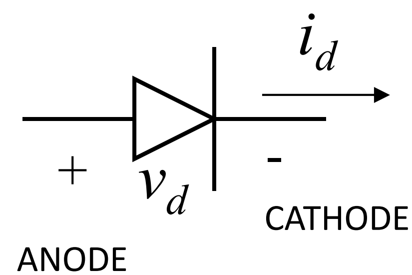
Semiconductors

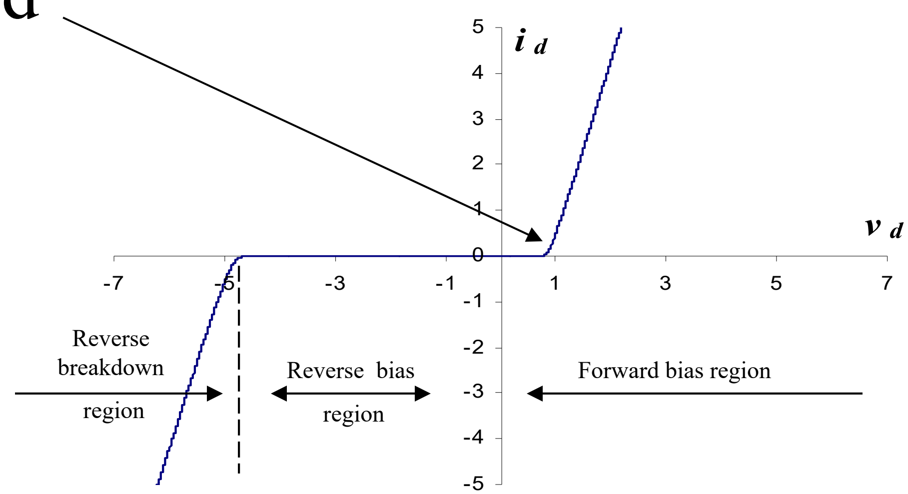
Diodes and BJ Transistors

Lecture 8

Diodes

- Typical Diode VI Characteristics
  - Forward Bias Region
  - Reverse Bias Region
  - Reverse Breakdown Region
  - Forward bias Threshold

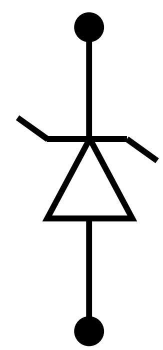




VI stands for Voltage Current

Zener Diodes

- Operated in the breakdown region.
- Used for maintain a constant output voltage

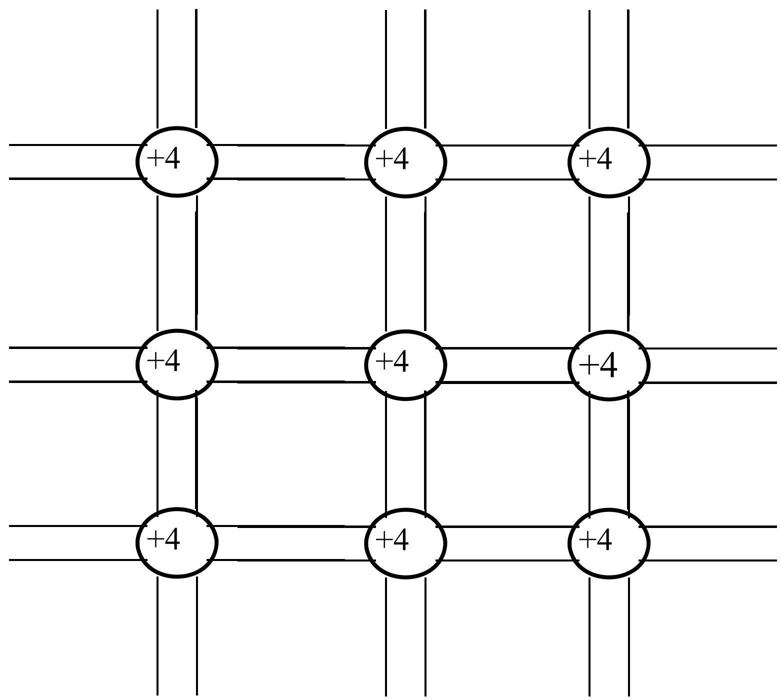


Basic Semiconductor Electronics

- Atomic Structure of Valence-4 elements like Carbon, Silicon, Germanium, etc.
  - have 4 valence electrons in its outer atomic shell
  - these atoms form covalent bonds with 4 other atoms in a lattice
- When the energy levels of these electrons are raised several of these bonds may become randomly broken and a free electron is created
  - as a result these electrons are free to move about in the material similar to electron conduction occurs in a metal
  - in addition to the free electron, a negative particle, a "hole" which is a positive "particle" is created which also moves freely within the material.
- As electrons and holes move through the material, they may encounter each other and recombine and, thereby, become electrically neutral
- This type of material is called an intrinsic semiconductor

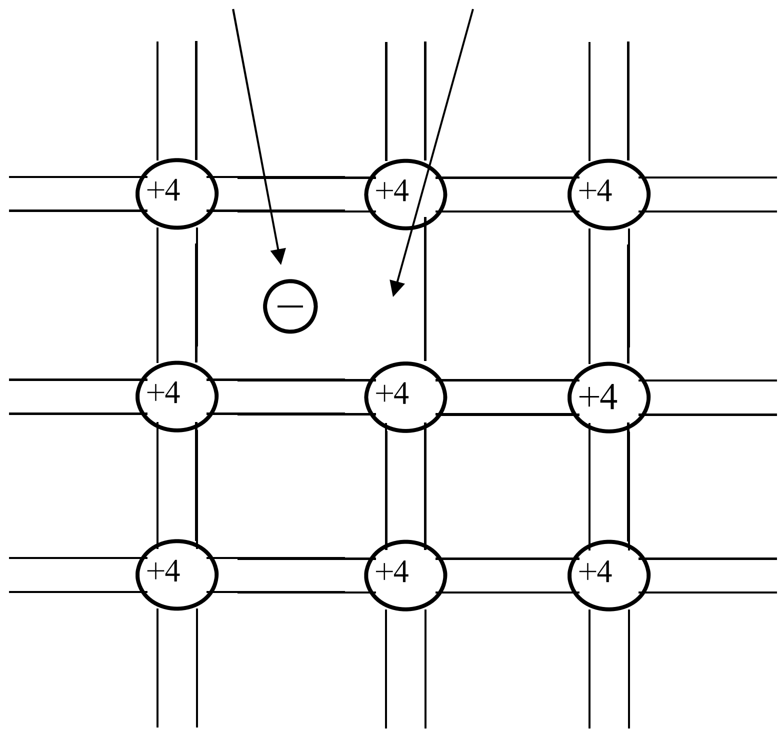
Intrinsic Silicon Crystal

Complete Lattice



Intrinsic Silicon Crystal

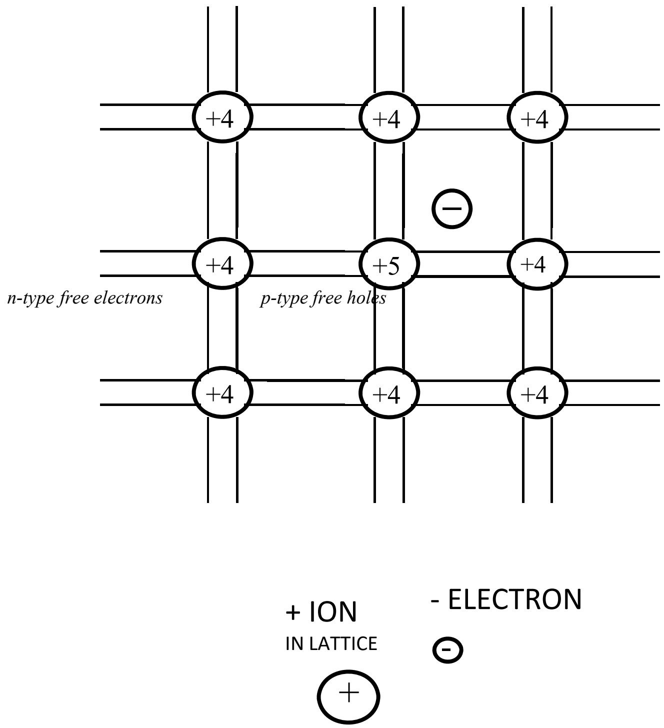
Thermal Energy causes a bond to be broken and a free electron and hole are created

