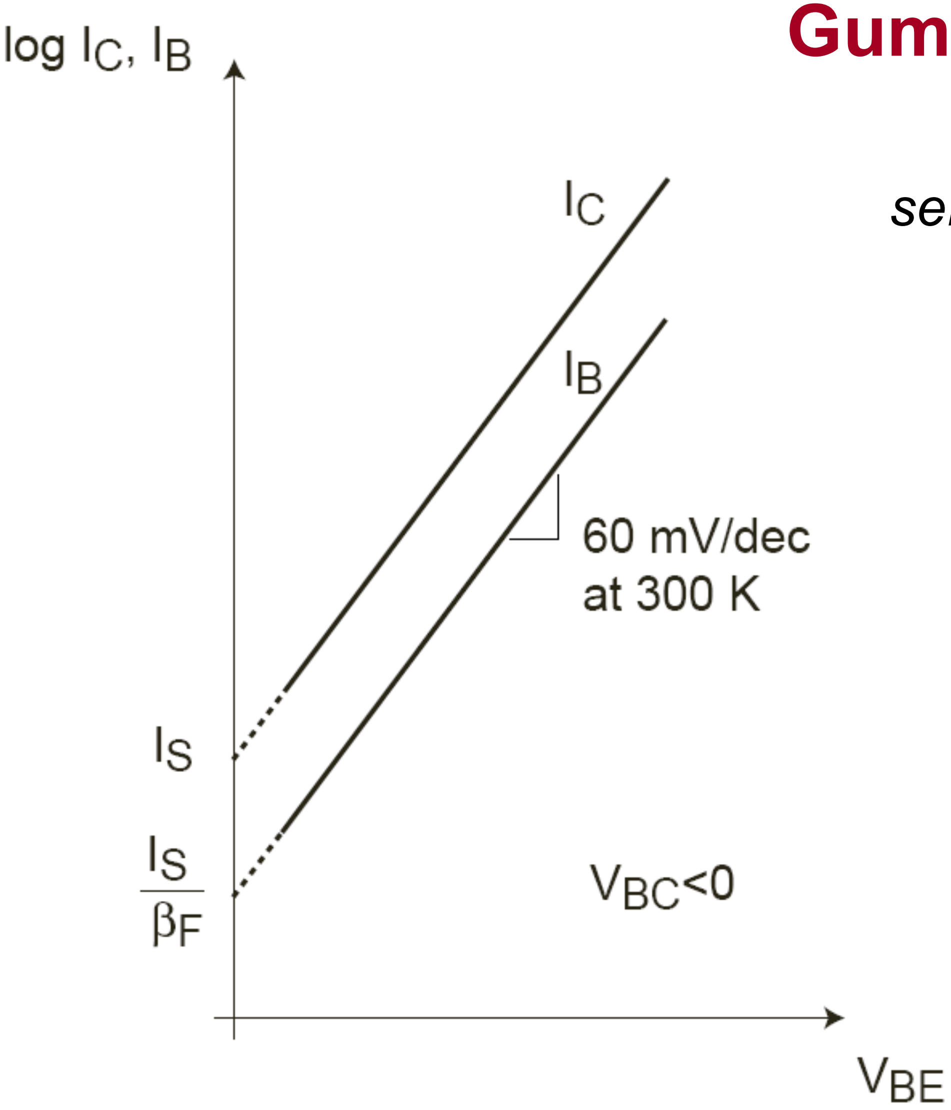


DC Current Gain:

$$I_C = \alpha_F I_E = \alpha_F (I_B + I_C)$$

$$I_C = \frac{\alpha_F}{1-\alpha_F} I_B = \beta_F I_B \qquad \beta_F = \frac{\alpha_F}{1-\alpha_F} = \frac{.999}{.001} = 999$$

Gummel plot



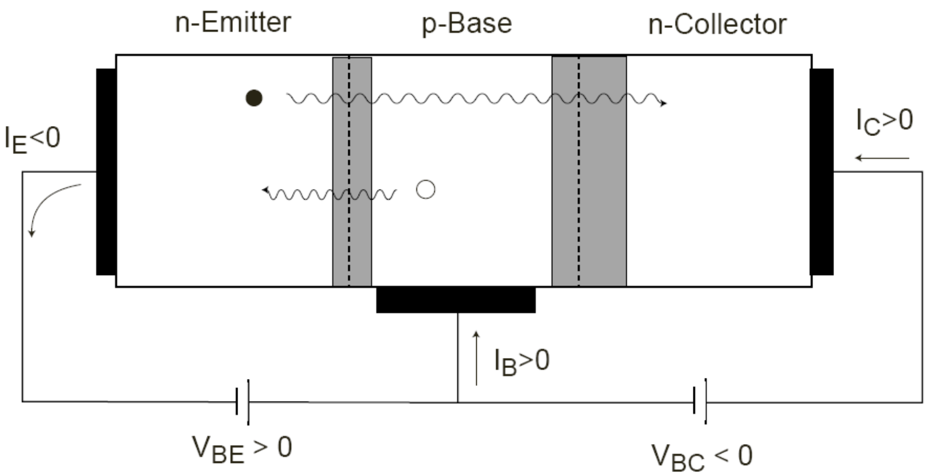
semilog plot of I_C and I_B vs. V_{BE}:

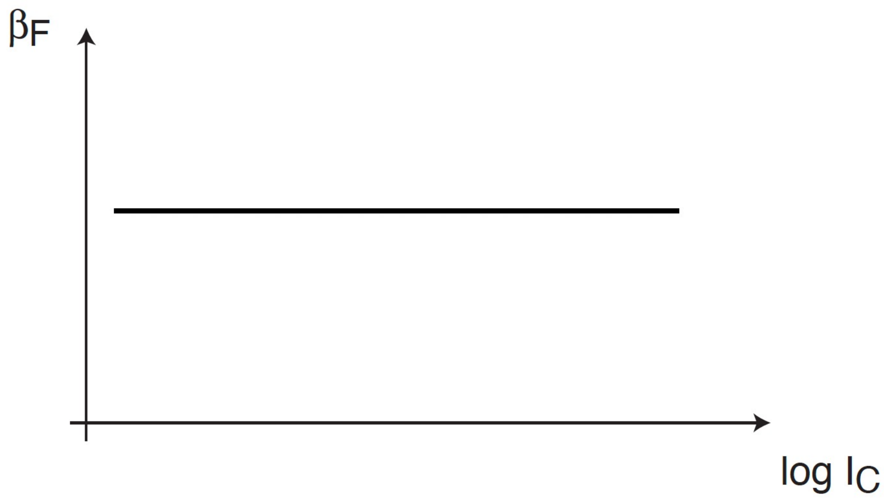
State-of-the-art IC BJT's :
I_C ~ 0.1−1 mA
β_F ~ 50 − 300
Current density 10-100A/cm^2
High-speed BJT: up to 10^{5}A/cm^2

