used in amplification of weak signals and swithing operations

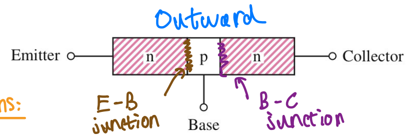
3 terminals

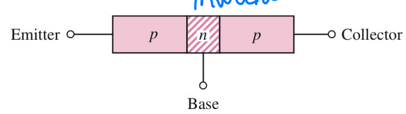
Bipolar Junction Transistor (BJT) Symbols

- Many people believe that the name Transistor came from: Transfer of Resistor = Transistor.
- Yes, it can transfer resistance, as we will see later in this course.

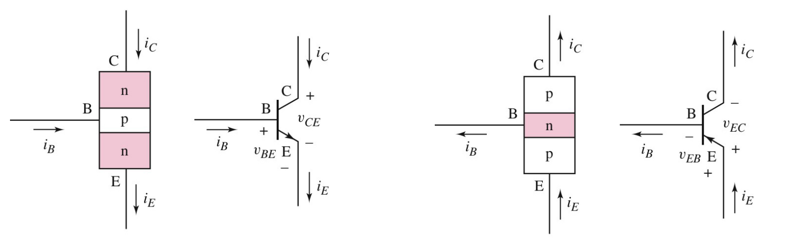
Outward inward

2 Regions:





- BJT is a 3-terminal device, where the Emitter emits charge carriers, the Collector collects them, and the Base controls the flow.



npn-type transistor npn symbol pnp-type transistor pnp symbol 1

- collector is largest region
- smallest region is base

width:

C > E > B

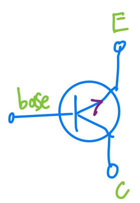
Doping:

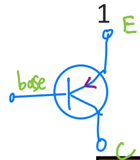
E > C > B

largest width cuz it has to collect electrons and heat is produced in it

E|B|C

1





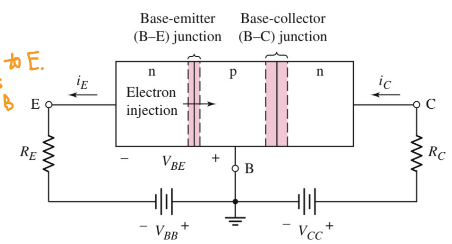
- one junction is forward biased while the other is reverse biased

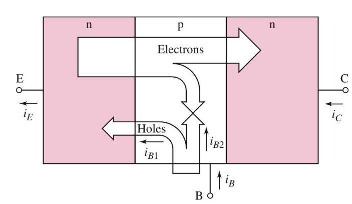
— plenty of questions in quizzes from class discussions

npn
- electrons move from E to B. So current is B to E

pnp
- electrons move from n to p, so B to E. ∴ current is E to B

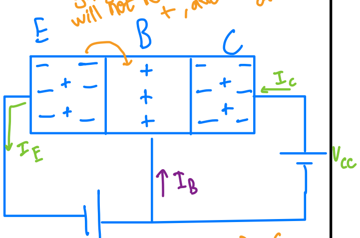
BJT Working Principle





-leakage current

electrons going into base will not recombine, with low conc of +, due to +



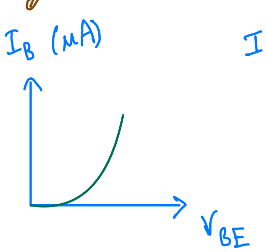
B-E is forward biased

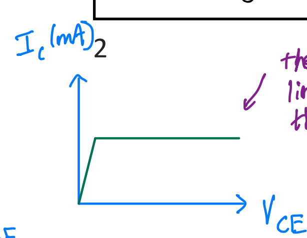
B-C is reverse biased

- Normally, the B-E junction is forward biased, and the B-C junction is reverse biased. We'll learn other cases later in this course.
- Emitter and collector are highly doped, but the base is lightly doped
- Emitter emits/injects electrons into base base region
- The base recombines only less than 1-2% of the emitted electrons
- Rest of the emitted electrons in base can easily cross the B-C junction if a positive potential (reverse bias) is applied at the collector (Why?)
- Thus, the collector collects the excess electrons from the base
- Analyze this on your own for a pnp transistor

