Bipolar Junction Transistor

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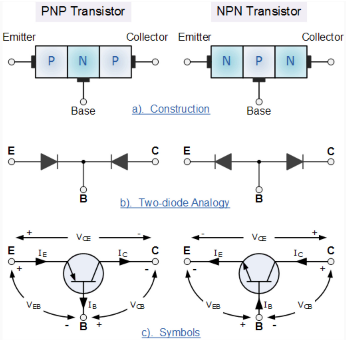
Intro

- BJT was invented by Bardeen, Brattain and Shockley at bell labs (not quite)
- It was the first commercially successful solid state device (previously there were bulbs)
- As the active region of the BJT is below the semiconductor surface, it is less dependent to surface properties or cleanliness
- BJT is composed of a sandwich of 3-doped semiconductor regions: *pnp* and *npn*
- BJT performance is driven by minority carrier drift and diffusion transport in the central region
- As carrier mobility and diffusivity is larger for e^- than h^+, npn transistor is inherently a higher performance device than *pnp* configuration

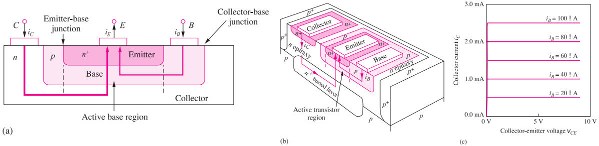
BJT structure

- BJT is a 3 alternating layers of n- & p-type semiconductor materials
- Layers are named as: base (B), emitter (E) and collector (C)
- Normal operation, current enters by colector terminal, passes through the base and output at the emitter terminal
- A rather small current also enter by the base terminal, crosses it and exits by the emmiter



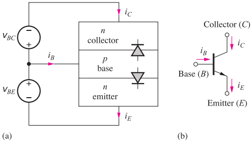
BJT structure

- Key section i the BJT is the active base region (dash line) under the heavily doped (n^+) emitter
- Carrier transport in this region drives the $i - v$ characteristics
- Figure b, shows the complexity to fabricate a BJT as well as to isolate it from others
- It is shown that i_C and i_B enter into the *pnp* structure and i_E comes out
- i.e. output characteristics of the BJT plots the i_C vs v_{CE} using i_B as key parameter

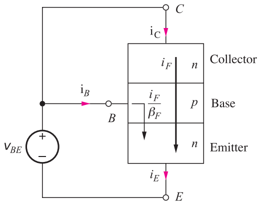


BJT Transport model

- BJT appears to be 2 *pn* junction connected back to back, nevertheless central region is rather thin $(0.1 - 100\mu\text{m})$
- The close proximity of both region allow the 2 diodes coupling, it is the essence of the bipolar device
- The emitter (n-type) inject e^- into p-type base, almost all e^- pas the narrow base and are removed by the upper n-type collector
- i_C, i_B & i_E are the current in the BJT, v_{BE} and v_{BC} are the base emitter and base colector voltages, respectively
- Arrows identifies the emitter terminal and shows that dc current exits by the emitter of the *pnp* BJT



BJT Forward Characteristics



- To properly analyze the behavior of the BJT, we use the above model
- In here, an arbitrary v_{BE} is applied and the $v_{BC} = 0$
- v_{BE} allows i_E that is equal to i_{BE}, it is made of two components
- Largest portion comes from forward-transport current I_F, that enters the collector, cross the base and exits by the emitter terminal
- $i_C = i_F$, that portraits the ideal diode current
  $i_C = i_F = I_S \left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1\right]$

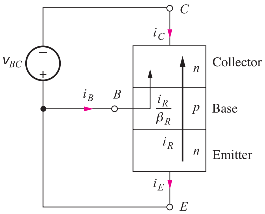
BJT Forward Characteristics

- I_S is defined as the transition saturation current, ranging from: $10^{-18} \leq I_S \leq 10^{-9}$A
- In addition to i_F, a quite small current is passing thru B-E junction. This current is considered as part of i_B as: $i_B = \frac{i_F}{\beta_F} = \frac{I_S}{\beta_F}\left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1\right]$
- β_F is known as forward common-emitter current gain, values are between: $10 \leq \beta_F \leq 500$
- i_E can be calculated as: $i_C + i_B = i_E$ or $i_E = \left(I_S + \frac{I_S}{\beta_F}\right)\left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1\right]$, it can be written as: $i_E = \frac{I_S}{\alpha_F}\left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1\right]$, α_F is known as forward common-base current gain and it ranges from $0.95 \leq \alpha_F < 1.0$