Key conclusions

• npn bipolar transistor operation in forward mode (**régime direct**):
$V_{BE} > 0$, $V_{BC} < 0$ (→ $V_{CE} > 0$)
• Emitter "injects" electrons into Base, Collector "collects" electrons from Base ⇒ IC controlled by VBE , independent of VBC (transistor effect)

$$I_C \propto \exp\frac{qV_{BE}}{kT} \qquad I_C = \beta_F \, x \, I_B$$





Key conclusions

Current gain:

$$\beta_F = \frac{I_C}{I_B} = \frac{n_{pBo}\frac{D_n}{W_B}}{p_{nEo}\frac{D_p}{W_E}} = \frac{N_{dE} D_n W_E}{N_{aB} D_p W_B}$$

To maximize β_F:

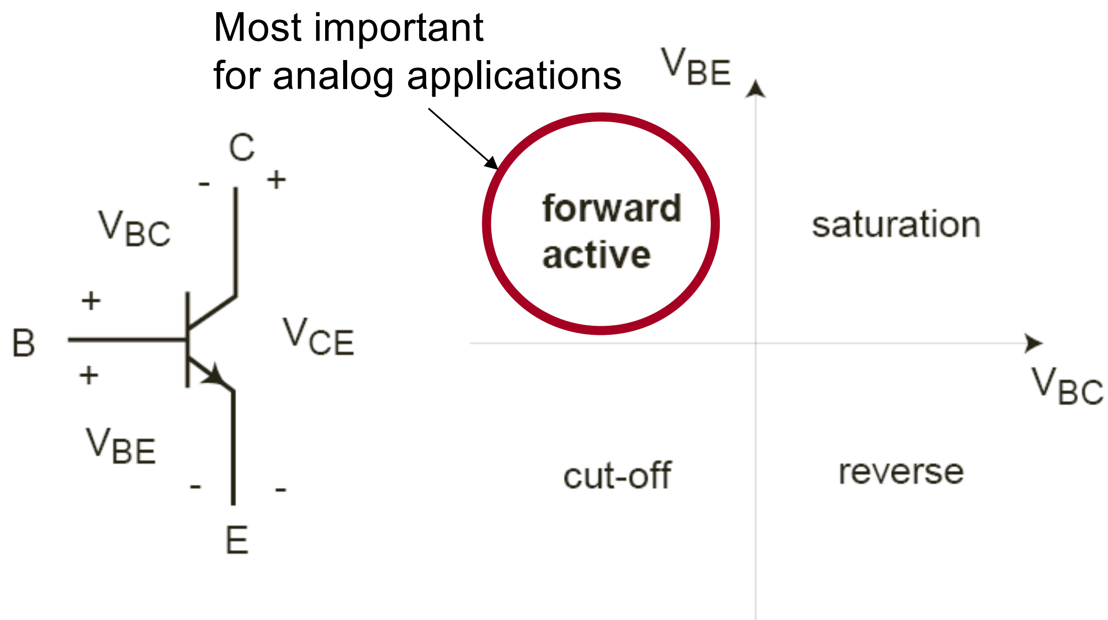
- $N_{dE} \gg N_{aB}$
- $W_E \gg W_B$

For best current gain:
Narrow base, wide, highly doped emitter
prefer npn rather than pnp because $D_n > D_p$

Other key questions about BJT

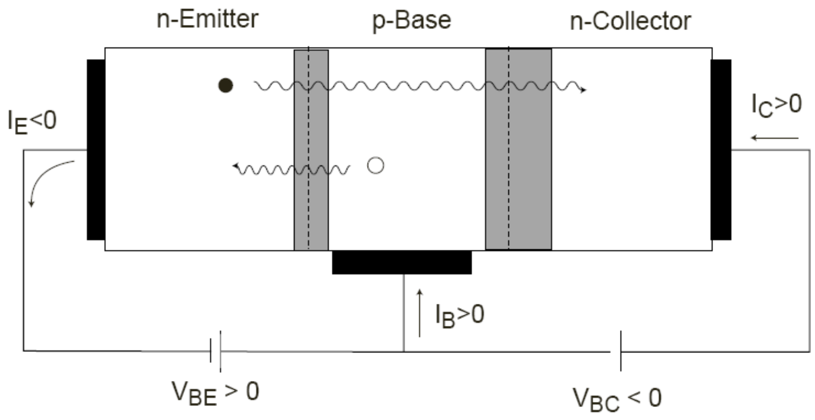
- What other regimes of operation are there for the BJT?
- What is important about each regime?
- How do equivalent circuit models for the BJT look like?

Regimes of BJT operation



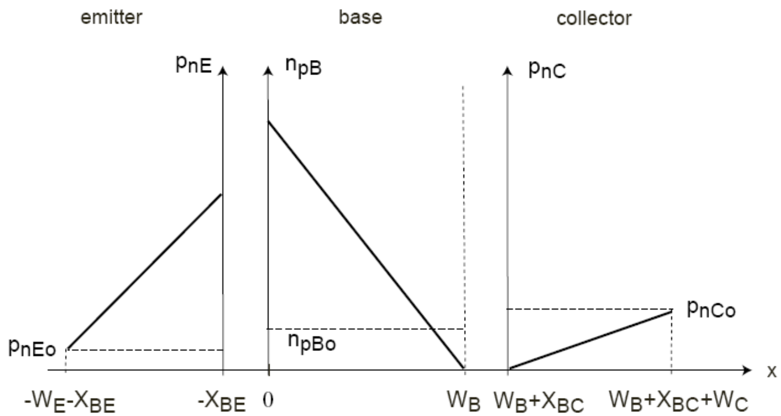
- **forward active**: device has good isolation and high gain; **most useful regime;**
- **saturation**: device has no isolation and is flooded with minority carriers ⇒ takes time to get out of saturation; **avoid it** for the majority of cases!
- **reverse**: poor gain; **not useful**;
- **cut-off**: negligible current: nearly an open circuit; **useful**.

Forward-active regime: VBE > 0, VBC < 0



• Emitter injects electrons into base, collector collects electrons from base
• Base injects holes into emitter, recombine at emitter contact