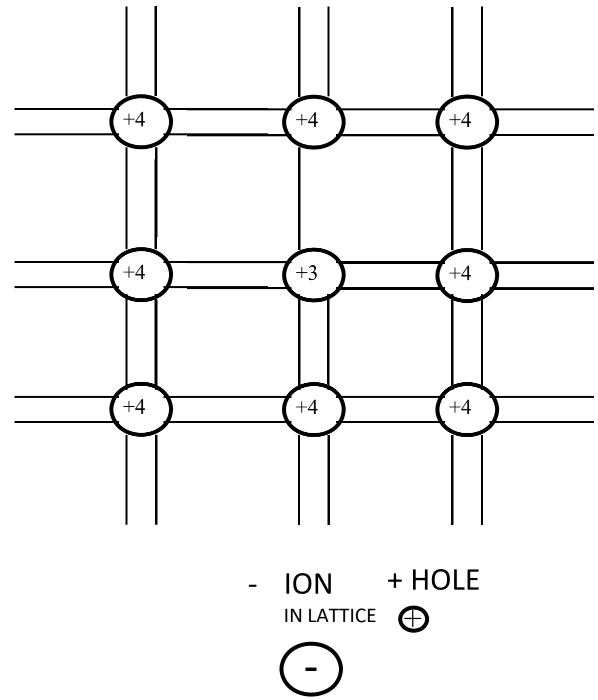


Doped Semiconductor Material

- If we incorporate a small impurity of five or three valence band materials into a 4 valence band lattice, we have created an extrinsic semiconductor which is doped with an impurity
- n-type semiconductor
  - Doping with five valence material (e.g. Arsenic) to create additional free (donor) electrons and a static positive charged ion in the core lattice
  - Majority carriers are electrons; minority carriers are holes
  - The concentration of electrons in a n-type semiconductor = concentration of the donor electrons + the concentration of free holes (which is the same as the number of electrons which have randomly broken their valence bonds)
- p-type semiconductor
  - Doping with three valence material (e.g., Gallium) to create additional free (donor) holes and a static negative charged ion in the core lattice
  - Majority carriers are holes; minority carriers are electrons
  - The concentration of holes in a p-type semiconductor = concentration of the donor holes + the concentration of free electrons (which is the same as the number of holes which have randomly broken their valence bonds)

Doped silicon material





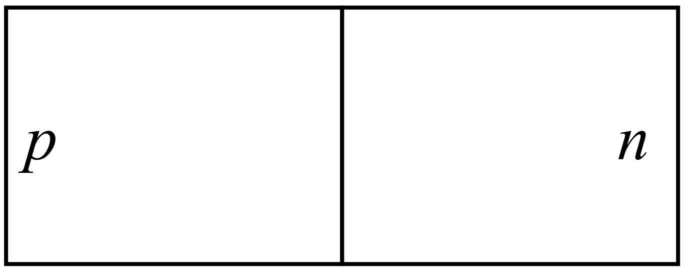
Carrier Concentrations and Recombination

- There are two types of carrier concentrations
  - Majority carriers due to the doping
    - Electrons in n-type
    - Holes in p-type
  - Minor carriers to due thermal excitation
    - Holes in n-type
    - Electrons in p-type
- Recombination: when an electron meets a hole, they combine to complete the bond
- Generation: thermal excitation creates new carriers
- Equilibrium exists when the rate of recombination equals the rate of generation

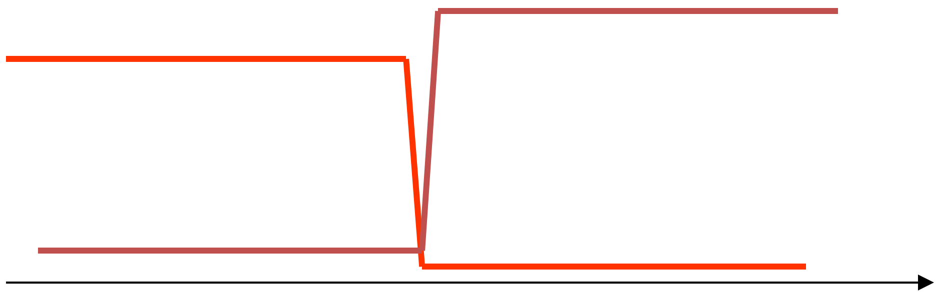
PN Junction

- When a p-type semiconductor is fused with a n-type, the following occurs at the junction.
  - Because the concentration of electrons is greater on n-type side, holes from the p-type diffuse across the junction to the n-type side
  - Likewise electrons diffuse across the junction from the n-type to the p-type material
  - These carriers recombine and what remains are the negatively charged ions on the p-type side and positively charged ion on the n-type side.
- The ions which are tied to the lattice form an electric field which prohibits the flow of carriers across the junction.
  - The area where these ions and their associated electric field are situated is called the depletion region since it is depleted of holes and electrons
  - The electric field which prohibits the flow of carriers is called the barrier potential

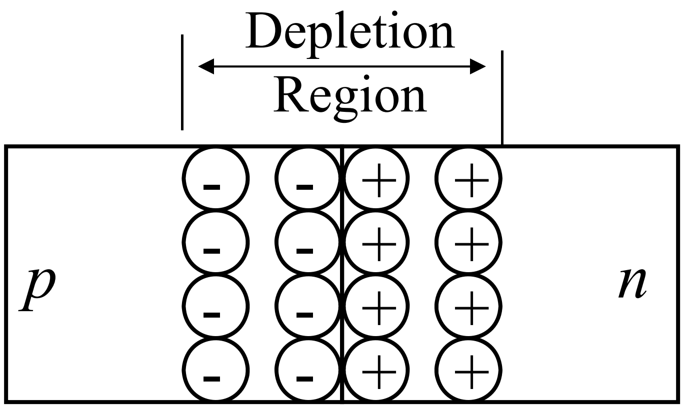
PN Junctions Prior to being Fused



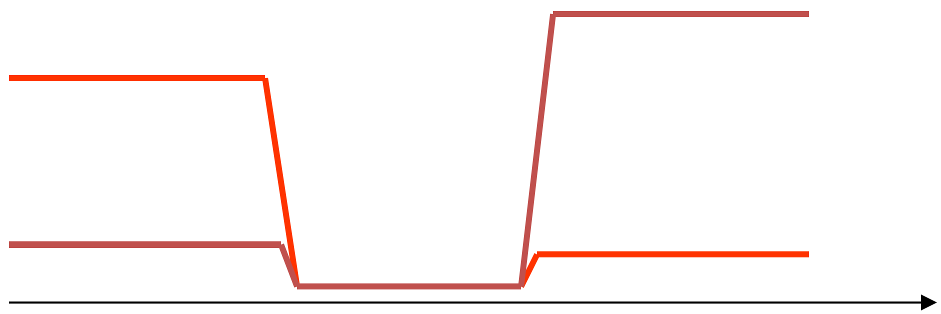
Unbiased PN Junction



PN Junctions Unbiased



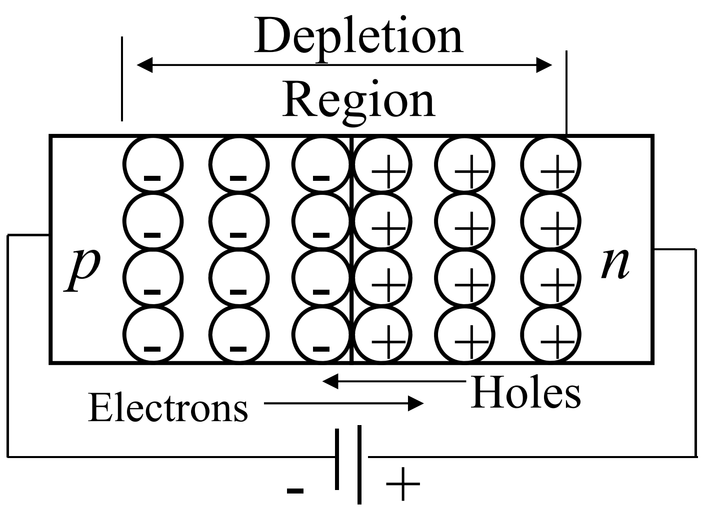
Unbiased PN Junction



Reverse Bias PN Junction

- When an external voltage is a applied to a PN junction such that the n-type is more positive than the p-type, then we say that the PN junction is reverse-biased and the following happens:
  - The external voltage creates an electric field which enhances the barrier potential and the depletion region becomes wider since the majority carriers are pulled away from the junction (e.g., the electrons in the n-type material are attracted away from the junction by the positive voltage).
  - However, this applied field supports the flow of minority carriers across the junction (e.g., the holes in the n-type material are attracted across the junction by the enhanced electric field of the widened depletion region) and when they cross the junction they become majority carriers (e.g., the minority carrier n-type holes now become majority carriers once they cross the junction to the p-type) and are attracted away from the junction as described above.
  - Since the flow across the junction is due to minority carriers the current flow is small (this is sometimes called the reverse-based leakage current).