BJT Forward Characteristics

- α_F and β_F parameters are defined as: $\alpha_F = \frac{\beta_F}{\beta_F+1}$ and $\beta_F = \frac{\alpha_F}{1-\alpha_F}$
- Key useful relationships are valid in forward-active region: $\frac{i_C}{i_B} = \beta_F$ or $i_C = \beta_F i_B$ and $i_E = (\beta_F + 1)i_B$
- $\frac{i_C}{i_E} = \beta_F$ or $i_C = \alpha_F i_E$
- Above equations implies that the BJT amplifies its base current by a factor of β_F. As $\beta_F \gg 1$, injection of small current into the base, produces a larger current at both colector and emitter terminals, due to $i_C = i_E$ as $\alpha_F \approx 1$

BJT Reverse Characteristics



- If now we bias v_{BC} and $v_{BE} = 0V$, v_{BC} allows i_C, the larges part of i_C, the reverse-transport current i_R, enter the emitter, pass thru base and exits at collector terminal
- i_R is similar as for i_F as: $i_R = I_S \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right]$ and $i_E = -i_R$
- A fraction of i_R is supplied thru i_B as $i_B = \frac{i_R}{\beta_R} = \frac{I_S}{\beta_R} \left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1 \right]$
- β_R is known as reverse common-emitter current gain

BJT Forward Characteristics

- As the impurity doping level for the emitter and colector are asymmetric, it causes the i_B for both modes, reverse and forward, are quite different
- For a typical BJT $0 < \beta_R \leq 10$ and $10 \leq \beta_F \leq 500$
- i_C can be found as: $i_C = -\frac{I_S}{\alpha_R}\left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1\right]$
- where α_R is defined as reverse common-base current gain: $\alpha_R = \frac{\beta_R}{\beta_R+1}$ or $\beta_R = \frac{\alpha_R}{1-\alpha_R}$, typical values are between the range of: $0 < \alpha_R \leq 0.95$

TABLE 5.1
Common-Emitter and Common-Base Current Gain Comparison

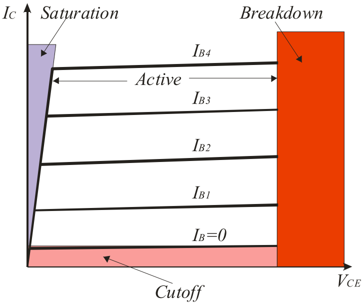
α_F or α_R	$\beta_F = \frac{\alpha_F}{1-\alpha_F}$ or $\beta_R = \frac{\alpha_R}{1-\alpha_R}$
0.1	0.11
0.5	1
0.9	9
0.95	19
0.99	99
0.998	499

Transport Model Equations for npn BJT

- By gathering the equations for i_c, i_E & i_B, follow equations are valid for a general bias voltage situation
$$i_C = I_S\left[\exp\left(\frac{v_{BE}}{V_T}\right) - \exp\left(\frac{v_{BC}}{V_T}\right)\right] - \frac{I_S}{\beta_R}\left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1\right]$$
$$i_E = I_S\left[\exp\left(\frac{v_{BE}}{V_T}\right) - \exp\left(\frac{v_{BC}}{V_T}\right)\right] - \frac{I_S}{\beta_F}\left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1\right]$$
$$i_B = \frac{I_S}{\beta_F}\left[\exp\left(\frac{v_{BE}}{V_T}\right) - 1\right] + \frac{I_S}{\beta_R}\left[\exp\left(\frac{v_{BC}}{V_T}\right) - 1\right]$$
- Above equations are required to characterize an individual BJT
- An equation that defined colector and emitter symmetry is shown as: $i_T = I_S\left[\exp\left(\frac{v_{BE}}{V_T}\right) - \exp\exp\left(\frac{v_{BC}}{V_T}\right)\right]$
- Above set of equations is a light version of the Gummel-Poon model widely used in SPICE