Minority carrier profiles

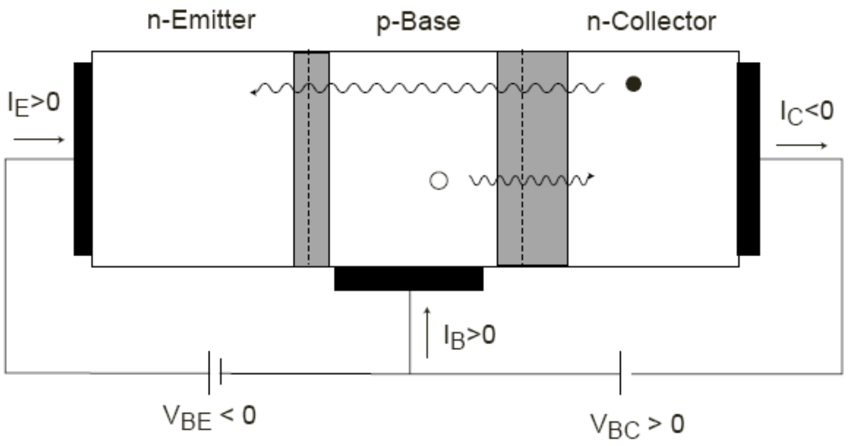


$$I_C = I_S \exp \frac{qV_{BE}}{kT}$$

$$I_B = \frac{I_S}{\beta_F}(\exp \frac{qV_{BE}}{kT} - 1)$$

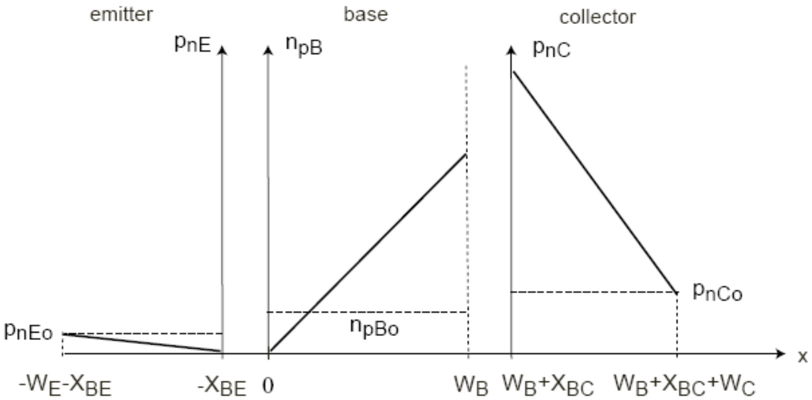
V_{BE} ~0.6 – 0.7V

Reverse regime: VBE < 0, VBC > 0



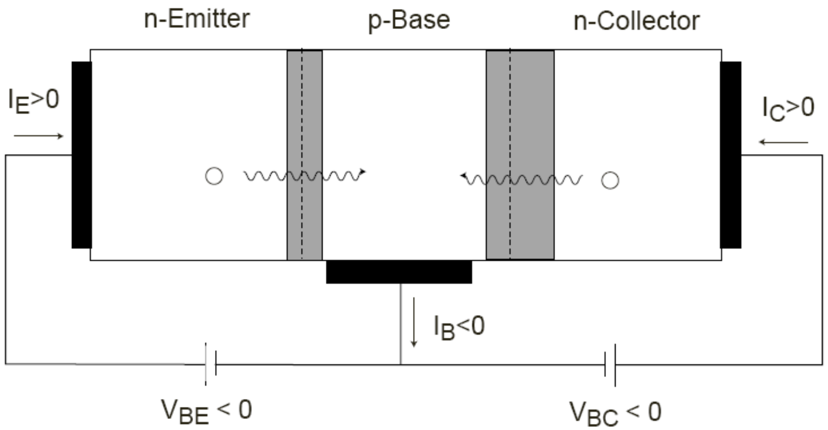
- Similar with the direct regime with the difference that β_F is replaced by β_R (the npn transistor is not symmetrical, the transistor effect is less efficient in reverse mode!)
- $I_E \rightarrow I_C$, $V_{BE} \rightarrow V_{BC}$

Minority carrier profiles

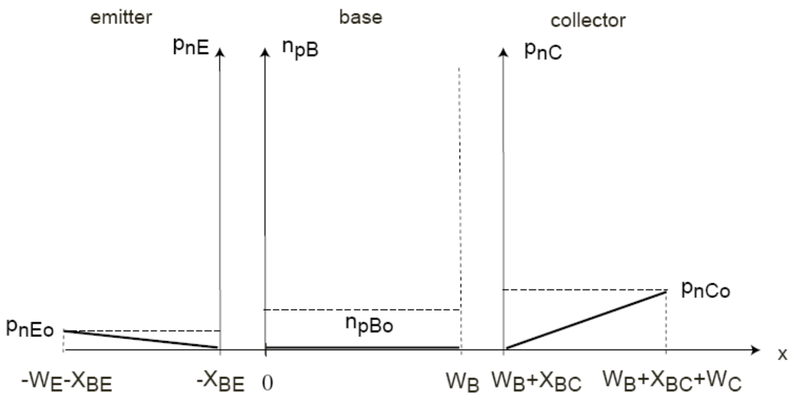


Typically, $\beta_R \simeq 0.1 - 5 \ll \beta_F$.

Cut-off regime: VBE < 0, VBC < 0



Minority carrier profiles



- Base extracts holes from emitter:

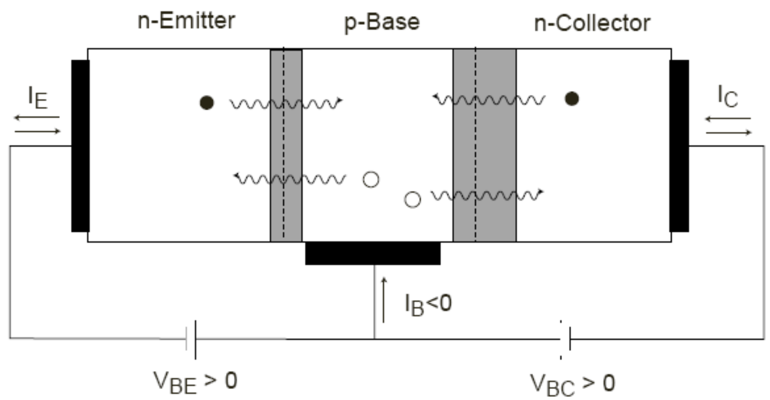
$$I_{B1} = -\frac{I_S}{\beta_F} = -I_E$$

- Base extracts holes from collector:

$$I_{B2} = -\frac{I_S}{\beta_R} = -I_C$$

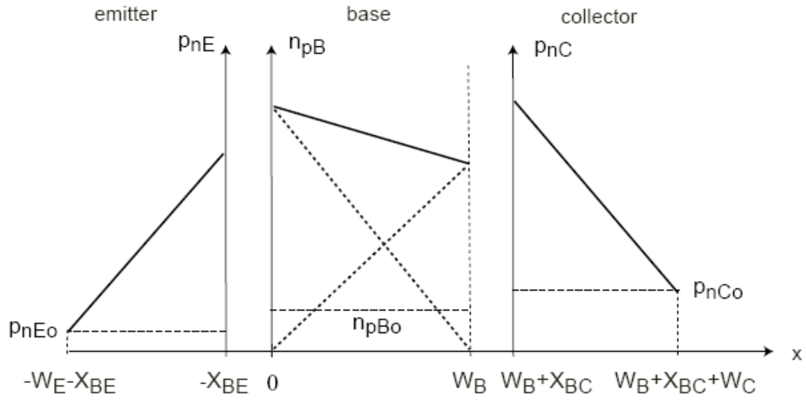
- junction leakage currents ($\sim 10^{-12}$ A) – junctions in reverse bias

Saturation: $V_{BE} > 0$, $V_{BC} > 0$ ($V_{CE} \sim 0V!$)