PN Junctions Reverse Biased



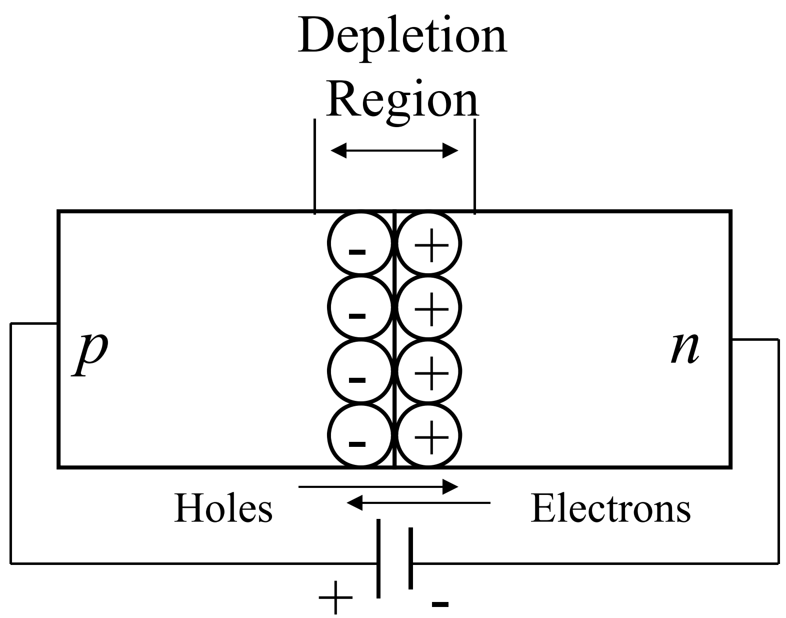
Reverse-biased PN Junction

These are minority carriers and therefore the RB current is small but not zero.

Forward Bias PN Junction

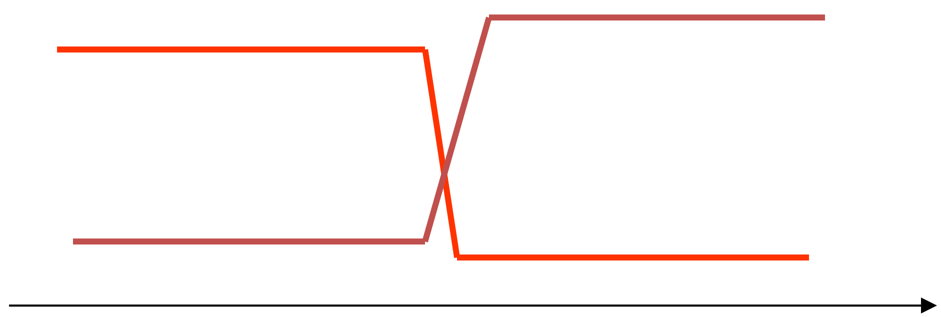
- When an external voltage is a applied to a PN junction such that the n-type is more negative than the p-type, then we say that the PN junction is forward-biased and the following happens:
  - The external voltage creates an electric field which opposes the barrier potential and the depletion region becomes smaller provided it is larger than the voltage barrier of the depletion region (typically, a few tenths of a volt)
  - This allows for the further flow of majority carriers across the junction
  - As the majority carriers cross the junction, the become minority carriers and then recombine the majority carriers on the other side
  - Since the flow across the junction is due to majority carriers the current flow is large.

PN Junctions Forward Biased

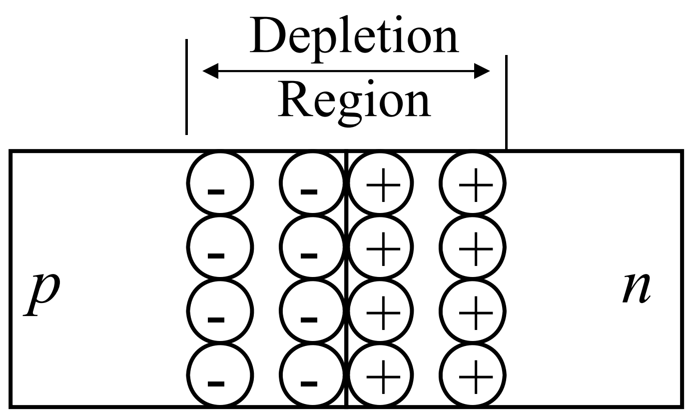


Forward-biased PN Junction

These are majority carriers and therefore the FB current can be large.



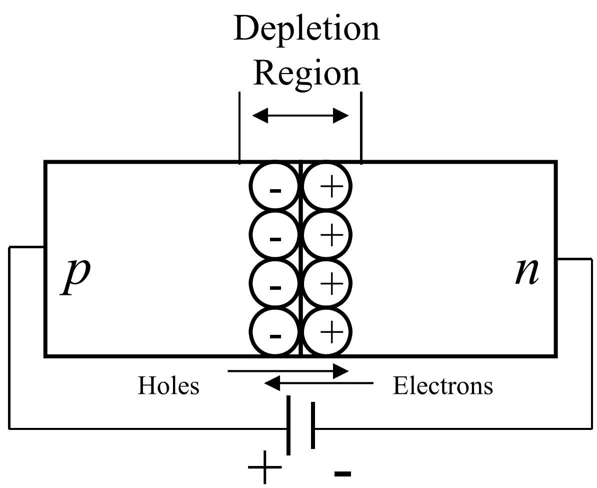
PN Junctions Junction Capacitance



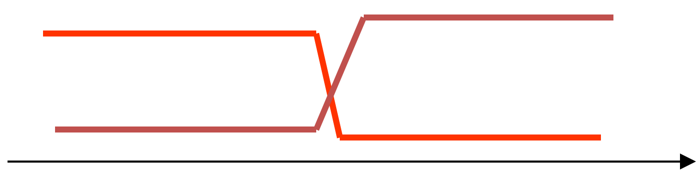
Unbiased PN Junction

- The ions at the junction look like charges on a two plates of a capacitor and, thereby, create a capacitance effect
- We call this the junction capacitance

PN Junctions Diffusion Capacitance



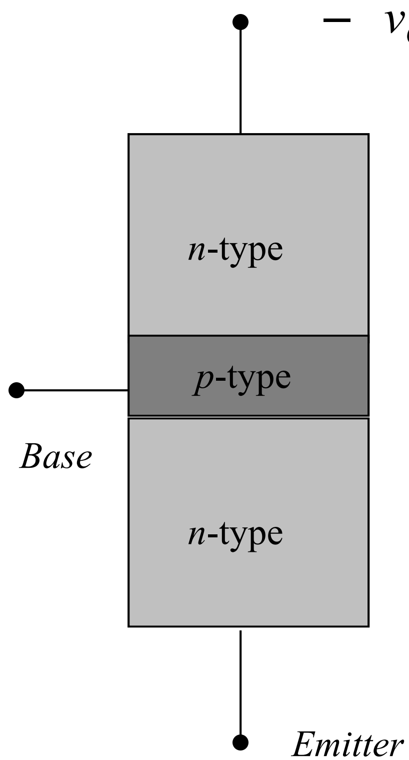
Forward-biased PN Junction

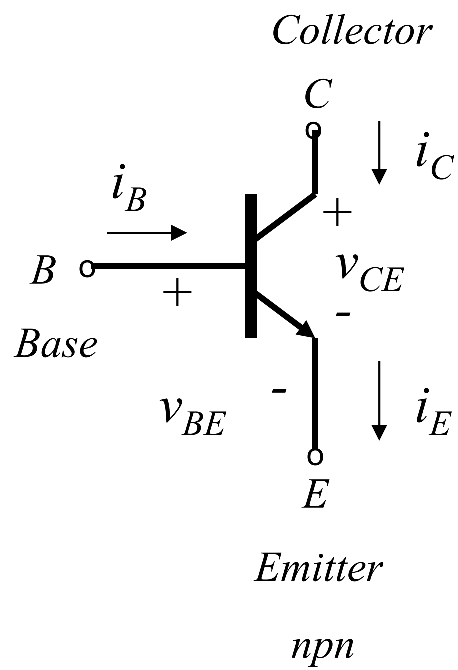


- The charges which cross the junction holes on the *n*-side and electrons on the *p*-side also looks like charges on a two plates of a capacitor and, thereby, adds to the capacitance effect
- We call this the diffusion capacitance