2

usually is much smaller compared to I_C

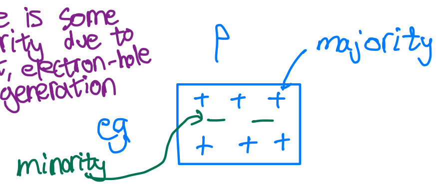




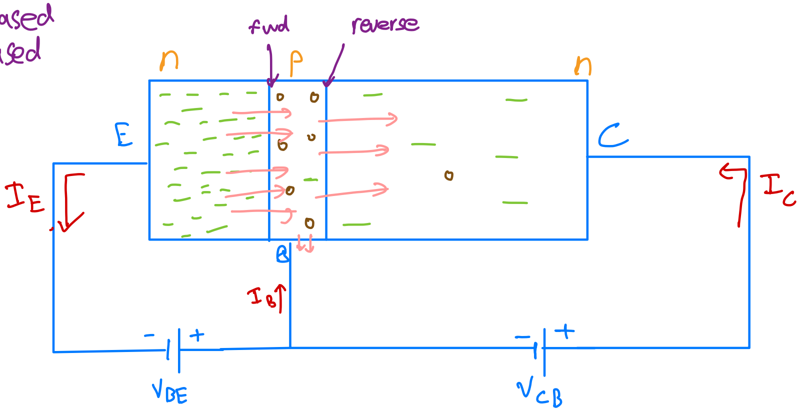
2

there is a limit, since there is a limited amount of electrons coming from emitter

-there is some minority due to heat, electron-hole generation



EB is fwd biased
BC is rev biased

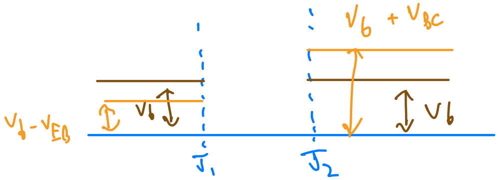


$\alpha = \frac{I_c}{I_E}$

$\beta = \frac{I_c}{I_B}$

looking at barrier potentials

V_b = barrier potential with no bias



for EB

- depletion width became smaller
- electrons on n-side will cross and combine with holes in base

* Note that base is small and lightly doped

∴ therefore there is small recombination that occurs in base. Most electrons go into collector

for CB

- there is reverse saturation current from minority charge carriers combining

leakage

??

$I_C = \alpha I_E + I_{CO}$

using KCL
$I_E = I_B + I_C$

for npn:

- base has +ve V with respect to emitter — fwd
- collector has +ve V with respect to base — rev

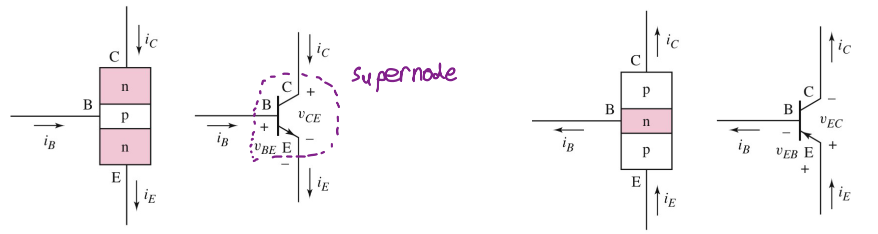
I think rule is when p is +ve wrt n then it's fwd

≈ n is -ve wrt +

4 possible ways of biasing BJT:

J_1	J_2	Region of operation	
f.b.	r.b.	Active	→ amplifier
f.b.	f.b.	Saturation	→ "ON"
r.b.	r.b.	Cutoff	→ "off"
r.b.	f.b.	inverted	↑ rarely used - E and B switch roles

Current Relationship



npn-type transistor npn symbol pnp-type transistor pnp symbol

By KCL for npn transistor,
$i_E - i_C - i_B = 0$
or, $i_E = i_C + i_B$

By KCL for pnp transistor,
$-i_E + i_C + i_B = 0$
or, $i_E = i_C + i_B$

Do NOT forget this

This is valid regardless

current equation remains the same

3

In active mode:
$J_1 \to$ f.b.
$J_2 \to$ r.b.

then resistance is 0 when ON and ∞ when off

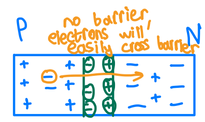
somehow transferred low resistance to high resistance