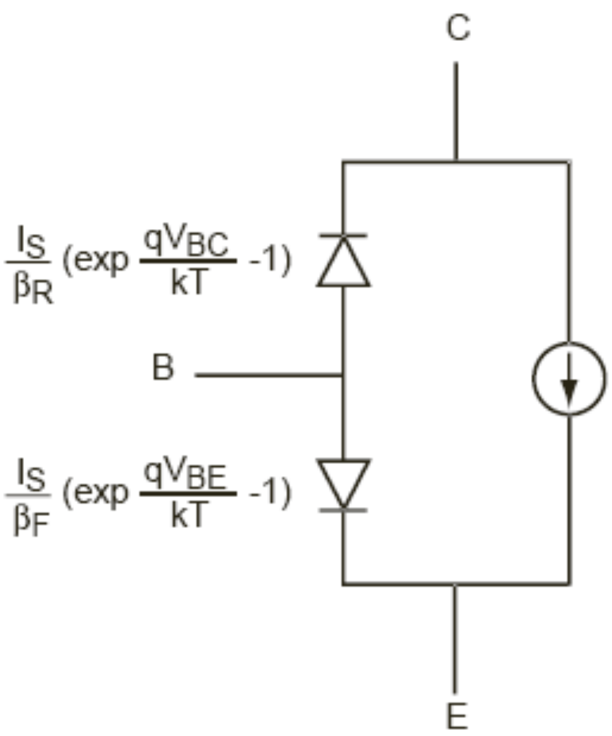
- Saturation is superposition of forward active + reverse
- IC and IE can have either sign, depending on relative magnitude of VBE and VBC , and βF and βR.
- In saturation, collector and base flooded with excess minority carriers ⇒ takes lots of time to get transistor out of saturation.

Minority carrier profiles



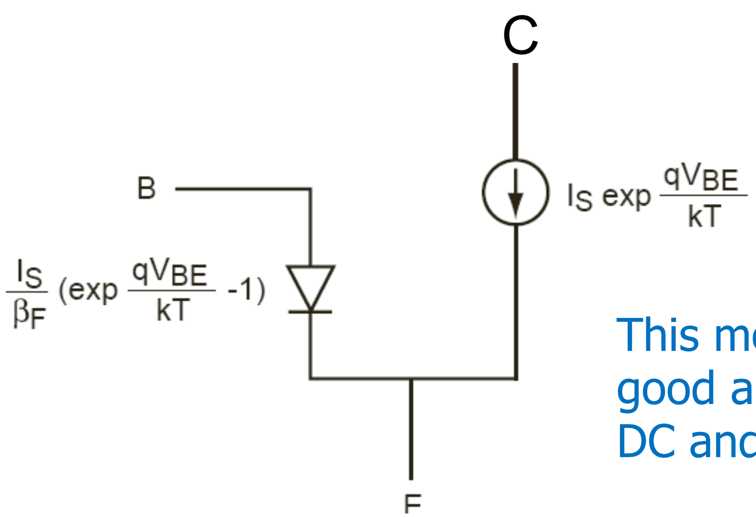
Large-signal equivalent circuit model

Equivalent circuit model



Only three parameters in this model:
I_S , β_F , and β_R.

Example: forward-active regime, $V_{BE}>0$, $V_{BC}<0$



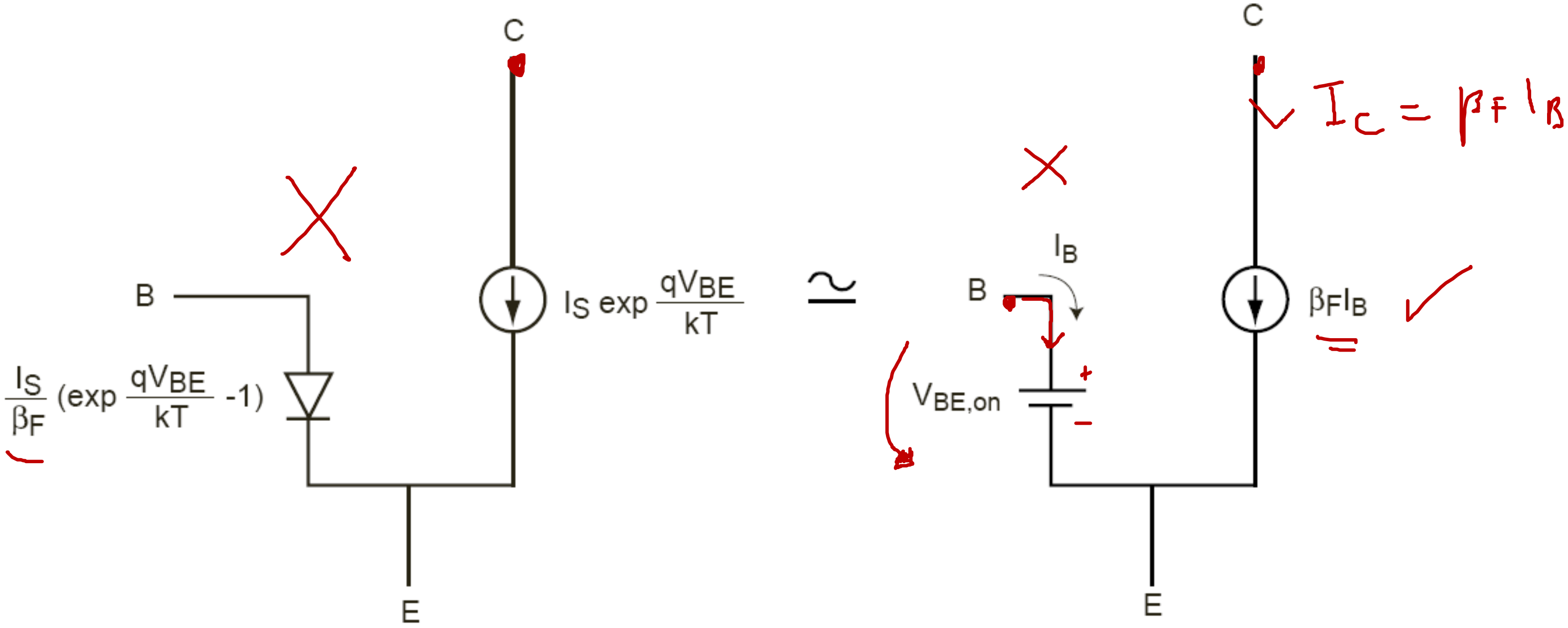
Ebers-Moll model

A functional model of the BJT utilizes ideal diodes to model the base-emitter and base-collector junctions and a current source.