npn Bipolar Junction Transistors

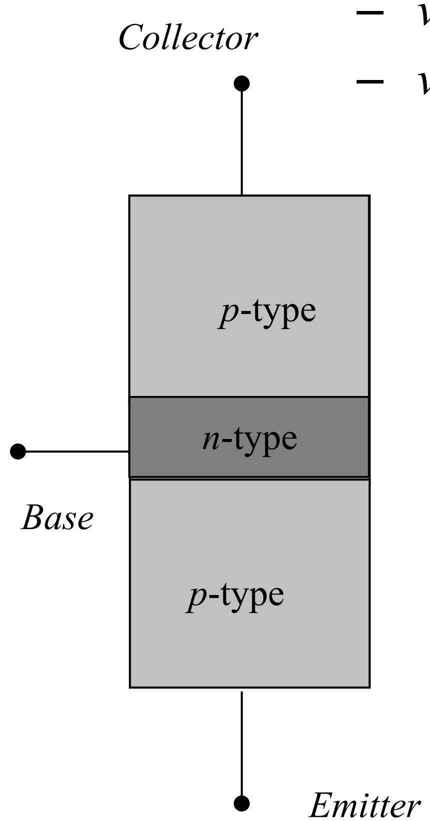
- Two junctions
  - Collector-Base and Emitter-Base
- Biasing
  - v_{BE} Forward Biased
  - v_{CB} Reverse Biased

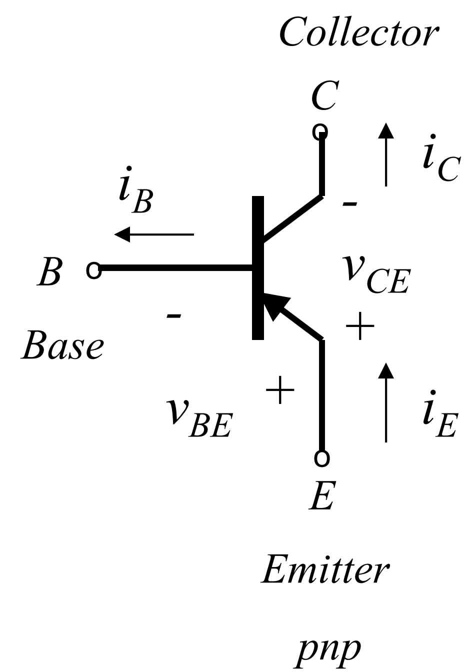




pnp Bipolar Junction Transistors

- Two junctions
  - Collector-Base and Emitter-Base
- Biasing
  - v_{BE} Forward Biased
  - v_{CB} Reverse Biased

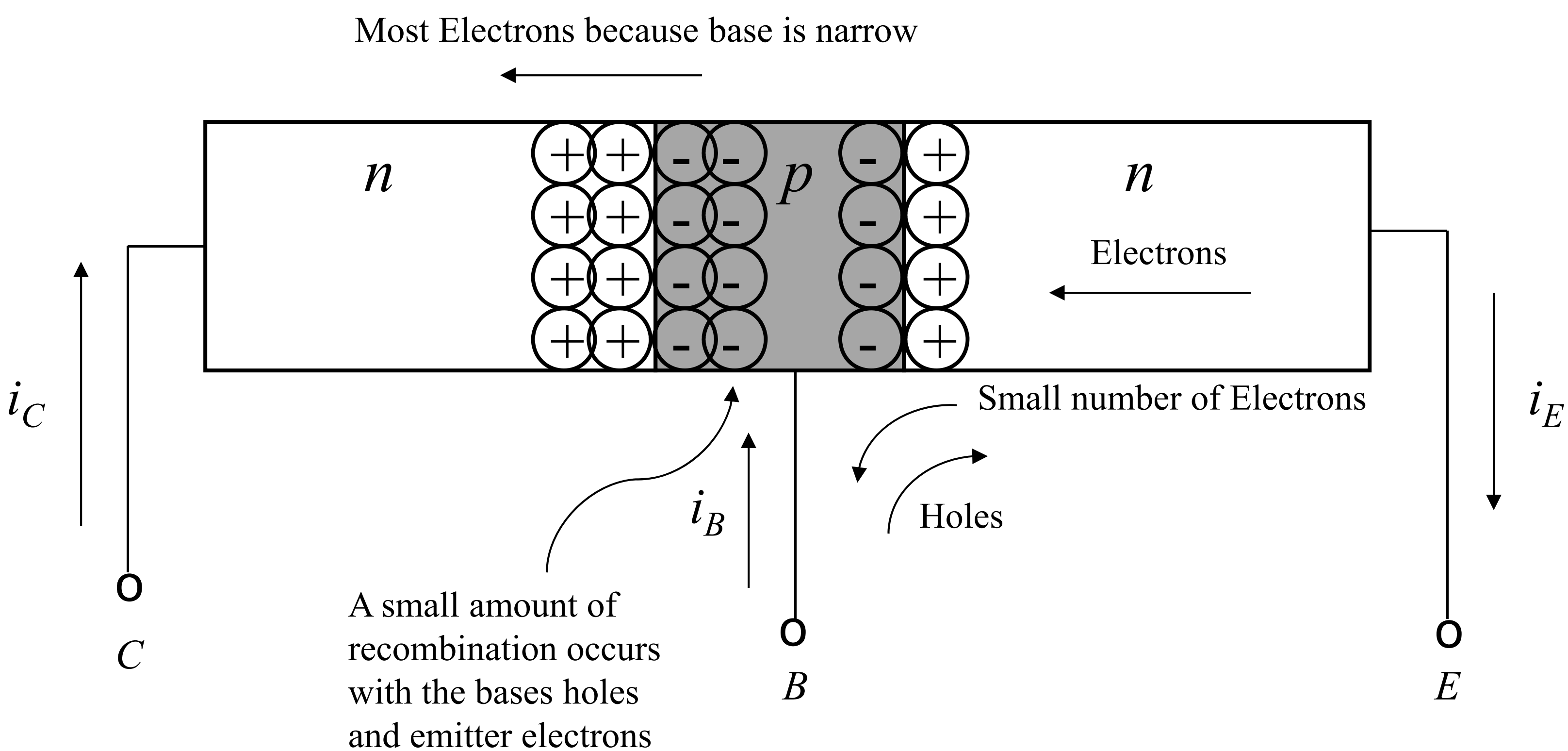




npn (pnp) BJT Semiconductor

- Physical characteristics:
  - Base is narrower than the emitter
  - Emitter is doped more than the base
    - Free electron (hole) concentration in the emitter greater than the hole (electron) concentration in base
- Base-emitter junction is forward biased
  - There is a flow of electrons (holes) from the emitter to base and holes (electrons) from the base to emitter; however since the concentration of emitter electrons (holes) are greater than the base holes (electrons), this current is primarily made of electrons (holes)
  - These emitter electrons (holes) become minority carriers in the base; however, since the base is narrow very little electron-hole recombination occurs in the base and these electrons (holes) are drawn towards the collector-base junction
- Collector-base junction is reverse biased
  - When these emitter electrons (holes) reach the collector-base junction, they are pulled across the junction into the collector by the electric field due to the depletion region ions.
  - The ratio of the electrons (holes) reaching the collector to the electrons (holes) provided by the emitter is know as α.