Operation regions

- BJT device shows different operating regimes. To differentiate among them, we've to look at $i - v$ characteristics of the device
- A key characteristic to analyze the BJT is thru i_C vs v_{CE} as function of several i_B values such as $i_{B4} > i_{B3} > i_{B2} > i_{B1}$

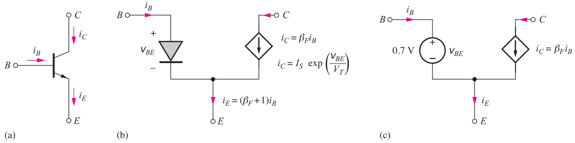


Characteristics for each region are:

1. Cutoff region: base-emitter junction is reverse biased, No current flow
2. Saturation region: base-emitter junction is forward biased, collector-base junction is forward biased, i_C reaches a maximum that is independent of i_B and β, there is no control, $v_{CE} < v_{BE}$
3. Active region: base-emitter forward biased, collector-base junction reverse biased, control, $i_C = \beta i_B$, $v_{BE} < v_{CE} < v_{CC}$
4. Breakdown region: i_c and v_{CE} exceed specifications, damage to the transistor

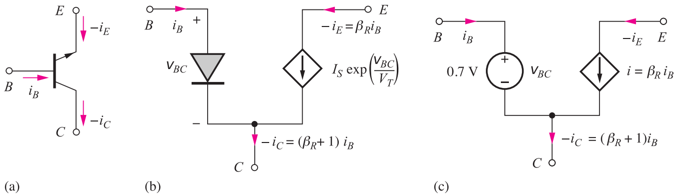
Model simplification for forward-active region

For an *npn* transistor $v_{BE} \geq 0$ and $v_{BC} \leq 0$
$v_{BE} > 4\frac{kT}{q} = 0.1\text{V}$ and $v_{BC} < -4\frac{kT}{q} = -0.1\text{V}$, by considering that $(v_{BC}/V_T) \ll 1$, it yields to $i_C = I_S \exp\left(\frac{v_{BE}}{V_T}\right) + \frac{I_S}{\beta_R}$;
$i_E = \frac{I_S}{\alpha_F}\exp\left(\frac{v_{BE}}{V_T}\right) + \frac{I_S}{\beta_F}$; $i_B = \frac{I_S}{\beta_F}\exp\left(\frac{v_{BE}}{V_T}\right) - \frac{I_S}{\beta_F} - \frac{I_S}{\beta_R}$
In above set of equations, exponential term are larger, ergo, forward region is defined as:
$i_C = I_S \exp\left(\frac{v_{BE}}{V_T}\right)$;$i_E = \frac{I_S}{\alpha_F}\exp\left(\frac{v_{BE}}{V_T}\right)$; $i_B = \frac{I_S}{\alpha_F}\exp\left(\frac{v_{BE}}{V_T}\right)$ Also, these approximations are highly required: $i_C = \alpha_F i_E$ and $i_C = \beta_F i_B$, as $i_E = i_C + i_B$, $i_E = (\beta_F + 1)i_B$



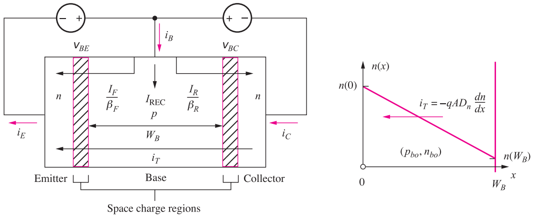
Simplified model for the reverse-active region

- In here, emitter and collector terminals are reversed, base-collector diode is forward biased and base-emitter is reverse biased
- $i_C = -\frac{I_S}{\alpha_R} \exp\left(\frac{v_{BC}}{V_T}\right)$, $i_E = -I_S \exp\left(\frac{v_{BC}}{V_T}\right)$; $i_B = -\frac{I_S}{\beta_R} \exp\left(\frac{v_{BC}}{V_T}\right)$
- ratios for those equations are: $i_E = -\beta_R i_R$ and $i_E = \alpha_R i_C$



Minority carriers at the base region

- Current at BJT is driven by minority carriers across the base terminal
- At *npn* BJT, transport current i_T result from the diffusion of minority carriers across the base
- The voltages applied to the base-emitter and base-collector junctions define the minority-carrier concentrations at the two ends of the base due to emitter is heavily doped in regard tothe colector, so the gradient appear