This model is sufficient to achieve good analysis results with a variety of DC and low frequency circuits

Simplified equivalent circuit (1)

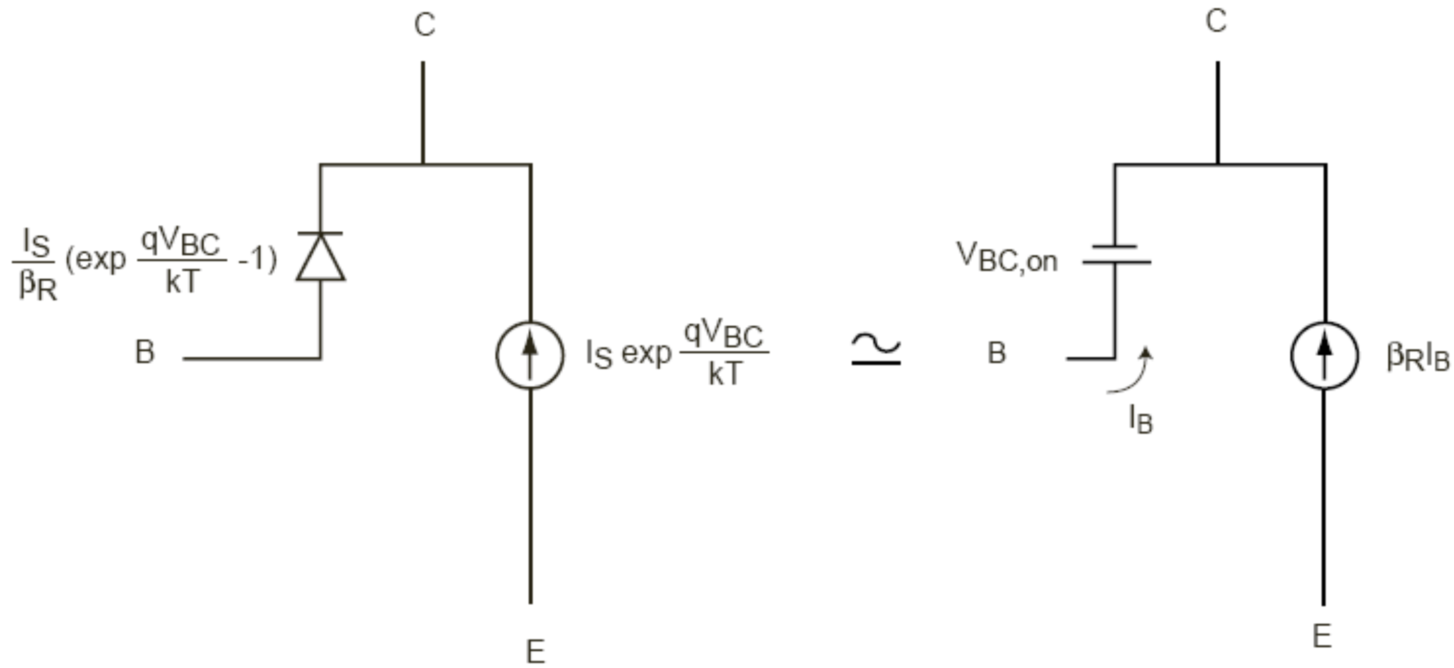
- Forward-active regime: $V_{BE} > 0,\ V_{BC} < 0$



For today's technology: $V_{BE,on}$ ~0.7 V .

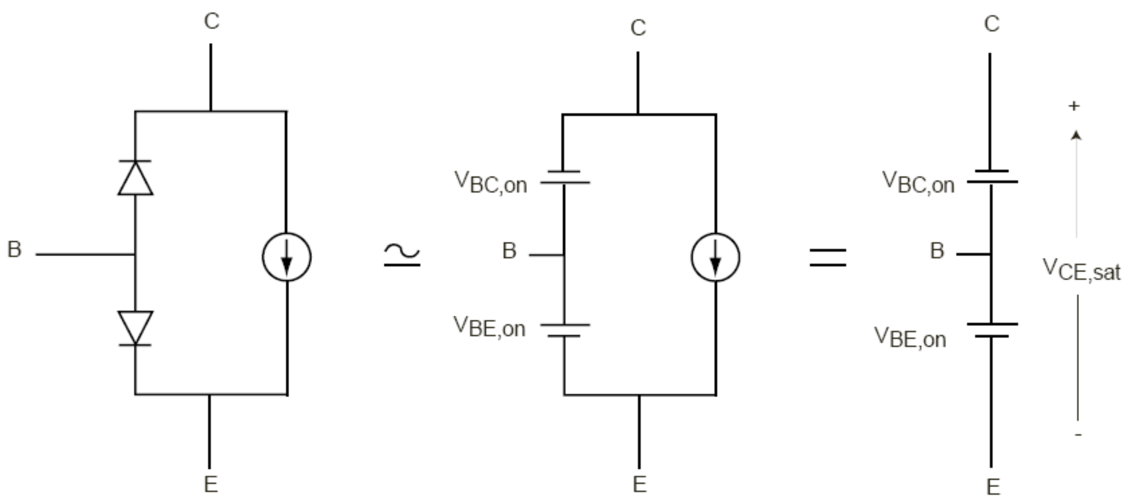
Simplified equivalent circuit (2)

- Reverse: $V_{BE} < 0$, $V_{BC} > 0$



Simplified equivalent circuit (3)

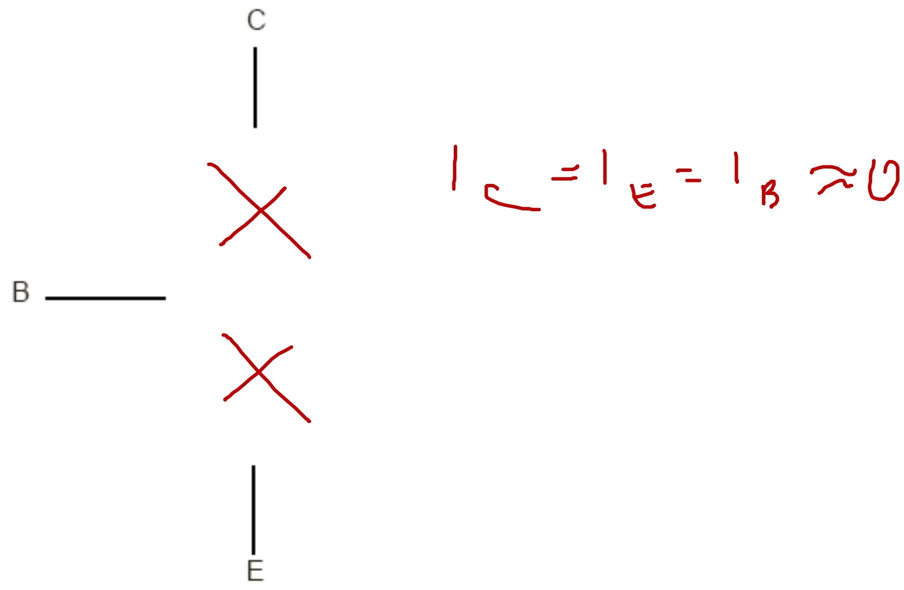
- Saturation: $V_{BE} > 0$, $V_{BC} > 0$



Today's technology: $V_{CE,sat} = V_{BE,on} - V_{BC,on} \simeq 0.2\ V$.
I_B and I_C depend on outside circuit.