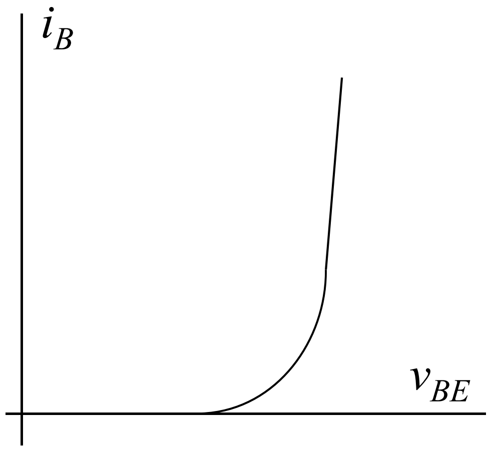
npn BJT

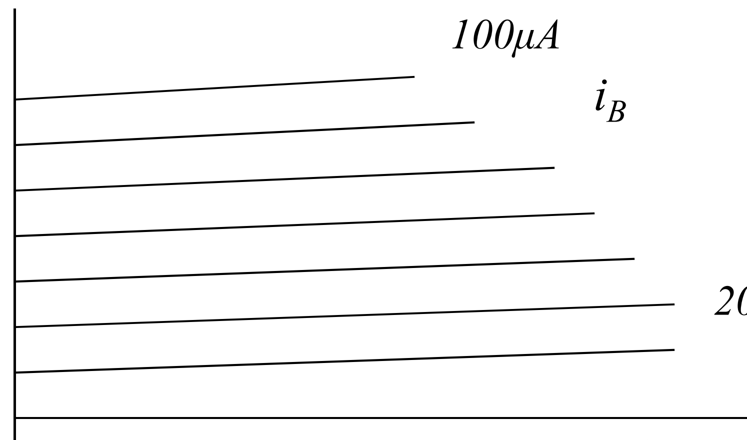

Most Electrons because base is narrow
n
p
n
Electrons
i_C
Small number of Electrons
i_E
i_B
Holes
C
A small amount of
recombination occurs
with the bases holes
and emitter electrons
B
E

BJT DC Analysis

- Using KVL for the input and output circuits and the transistor characteristics, the following steps apply:
  1. Draw the load lines on the transistor characteristics
  2. For the input characteristics determine the Q point for the input circuit from the intersection of the load line and the characteristic curve (Note that some transistor do not need an input characteristic curve.)
  3. From the output characteristics, find the intersection of the load line and characteristic curve determined from the Q point found in step 2, determine the Q point for the output circuit.

VI Characteristics of the BJT
npn
Common Emitter Configuration





Base-emitter junction looks like a forward biased diode

Collector-emitter is a family of curves which are a function of base current

BJT Equations

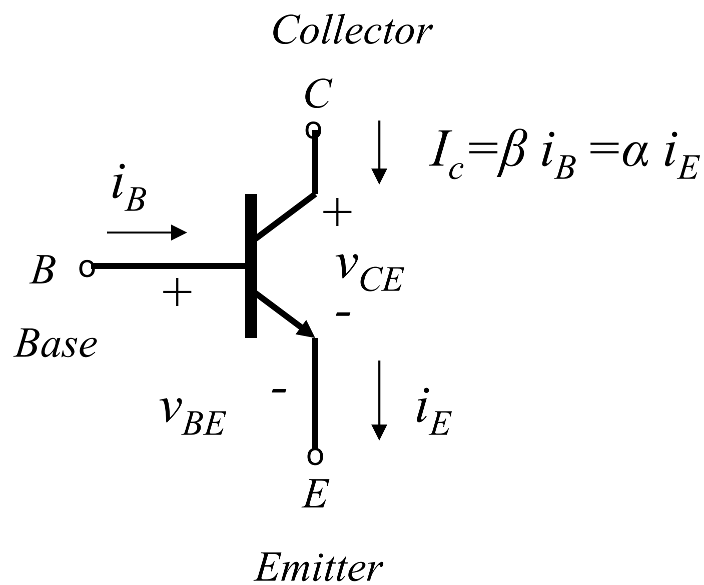
$$i_E = i_C + i_B$$

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

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

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

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

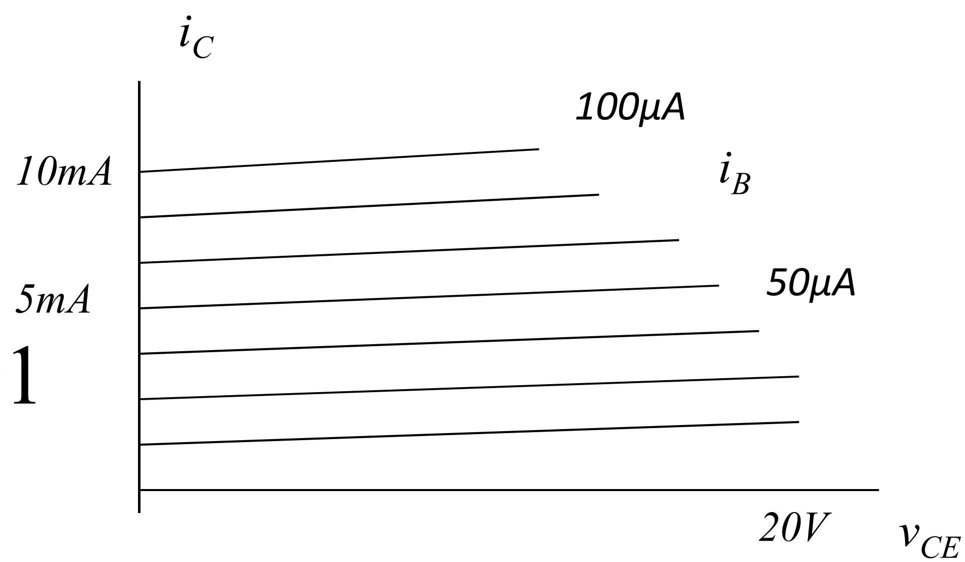


Since α is less than unity then β will be greater than unity and there is current gain from base to collector.

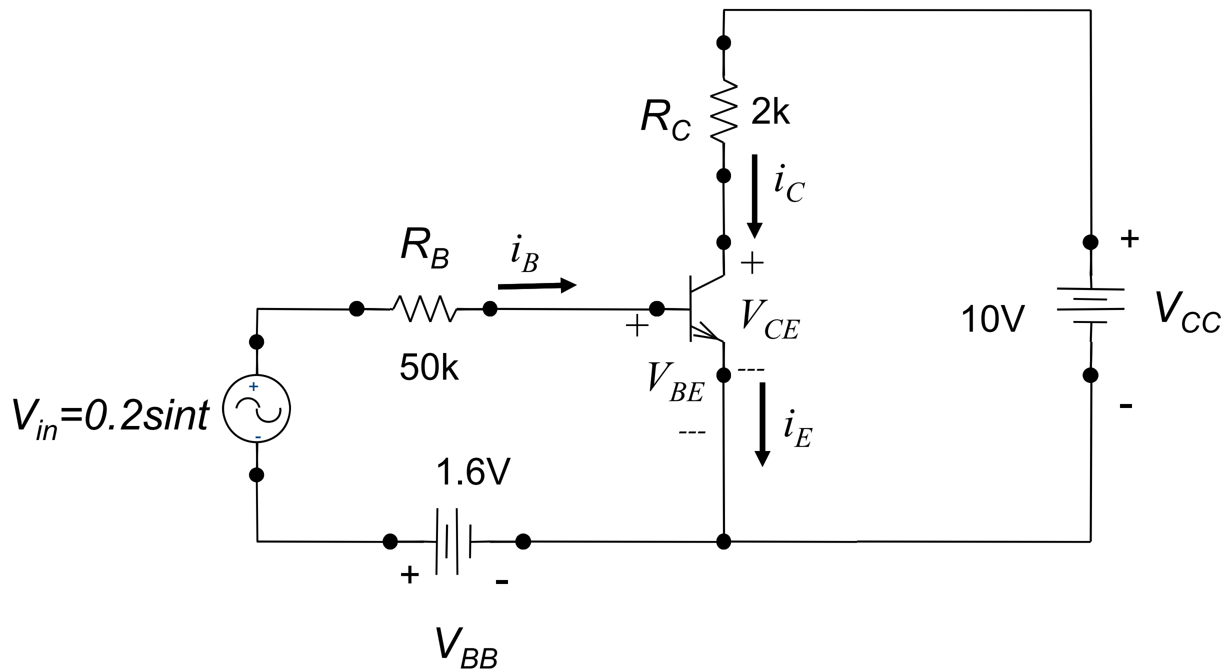
Example

- Calculate the values of β and α from the transistor shown in the previous graphs.

$$\beta = i_c / i_b$$
$$= 5m/50\mu = 100$$
$$\alpha = \beta /(\beta+1) = 100/101$$
$$=.99$$