$V_i = I \times r$ $V_0 = I \times R$

$V_i < V_0$

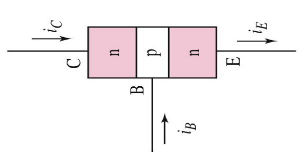
had weak signal at input now we have large at output ∴ amplification

3



- the charges in depletion region determine direction of electric field

Current Relationship



Common-base* current gain $\alpha = \dfrac{i_C}{i_E}$

Common-emitter* current gain $\beta = \dfrac{i_C}{i_B}$

*We will learn common-base and common-emitter later in this course

- The value of α cannot be higher than one ← due to equations next page
- The value of α is approximately equal to 1 i.e., ($\alpha \approx 1$)
- The value of β can widely vary. Examples: β=20, β=75, β=112, β=165, β=200
- α and β have no units
- α and β are inherent properties, available in transistor datasheet
- α and β must be related to each other

4

typical β value is usually high. Many more electrons cross while only 1 recombines

4

α is usually 0.99 .....

$I_C < I_E$

Current Relationship

Recall, $i_E = i_C + i_B$
Using this equation and the definitions of α & β,
one can easily derive the following relationships

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

$$i_E = i_C + i_B$$

$$\frac{i_E}{i_B} = \frac{i_C}{i_B} + \frac{i_B}{i_B}$$

$$\frac{i_E}{i_B} = \beta + 1$$

$$i_E = i_B(\beta + 1)$$

relates emitter and base currents

$$\alpha = \frac{i_C}{i_E}$$

$$\alpha = \frac{i_C/i_B}{i_E/i_B}$$

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

$$\beta = \frac{i_C}{i_E - i_C}$$

$$\beta = \frac{i_C/i_E}{i_E/i_E - i_C/i_E}$$

$$\beta = \frac{\alpha}{1 - \alpha}$$

relate α and β

** V.I.P
- will not be given in formula sheet
- need to memorise

5

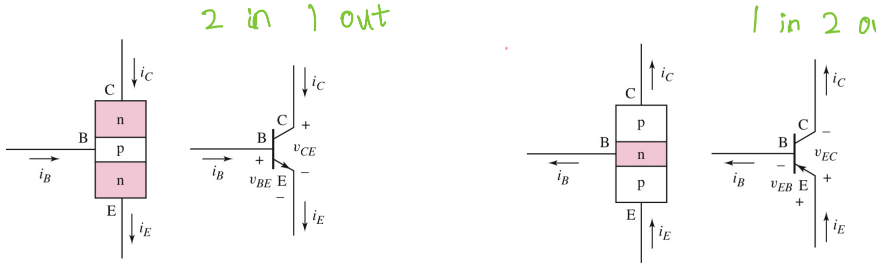
5

To remember NPN and PNP

Voltage Relationship

2 in 1 out

1 in 2 out



npn-type transistor npn symbol pnp-type transistor pnp symbol

how is KVL used? I don't see it

By KVL for npn transistor,
$-V_{BE} - V_{CB} + V_{CE} = 0$

or, $V_{CB} = V_{CE} - V_{BE}$

By KVL for pnp transistor,
$V_{EB} - V_{CB} - V_{EC} = 0$

or, $V_{CB} = -V_{EC} + V_{EB}$

or, $V_{CB} = V_{CE} - V_{BE}$

Do NOT memorize this

This is valid regardless

6

6

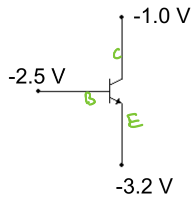
Perfect biasing

B-E junction is forward biased

C-B junction is reverse biased

NPN

Voltage Relationship: Example



$V_B - V_E = -2.5 - -3.2 = 0.7$

$V_C - V_B = -1 - -2.5 = 1.5$

Example: Consider the npn transistor with given voltages. Determine the type of biasing applied to B-E and C-B junctions of this transistor.

Soln: Here $V_{BE} = V_B - V_E$

or, $V_{BE} = -2.5 - (-3.2) = 0.7$ V

Since the base has a positive voltage with respect to emitter, the B-E junction of this npn transistor is forward biased.

Again, $V_{CB} = V_C - V_B$

or, $V_{CB} = -1 - (-2.5) = V_{CB} = 1.5$ V

Since the collector has a positive voltage with respect to base, the C-B junction of this npn transistor is reverse biased.