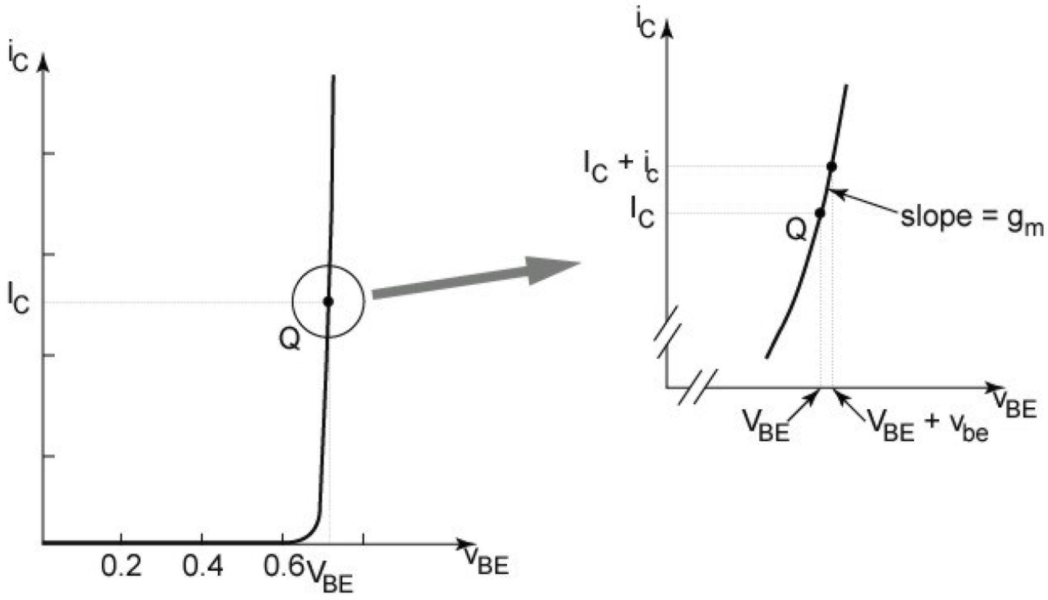
Simplified equivalent circuit (4)

- Cut-off: $V_{BE} < 0$, $V_{BC} < 0$



Only negligible leakage currents.

Transfer chracteristics, $I_C(V_{BE})$: BJT transconductance



Differentiating and evaluating at $Q = (V_{BE,} V_{CE})$

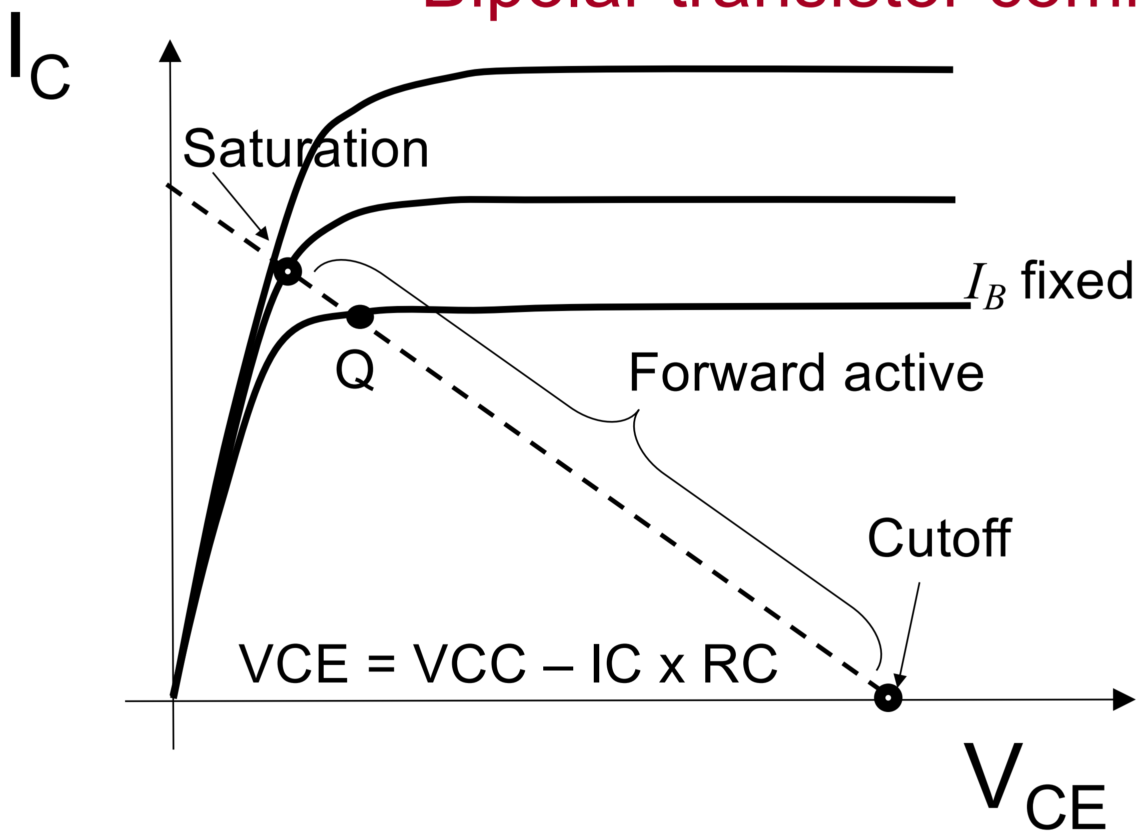
$$\left.\frac{\partial i_C}{\partial v_{BE}}\right|_Q = \frac{q}{kT} I_S e^{qV_{BE}/kT}(1 + V_{CE}/V_A)$$

$$g_m = \left.\frac{\partial i_C}{\partial v_{BE}}\right|_Q = \frac{qI_C}{kT}$$

- The transconductance is analogous to diode conductance

Q-point - “Quiescent” means "at rest"—so the Q-point represents the steady-state values of collector current

Bipolar transistor common-emitter I-V with load line



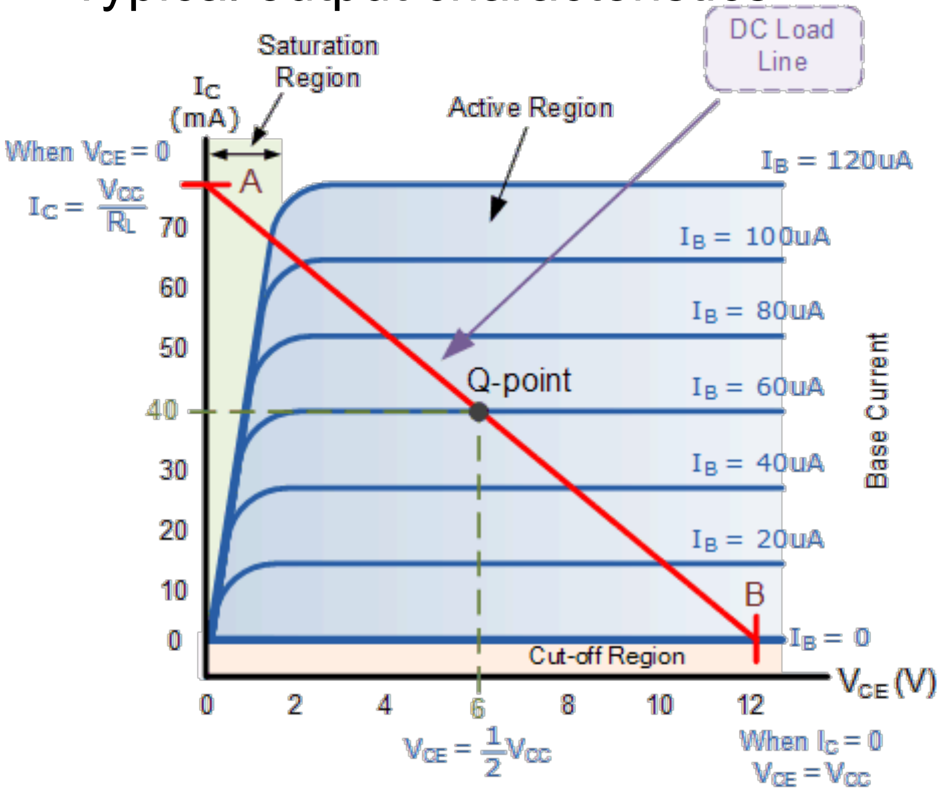
- The Q-point of a BJT is the point on its output characteristics that defines the transistor's DC operating condition—specifically, when no input signal is present
- Q-point represents the steady-state $\boldsymbol{I_c}$ and $\boldsymbol{V_{ce}}$
- Q-point is the intersection point of the transistor's DC load line and the output characteristic curve ***for a given base current***
- The Q-point determines how the transistor will behave when an AC signal is applied (i.e., how it will amplify signals)