BJT Analysis



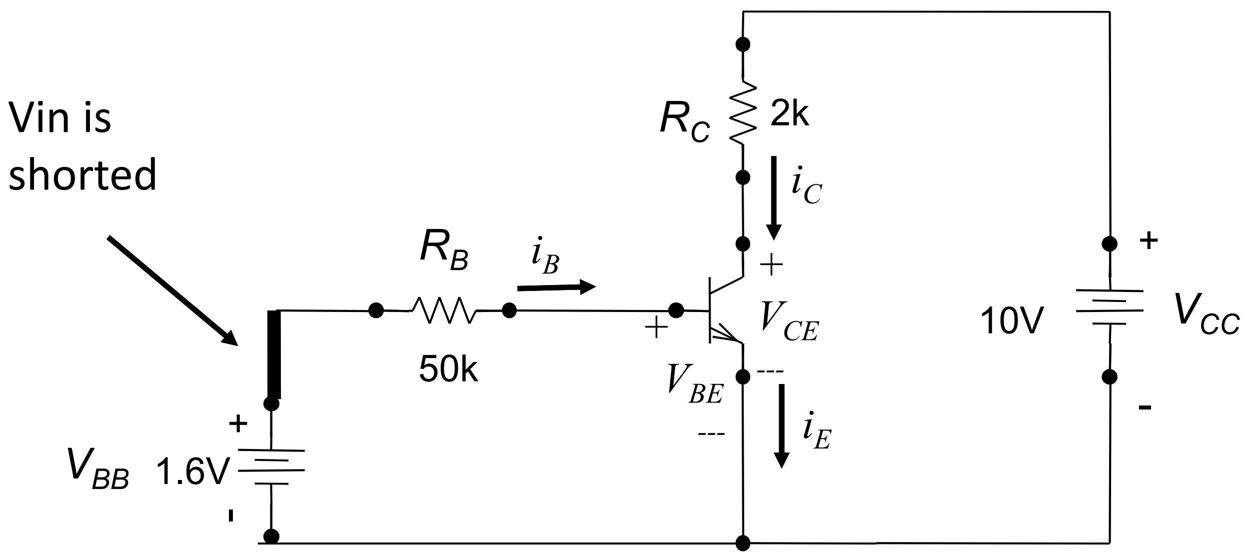
Here is a common emitter BJT amplifier:

What are the steps?

BJT Analysis

1. First step is to perform DC Analysis
   a. Analyze the base circuit
      i. Replace Base to Emitter junction as forward biased diode
      ii. Perform graphical analysis on the VI characteristics of this “FB diode” to find the operating point for the base current, I_{BQ}, and the base to emitter voltage, V_{BEQ}.
      iii. Using the VI characteristics of the Base to Emitter diode and Kirchhoff’s voltage law around the base circuit (called the load line of the base circuit), find the intersection of KVL and the VI characteristics.
      iv. This is the operating point (Q-point, bias point…) for the base circuit I_{BQ} and V_{BEQ}.
   b. Analyze the collector circuit
      i. Using the base current found in step a.iv., find the corresponding collector curve on the VI charateristics of the collector circuit.
      ii. Using Kirchhoff’s voltage law around the collector circuit (called the load line of the collector circuit)and the corresponding collector curve, find the intersection of KVL and the VI characteristics.
      iii. Drop perpendicular lines to the collector current axis and collector to emitter voltage axis to find the collector current, I_{CQ}, and the collector to emitter voltage, V_{CEQ}.
      iv. This is the operating point (Q-point, bias point…) for the collect circuit I_{CQ} and V_{CEQ}.

BJT DC Analysis
Base-Emitter Circuit Q point



First let's set $V_{in}(t)$ =0 to get the Q-point for the BJT.

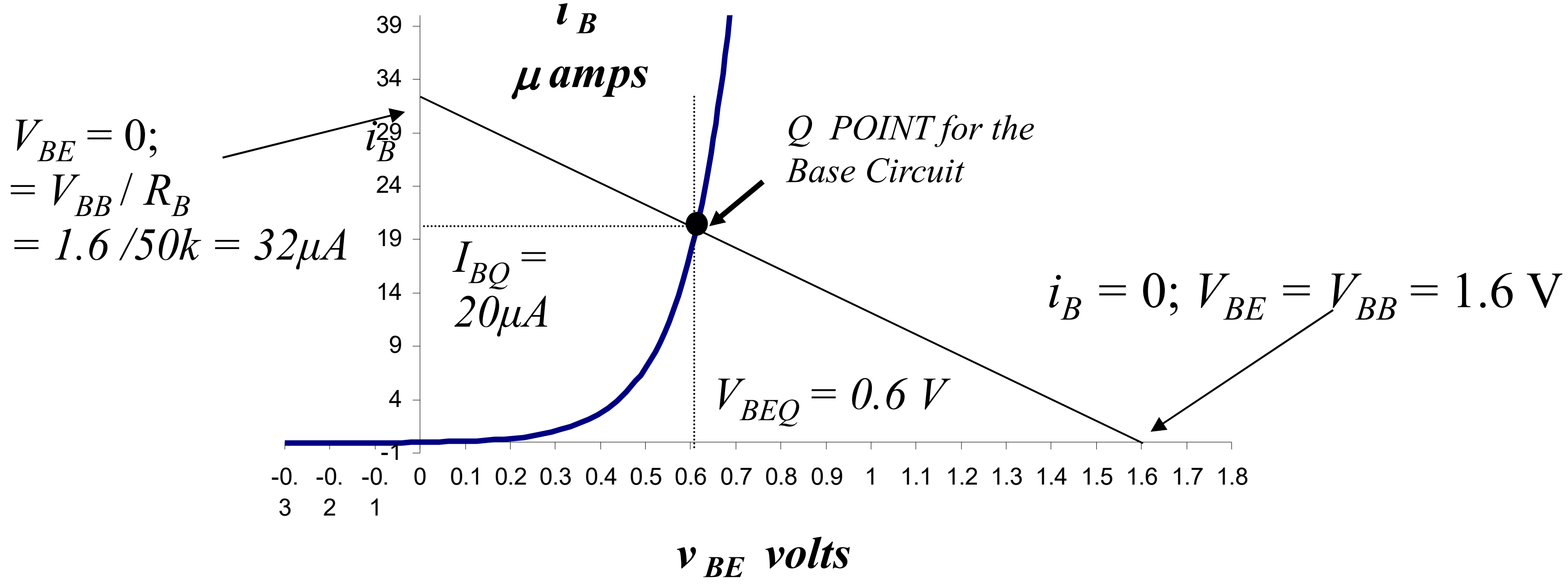
We start with the base circuit. Then KVL for the Base Circuit is

$$V_{BB} = i_B R_B + V_{BE}$$

And the intercepts occur at $i_B = 0$; $V_{BE} = V_{BB} = 1.6$ V

and at $V_{BE} = 0$; $i_B = V_{BB} / R_B = 1.6 / 50k = 32 \mu A$

BJT DC Analysis
Base-Emitter Circuit Q point

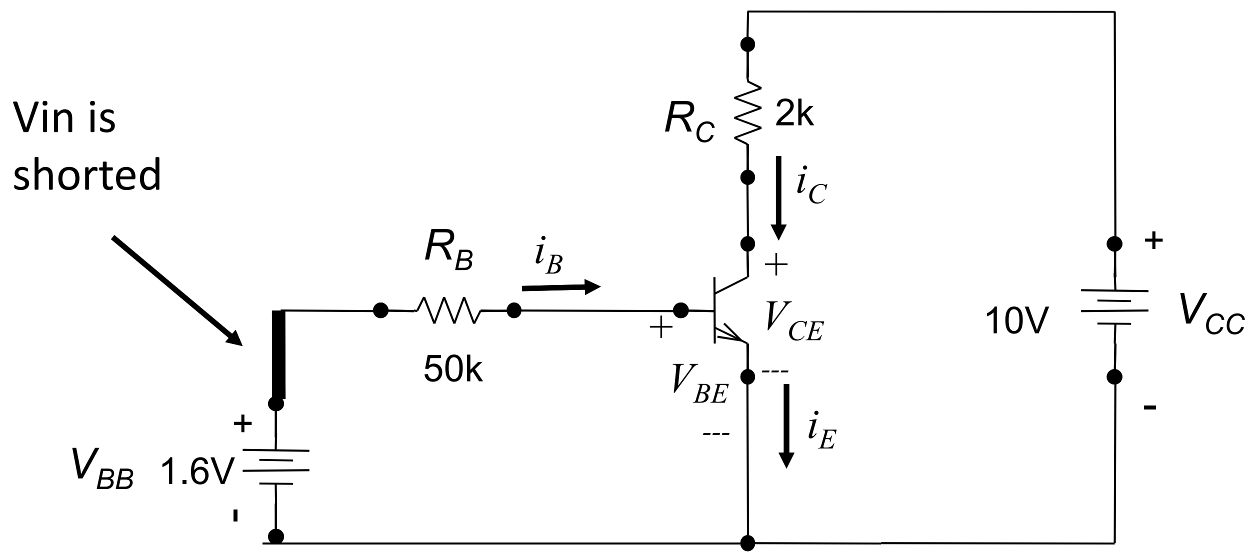


Drawing KVL as a straight line connecting the intercepts. We call this line the Load Line.