∴ Therefore transistor is properly biased

Notes:

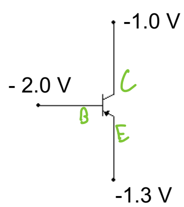
- Notice that the collector base junction is reverse biased although the n-type collector has a negative voltage applied to it
- The biasing depends on voltage difference across the junction

7

7

PNP

Voltage Relationship: Example



Example: Consider the given transistor. Determine the type of biasing applied to B-E and C-B junctions of this transistor.

Soln: Here $V_{BE} = V_B - V_E$

or, $V_{BE} = -2 - (-1.3) = -0.7$ V

Since the base has a negative voltage with respect to emitter, the B-E junction of this pnp transistor is forward biased.

Again, $V_{CB} = V_C - V_B$

or, $V_{CB} = -1 - (-2) = V_{CB} = 1$ V

Since the collector has a positive voltage with respect to base, the C-B junction of this pnp transistor is forward biased.

Notes:

- Notice that the collector base junction is forward biased although the p-type collector has a negative voltage applied to it
- The biasing depends on voltage difference across the junction

-both forward biased so transistor won't work

8

8

-never used this equation in assignments or quiz

where do these equations come from?

Do I just need to memorize as is?

Collector Current

We know, $i_C = I_S e^{\left(\frac{v_{BE}}{V_T}\right)}$

Also, $i_B = \frac{1}{\beta} I_S e^{\left(\frac{v_{BE}}{V_T}\right)}$

Also, $i_E = \frac{1}{\alpha} I_S e^{\left(\frac{v_{BE}}{V_T}\right)}$

Where,
I_S = Saturation current or scale current
V_T = Thermal voltage = (kT/q)
k = Boltzmann's constant
k = 1.38×10^{-23} J/K
T = Temperature in °K
q = electron charge = 1.6×10^{-19} C
Thus, at 20 °C V_T = 25.27 mV
Use V_T = 25 mV in this course

this is also the drift current, from min carriers, right?

Notes:
- Above equations are for npn transistors
- Use V_{EB} instead of V_{BE} for pnp transistors
- Collector current (also I_B and I_E) depends on temperature
- $|V_{BE}|$ controls collector current and other currents
- Scale current is an inherent parameter of a transistor
- I_S is typically in the order of 10^{-12} to 10^{-15} A

why??

9

9

Collector Current Examples

I_S = drift current, saturation, scale

Example: A transistor gives 4 mA of collector current at V_{BE} = 0.72 V. Determine scale current I_S of the transistor.

Soln: $I_S = (0.004)/e^{(0.72/0.025)}$
$I_S = 1.24 \times 10^{-15}$ A

$I_S = \frac{I_C}{e^{\frac{V_{BE}}{V_T}}}$

Example: The saturation current of a transistor is given $I_S = 2.1 \times 10^{-13}$ A. What base-emitter voltage is required to generate 2.5 mA of collector current?

Soln: $\ln\left(\frac{i_C}{I_S}\right) = \frac{v_{BE}}{V_T}$

or, $v_{BE} = V_T \ln\left(\frac{i_C}{I_S}\right) = 0.58$ V

just rearranging of equation

10

10

Collector Current Example

rearrange equations and plug numbers

Example: Given that a transistor with $\beta = 150$ has a base current of $15\ \mu A$. Determine a) collector current iC, b) emitter current iE, and c) the common-base current gain α.

Soln:

a) We know, $i_C = \beta\, i_B = 150 \times 15 \times 10^{-6}$
or, $i_C = 2.25$ mA

b) We know, $i_E = i_C + i_B$
or, $i_E = 2.25 \times 10^{-3} + 15 \times 10^{-6}$
or, $i_E = 2.265$ mA

Also, $i_E = (\beta + 1) i_B$
or, $i_E = 151 \times 15 \times 10^{-6}$
or, iE $= 2.265$ mA

c) We know, $\alpha = \beta / (\beta + 1)$
or, $\alpha = 150/151$
or, $\alpha = 0.9934$

Verify: $\beta = \alpha / (\alpha + 1)$
$\beta = 150.5$ (0.3% error)
if we take $\alpha = 0.993$,
$\beta = 141.9$ (5.4% error)

if we take $\alpha = 0.99$,
$\beta = 99.0$ (51.5% error)

It is not just the math, you need to fully understand how your design is changing.