- ***Why Q-point Matters:***

- A properly chosen Q-point ensures linear amplification and avoids distortion.
- If the Q-point is too close to cutoff (where the transistor is off) or saturation (where it's fully on), the output signal may get clipped.

Bipolar transistor common-emitter I-V with load line

Typical output characteristics



• This BJT output characteristics helps to avoid the saturation regime

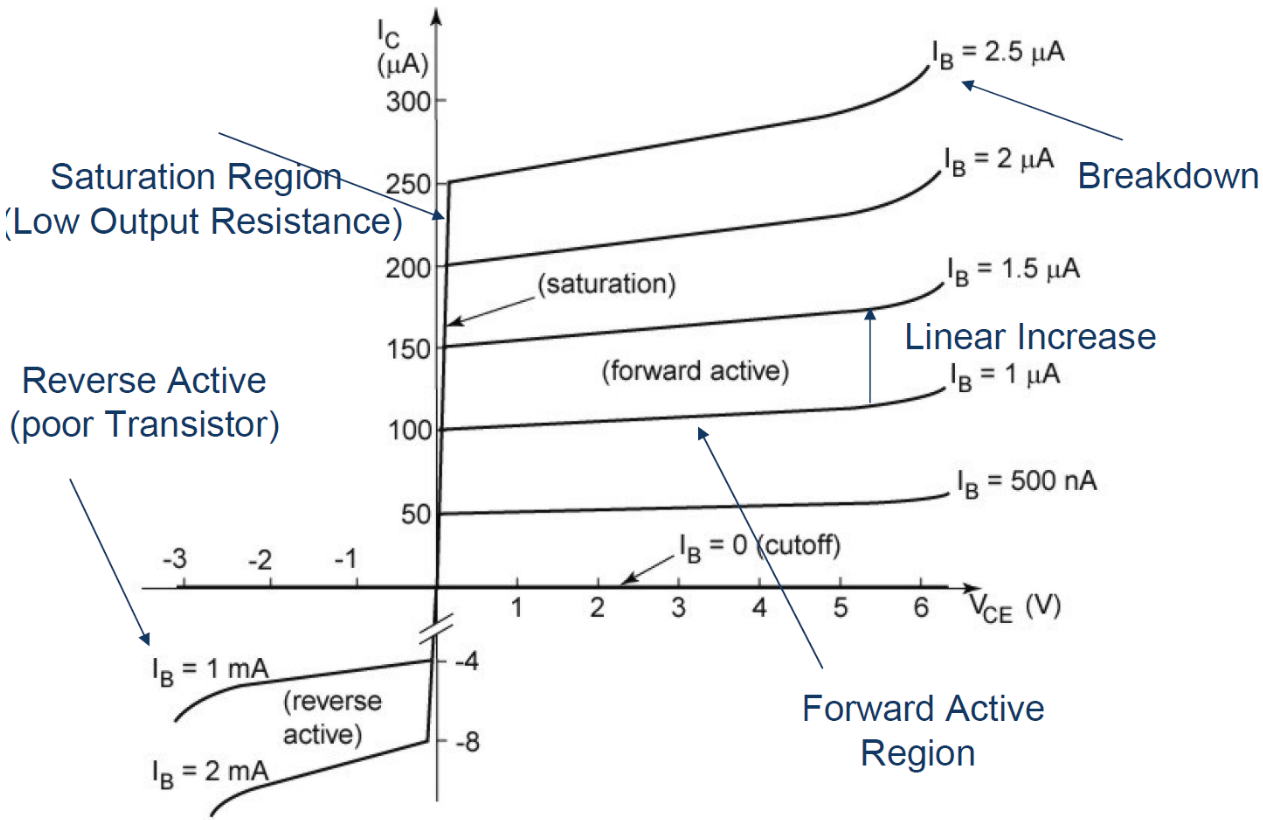
Pick a Q-point in the middle third of the load line:
This gives room for the signal to swing up and down without pushing the transistor into saturation (left) or cutoff (right)

• If your Q-point (red dot) is too close to the bottom-left corner of the graph low V_{CE}, it's entering saturation. Thern moved the Q-point to the right by reducing $\boldsymbol{I_B}$

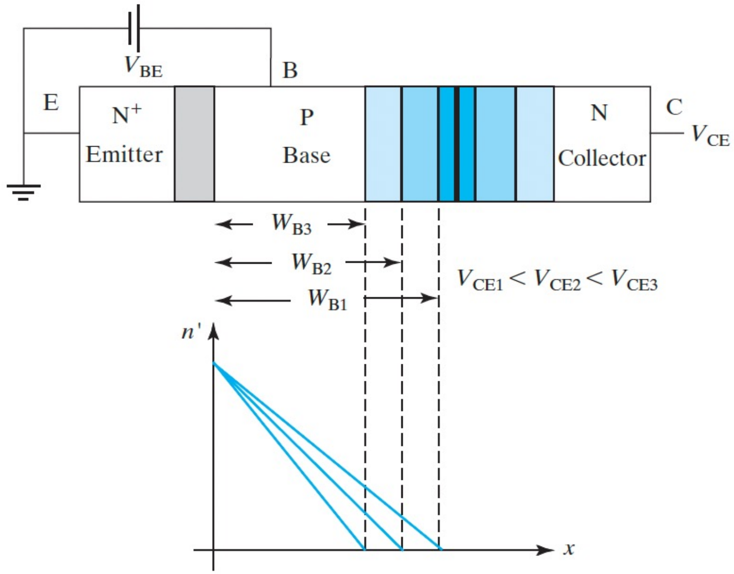
• ***Why Q-point Matters:***
- A properly chosen Q-point ensures linear amplification and avoids distortion.
- If the Q-point is too close to cutoff (where the transistor is off) or saturation (where it's fully on), the output signal may get clipped.