The base transit time τ_F

- It the average time reuired for the carriers send by the emitter to arrive into the collector, it defined by $\tau_F = \frac{Q}{i_T}$, where

$$Q = qAn(0)\frac{W_B}{2} = An_{bo}\exp\left(\frac{v_{BE}}{V_T}\right)\frac{W_B}{2}$$

- $i_T \approx i_{En} = qAD_n\frac{n_{bo}}{W_B}\exp\left(\frac{v_{BE}}{V_T}\right)$
- $\tau_F = \frac{Q}{i_T} = \frac{W_B^2}{2D_n} = \frac{W_B^2}{2V_T\mu_n}$
- Above equation shows why it is key to reduce the base width W_B
- Transit time places a maximum level at the highest operating frequency f of the BJT

$$f \leq \frac{1}{\tau_F}$$

Diffusion capacitance

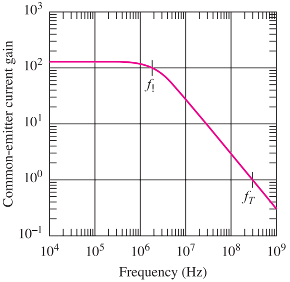
- As charge Q varies according to v_{BE}, the variation in charge with voltage can be modeled by using a capacitance C_D known as diffusion capacitance
-
$$C_D = \frac{dQ}{dv_{BE}\,|_{Q-point}} = \frac{1}{V_T}\frac{qAn_{bo}W_B}{2}\exp\left(\frac{v_{BE}}{V_T}\right)$$
$$C_D = \frac{1}{V_T}\frac{qAn_{bo}}{\exp}\left(\frac{v_{BE}}{V_T}\right)\frac{W_B^2}{2D_n} = \frac{i_t}{V_T}\tau_F = \frac{i_C}{V_T}\tau_F$$

Frequency dependence of C-E current gain

- The forward biased diffusion and reverse-biased *pn* junction capacitance of the BJT allows the current gain to be frequency dependent

$$\beta(f) = \frac{\beta_F}{\sqrt{1 + \left(\frac{f}{f_\beta}\right)^2}}$$

where f_β is the β cutoff frequency



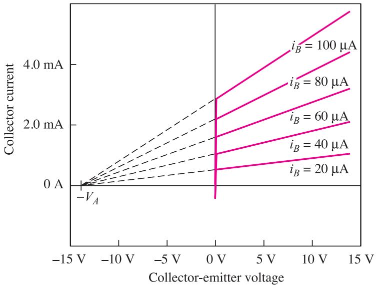
Frequency dependence of C-E current gain

- The unity gain frequency f_T is the frequency at which the total magnitude of the current gain is "1"

$$1 = \beta(f_T) = \frac{\beta_F}{\sqrt{1 + \left(\frac{f}{f_\beta}\right)^2}} \approx \frac{\beta_F}{f_T / f_\beta}$$

Early effect

- In a BJT, i_C does depend on v_{CE}
- When the output characteristic curves are extrapolated to the origin (point zero) at i_C
- All curves intersect at $v_{CE} = -V_A$, this is called Early effect
- V_A is known as Early voltage, ranging from $15 \leq V_A \leq 150$V



Early effect

- Early effect is the modulation of the base width of the BJT by v_{CE}
- As the reverse bias across the C-B junction increases
- The width of the C-B SCR increases and W_B decreases

$$i_C = I_S \exp(\frac{v_{BE}}{v_T})(1 + \frac{v_{CE}}{V_A})$$

$$\beta_F = \beta_{FO} = (1 + \frac{v_{CE}}{V_A})$$

$$i_B = \frac{I_S}{\beta_{FO}} \exp(\frac{v_{BE}}{V_A})$$

β_{FO} is the value of β_F extrapolated to $v_{CE} = 0$

Transconductance

- Transconductance is defined as g_m

$$g_m = \frac{di_C}{dv_{BE}} \mid_{Q-point} = \frac{d}{dv_{BE}} \left\{ I_S \exp(\frac{v_{BE}}{V_T}) \right\} \mid_{Q-point}$$