Therefore, the Load Line intersects the Base-emitter characteristics at $V_{BEQ} = 0.6\ V$ and $I_{BQ} = 20\mu A$.

This point is called the Operating Point for the Base or the Quiescent Point or Q Point, for short.

BJT DC Analysis
Collector-Emitter Circuit Q point

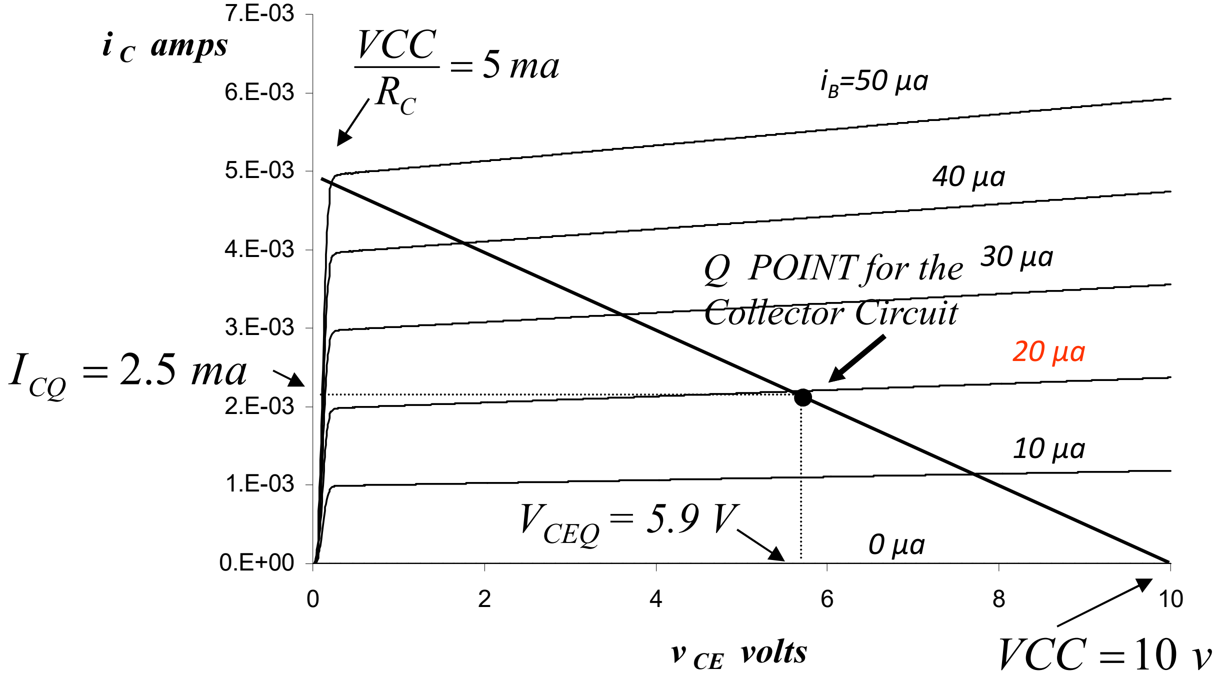


Now that we have the Q-point for the base circuit, let's proceed to the collector circuit. KVL for the Collector Circuit is:

$$V_{CC} = i_C R_C + V_{CE}$$

The intercepts occur at $i_C = 0$; $V_{CE} = V_{CC} = 10$ V; and at $V_{CE} = 0$; $i_C = V_{CC} / R_C = 10/2k = 5mA$

BJT DC Analysis
Collector-Emitter Circuit Q point



We draw KVL for the Collector Circuit connecting the intercepts. This is called the Load Line for the Collector Circuit.

Now we next find the curve on the Collector Characteristics that corresponds to the Q Point Base current, $I_{BQ} = 20\mu A$.

The Load Line for intersects the Collector-emitter characteristic, i_B=20mA at $V_{CEQ} = 5.9\ V$ and $I_{CQ} = 2.5mA$

This is called the Q Point for the Collector Circuit.

Note that $\beta = 2.5m/20\mu = 125!$

BJT Analysis Continued

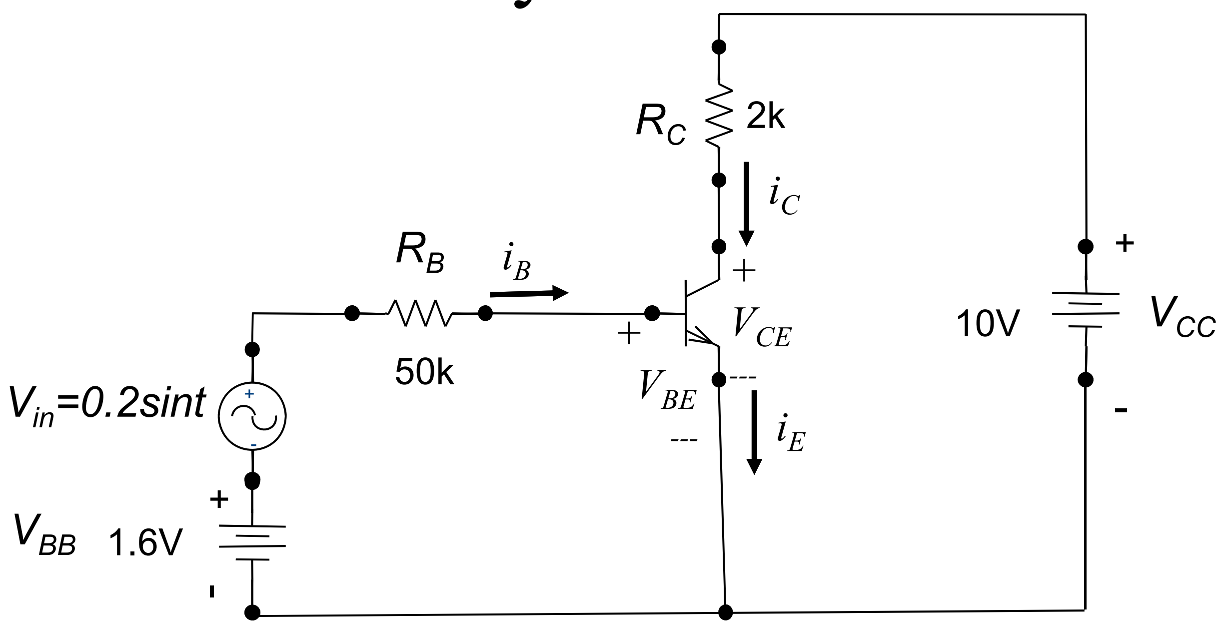
2. Next step is to perform AC Analysis
   a. Analyze the base circuit
      i. Using the VI characteristics of the base equivalent FB diode used in step 1, find the load line for the maximum and minimum cases of the DC+AC$_{max}$ and DC+AC$_{min}$ voltages.
      ii. Find the intersect of the VI characteristics and these two load lines to yield I_{BMAX} and V_{BEMAX} and I_{BMIN} and V_{BEMIN}.
   b. Analyze the collector circuit
      i. Using I_{BMAX} and I_{BMIN} find the corresponding collector curves on the VI characteristics of the collector circuit.
      ii. Using Kirchhoff's voltage law around the collector circuit and the corresponding collector curves, find the intersection of KVL and the VI characteristics.
      iii. Drop perpendicular lines to the collector current axis and collector to emitter voltage axis to find the collector currents, I_{CMAX}, I_{CMIN} and the collector to emitter voltages, V_{CEMAX} and V_{CEMAX}.
3. Calculate the gains:
   a. Voltage gain from the Base to the Collector
   b. Voltage gain from the Source to the Collector
   c. Current gain

$$A_v = \frac{V_{CEMIN} - V_{CEMAX}}{V_{BEMAX} - V_{BEMIN}}$$

$$A_{vs} = \frac{V_{CEMIN} - V_{CEMAX}}{V_{SP-P}}$$

$$A_i = \frac{I_{CEMAX} - I_{CEMIN}}{I_{BEMAX} - I_{BEMIN}}$$

BJT AC Analysis Base-Emitter Circuit



From this circuit, the total input voltage connected to this circuit is the sum of the DC voltage, V_{BB},

and the AC voltage , V_{IN}:

$$V_{BB} + V_{IN} = I_B R_B + V_{BE}$$

Because Vin is a sinusoidal signal, the maximum input voltage to the Base Circuit is 1.6 + 0.2= 1.8 volts