–need to understand that if it's +ve or –ve, what it means in circuit

I don't quite understand this point

11

11

Transistor Characteristics: Base-Emitter

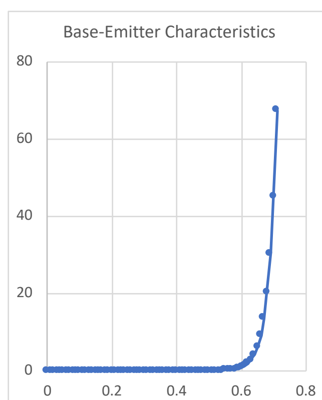
- This is the same as a diode
- Note the slope changes from infinite to almost zero
- What happens if the voltage is increased to 0.8 or higher? For this particular graph with I_S=5x10^{-15}A and β=150, we'll have:

  $I_B = 247\ \mu A$ at $V_{BE} = 0.8$ V

  $I_B = 0.135$ A at $V_{BE} = 0.9$ V

  $I_B = 7.356$ A at $V_{BE} = 1.0$ V
- V_{BE} decreases by 2 mV for temperature rise of 1°C
- Consider $V_{BE(on)} = 0.7$V throughout this course

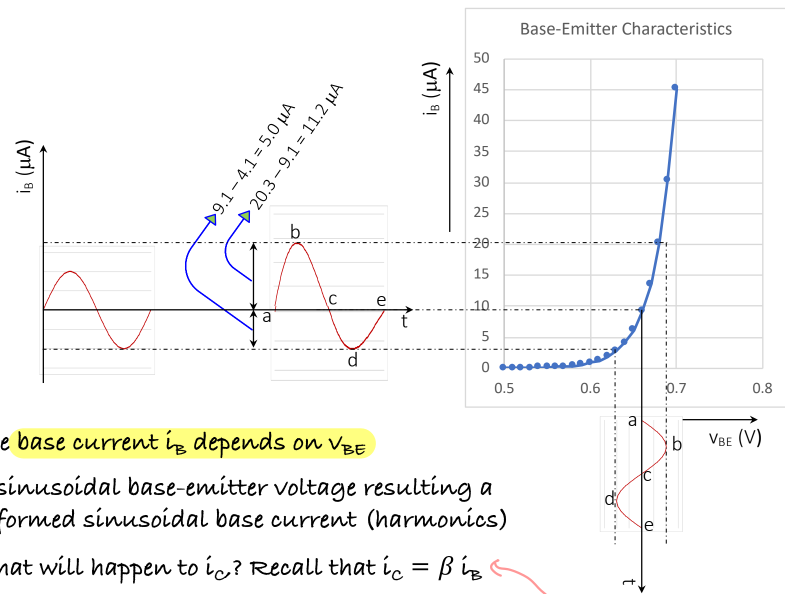
exponential increase



12

12

Effect of Nonlinearity in Base-Emitter Characteristic



- The base current i_B depends on V_{BE}
- A sinusoidal base-emitter voltage resulting a deformed sinusoidal base current (harmonics)
- What will happen to i_C? Recall that $i_C = \beta\, i_B$
- Select linear region by applying small signal

it will also exponentially increase

13

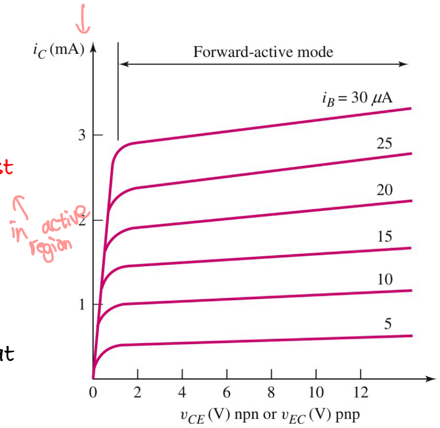
13

Transistor Characteristics: Collector-Emitter

$I_C \approx I_E$

- Ideally, all curves should be horizontal in the active region
- Why does the current increase so rapidly (≈ zero slope)? (homework)
- Why does the current become almost constant after a fraction of voltage (≈ infinite slope)? (homework)
- Notice that in practice the slope decreases with the increase of i_B
- How much current can you expect at i_B = 0? What is the source of the current at i_B =0?
- What happens at very large $|V_{CE}|$?
- What is the effect of temperature?

in active region



14

14