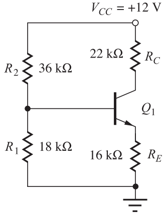
$$= \frac{1}{V_T} I_S \exp\left(\frac{v_{BE}}{V_T}\right) = \frac{i_C}{V_T}$$

τ_F can be written as $\tau_F = \left(C_D \frac{V_T}{i_C}\right) = \frac{C_D}{gm}$ or $C_D = g_m \tau_F$

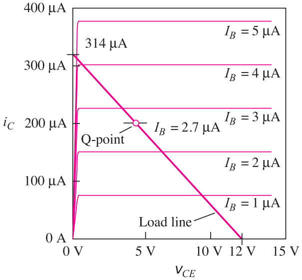
A few considerations

- The key point to bias the BJT is to get the Q-point
- Q-point get the values for diffusion, capacitances, transconductance, $\cdots$
- We, in most cases, use the simplified transistor model
- 2 key arrays are 4-resistor and 2-resistor bias networks

Q-point of the transistor Q1



$v_{EQ} = v_{CC}\frac{R_1}{R_1+R_2} = 12\frac{18}{18+36} = 4V$; $R_{EQ} = R_1 \mid\mid R_2 = 18 \mid\mid 36 = 12$ kΩ



Q-point of the transistor Q1

From the above figure, we can infer that: $\beta_F = 300/4 = 75$

$v_{EQ} = I_B R_{EQ} + V_{BE} + I_E R_E = I_B R_{EQ} + V_{BE} + (1+\beta_F) I_B R_E$

$I_B = \frac{v_{EQ} - v_{BE}}{R_E Q + (1+\beta_F) R_E} = \frac{4-0.7}{12+(1+75)16} \approx 2.69 \times 10^{-6}\text{A}$

$I_C = \beta_F I_B = 75 \cdot 2.69 \times 10^{-3} \approx 0.202$ mA

$I_E = (1+\beta_F) I_B = (1+75) \cdot 2.69 \times 10^{-3} \approx 0.202$ mA

$v_{CE} = v_{CC} - I_C R_C - I_E R_E = 12 - 0.202 \cdot 22 - 0.204 \cdot 16 \approx 4.29\text{V}$

$Q - point : (I_C, v_{CE})$=0.202 mA @ 4.29 V

Q-point of the transistor Q1

Design a 4 resistor bias circuit to give a Q-point of (750 μA@5 V), considering a 12 V source with an *npn* transistor, having a minimum current gain of 100)

$I_B = \frac{I_C}{\beta_F} = \frac{0.75}{100} = 7.5 \times 10^{-3}$mA

$V_B = \frac{1}{3} V_{CC} = \frac{1}{3} \cdot 12 = 4V$

$R_1 = \frac{V_B}{9 I_B} = \frac{4}{9 \cdot 7.5m} \approx 59.3$ kΩ

$R_2 = \frac{V_{CC} - V_B}{10 I_B} = \frac{12-4}{10 \cdot 7.5m} \approx$106.7k$\Omega$

$R_E \approx \frac{V_B - V_{BE}}{I_C} = \frac{4-0-7}{7.5m}$=4.4 k$\Omega$

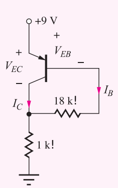
$R_C \approx \frac{V_{CC} - V_{CE}}{I_C} - R_E = \frac{12-5}{7.5m} - 4.4 \approx 4.93k\Omega$

where the closest values for Rs are:

R_1= 62kΩ, R_2= 110 kΩ, R_E= 4.3 kΩ and R_C= 5.1kΩ

Find the Q-point

Find the Q-point for the *pnp* transistor in the 2 resistor bias circuit as portrait in Fig. assuming a β=50



$9 = V_{EB} + I_B \cdot 18 + (I_C + I_B) \cdot 1 \; I_C = \beta_F I_B = 50 I_B$
$I_B = \frac{9-0.7}{69} \approx 0.12$ mA
$I_C = 50\cdot\ 0.12 = 6$ mA
$9{=}V_{EC}{+}(I_C + I_B)\cdot\ 1$
$V_{EC} = 9 - (6 + 0.12)\cdot\ 1{=}2.88$ V
Q-points are $(I_C, V_{CE}) = 6$ mA@2.88 V