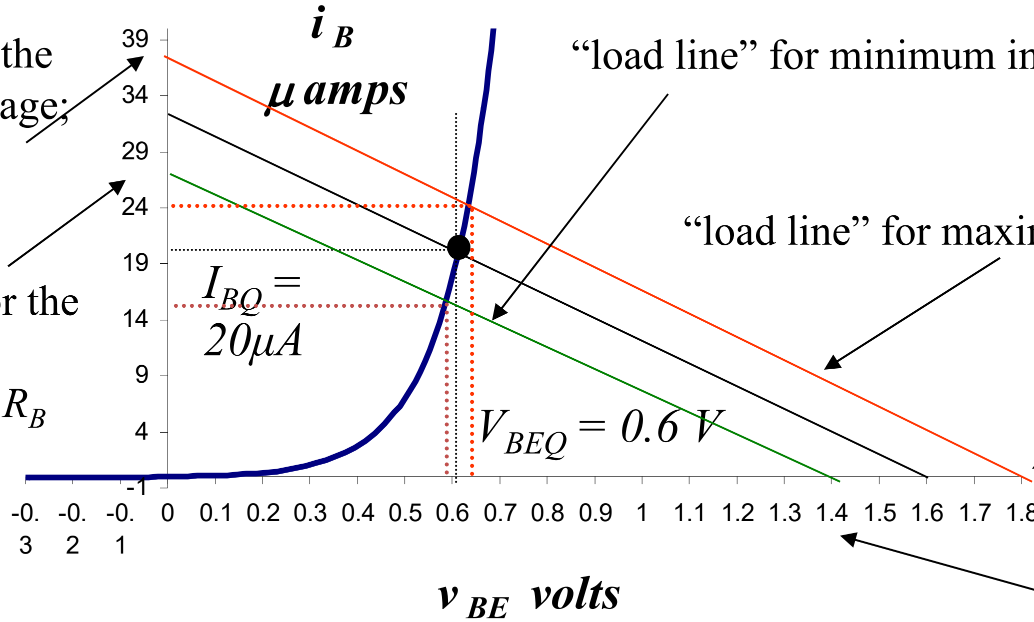
and the minimum input voltage to the Base Circuit is 1.6 – 0.2 = 1.4 volts.

We can now draw two more Load Lines on the Base Circuit Characteristics corresponding to the Maximum Voltage at the Base and the Minimum Voltage to the Base.

BJT AC Analysis Base-Emitter Circuit

V_{BE} = 0 Intercept for the Maximum Input Voltage; $i_B = V_{inMax} / R_B$ $=36\mu A$

V_{BE} = 0 Intercept for the Minimum Input Voltage; $i_B = V_{inMin} / R_B$ $=28\mu A$



"load line" for minimum input voltage

"load line" for maximum input voltage

I_B=0 Intercept for the Maximum Input Voltage is 1.8v

I_B=0 Intercept for the Minimum Input Voltage is 1.4v

From this graph, we find:

At Maximum Input Voltage: V_{BEMAX} = 0.63 V, i_{BMAX} = 24μa

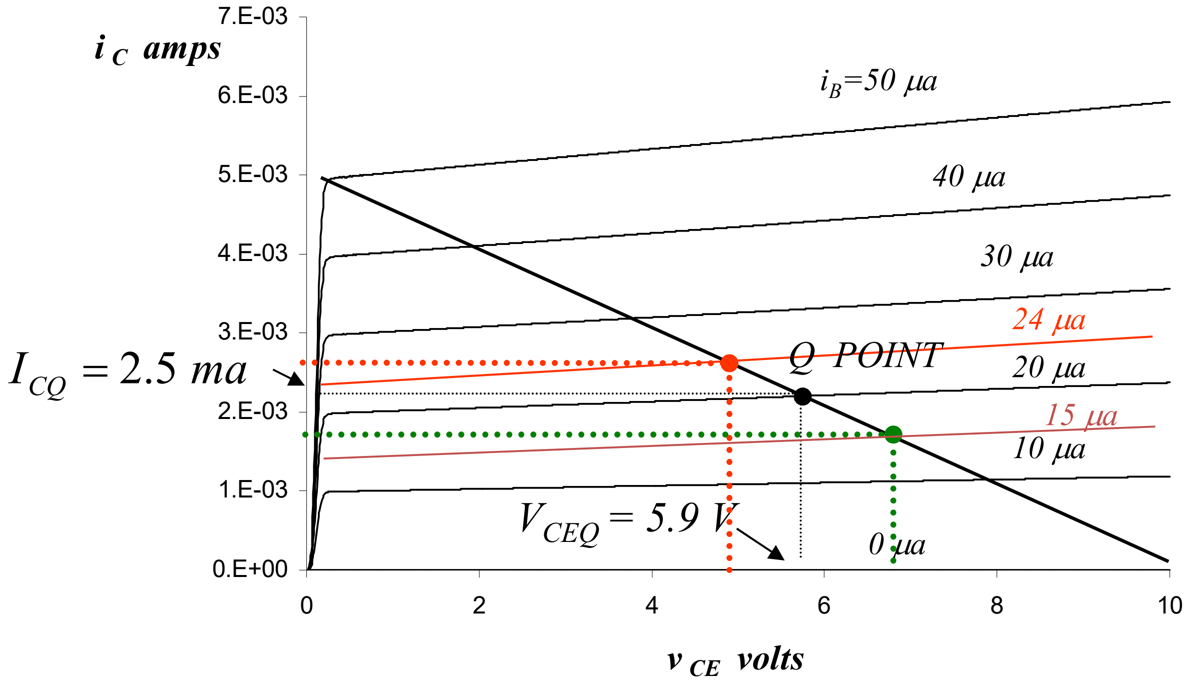
At Minimum Input Voltage: V_{BEMIN} = 0.59 V, i_{BMIN} = 15μa

Recall: At Q-point: V_{BEQ} = 0.6 V, i_{BQ} = 20μa

Note the asymmetry around the Q-point of the Max and Min Values for the base current and voltage which is due to the non-linearity of the base-emitter characteristics

$\Delta i_{Bmax}=24\text{-}20=4\mu a;\ \Delta i_{Bmin}=20\text{-}15=5\mu a$

BJT Characteristics-Collector Circuit



Using these maximum and minimum values for the base current intersections on the collect circuit load line, we find the curve on the Collector Characteristics that corresponds to the Q Point Base current, $I_{BMAX} = 24\mu A$ and $I_{BMIN}=15\mu A$.

At Maximum Input Voltage: $V_{CEMAX} = 5$ V, $i_{CMAX} = 2.7$ma

At Minimum Input Voltage: $V_{CEMIN} = 7$ V, $i_{CMIN} = 1.9$ma

Recall: At Q-point: $V_{CEQ} = 5.9$ V, $i_{CQ} = 2.5$ma

Note that in addition to the asymmetry around the Q-point there is an inversion between the input voltage and the collector to emitter voltage

BJT AC Analysis
Amplifier Gains

- From the values calculated from the base and collector circuits we can calculate the amplifier gains:
  - $\beta = 125$
  - Current gain $= \Delta i_c / \Delta i_b = (i_{Cmax} - i_{Cmin})/(i_{Bmax}\text{-}i_{Bmin}) =$
  - $(2.7 - 1.9)\text{m} / (24 - 15)\,\mu = .8/9*10^3 = 88.9$
  - Voltage gain $= \Delta V_{CE} / \Delta V_{BE} = (V_{CEmax} - V_{CEmin})/(V_{BEmax}\text{-}V_{BEmin})$
    $= (5 - 7) / (.63 - .59) = -2/0.04 = -50$
  - Voltage gain $= V_o / V_s = \Delta V_{CE} / \Delta V_S = (5 - 7) / .4 = -2 / .4 = -5$

BJT DC Analysis Summary

- Calculating the Q-point for BJT is the first step in analyzing the circuit
- To summarize:
  - We ignored the AC (variable) source
    - Short circuit the voltage sources
    - Open Circuit the current sources
  - We applied KVL to the base-emitter circuit and using load line analysis on the base-emitter characteristics, we obtained the base current Q-point
  - We then applied KVL to the collector-emitter circuit and using load line analysis on the collector-emitter characteristics, we obtained the collector current and voltage Q-point
- This process is also called DC Analysis
- We now proceed to perform AC Analysis

Homework

- Probs. 4.8, 4.10, 4.14, 4.15, 4.19, 4.20, 4.21, 4.22,