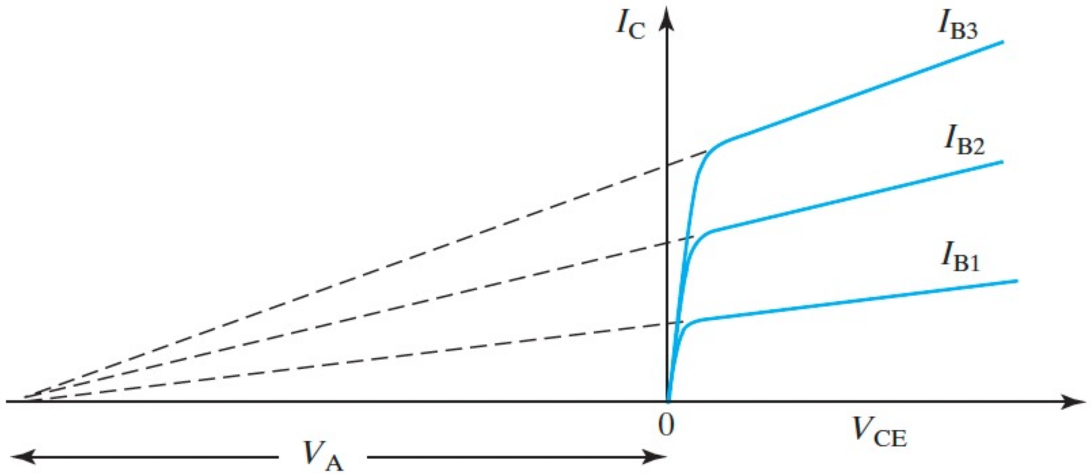
Output characteristics: in real transistors Ic tensd to increase with V_{CE}

Why?



Output characteristics: varying width of the base



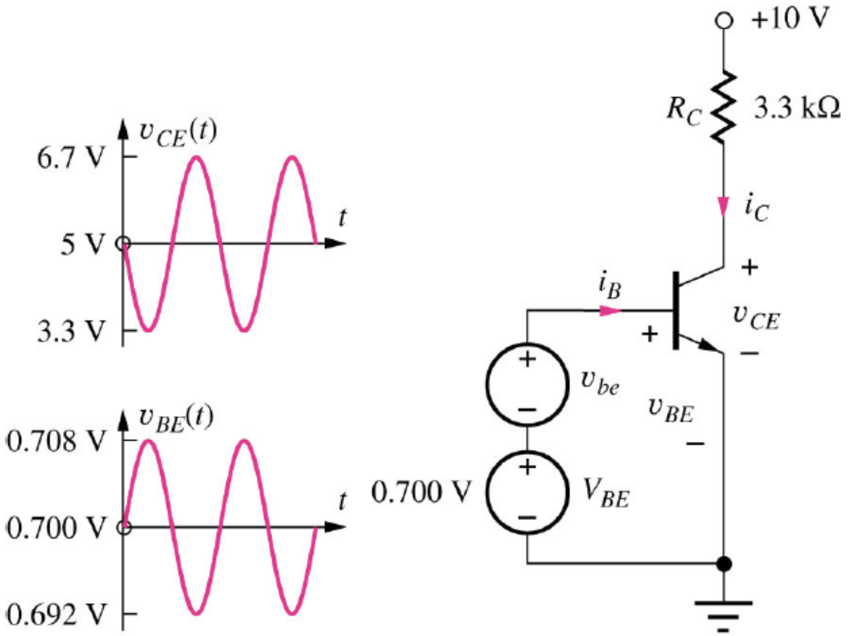


V_A –Early voltage

As V_C increases, the BC depletion layer width increases and W_B decreases causing dn/dx and I_C to increase.
The effect is described using the Early voltage approximation
(avoids complex maths)

BJT amplifier concept (1)

Common emitter configuration – the most used one



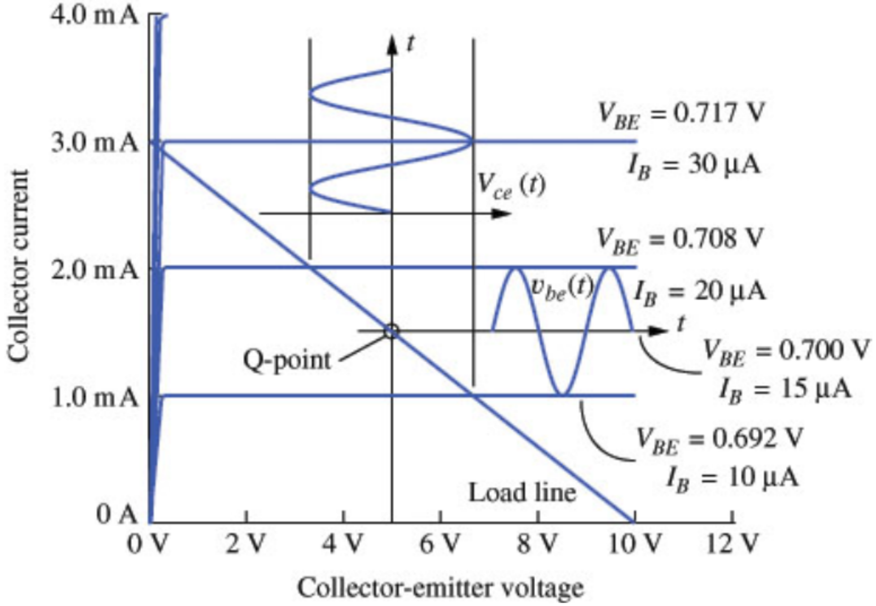
- Q-point is set at (I_C, V_{CE}) = (1.5 mA, 5 V) with I_B = 15 µA (βF = 100)
- Total base-emitter voltage is: $V_{BE} = V_{BE\ const} + v_{be}$
- Collector-emitter voltage is:

  vCE = VCC – $i_C R_C$

  This is the load line equation.

(10V / 3300 Ohm = 3mA; 1.5mA is a good Q-point)

BJT amplifier concept (2)



8 mV peak change in v_{BE} gives 5 µA change in i_B and 0.5 mA change in i_C.

0.5 mA change in i_C produces a 1.65 V change in v_{CE} .

For 8mV ac signal added to V_{BE}

$\Delta I_C/\Delta V_{BE} = I_c\, q/kT$ (low-signal conduction)

A small voltage change at the base causes a large voltage change at collector. Voltage gain is given by:

$$A_v = \frac{V_{ce}}{V_{be}} = \frac{1.65\angle 180^o}{0.008\angle 0^o} = 206\angle 180^o = -206$$

Minus sign indicates 180º phase shift between the input and output signals.

BJT - applications

- TTL logic (Transistor-Transistor Logic) - digital logic design built using BJTs. It's used to implement logic operations like AND, OR, NOT - basic building blocks of digital circuits
  - Legacy design - Introduced in the 1960s, was popular in the 70s and 80s, now replaced by CMOS

- Amplifiers: BJTs are still widely used in audio, RF, and instrumentation amplifiers due to their high gain and linearity.

- RF (Radio Frequency) Circuits: BJTs perform well at high frequencies and are used in oscillators, mixers, and RF amplifiers

Advantages (compared to MOSFET):

- Lower output impedance (great for analog)
- Better performance in certain linear applications
- Less sensitive to static discharge (unlike MOSFETs)

Disadvantages of BJT :

- large chip area is needed for fabrication
- Power loss is high
- very temperature sensitive
- more sensitive to radiations than MOSFET