ROCHESTER INSTITUTE OF TECHNOLOGY
MICROELECTRONIC ENGINEERING

Bipolar Junction Transistor - Basics

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DEFINITIONS

Bipolar Junction Transistor - (BJT) Both holes and electrons participate in the conduction of current, hence the name bipolar.

Minority carrier - In a p-type semiconductor electrons are the minority carrier type, in an n-type semiconductor holes are the minority carrier type.

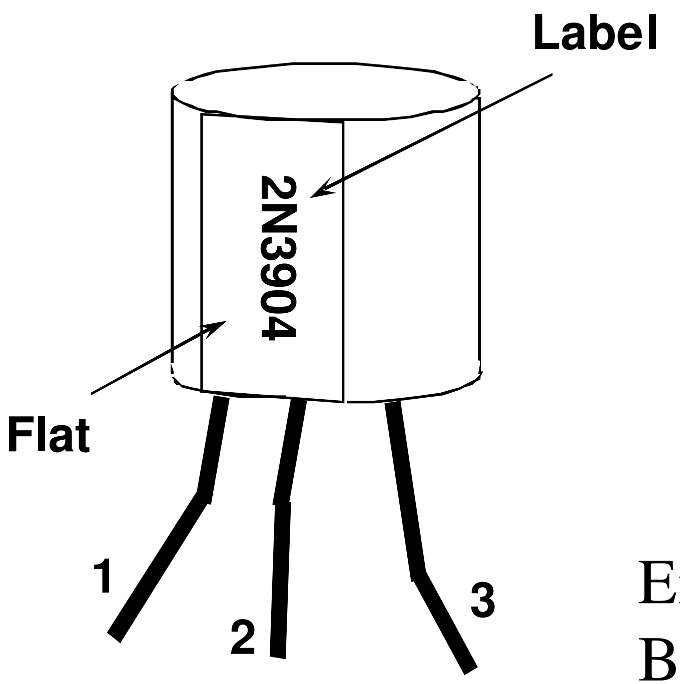
Emitter - Emits minority carriers into the base region of a BJT. For example, in an NPN BJT the n-type emitter, emits electrons into the p-type base. The emitter usually has the highest doping levels of the three regions of a BJT.

Base - Thin region which is used to control the flow of minority carriers from the emitter to the collector

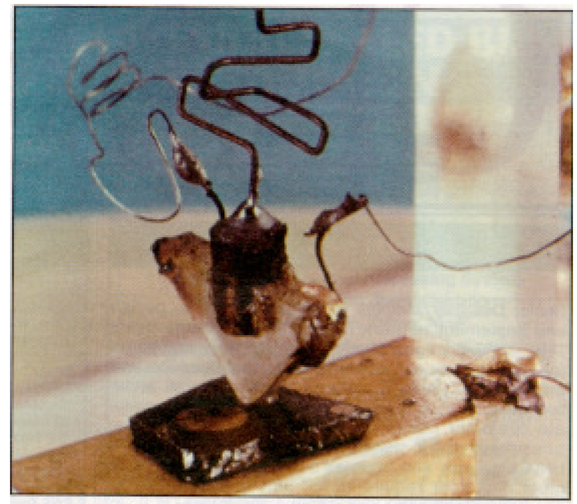
Collector -Collects the minority carriers that make it through the base from the emitter. The collector usually has the lightest doping concentrations of the three regions.

DC Beta (β_{dc}) - The ratio of the collector current to the base current. $\beta_{dc} = I_C / I_B$
AC Beta (β_{ac}) - The ratio of the change in the collector current to the change in the base current. $\beta_{ac} = \Delta I_C / \Delta I_B$

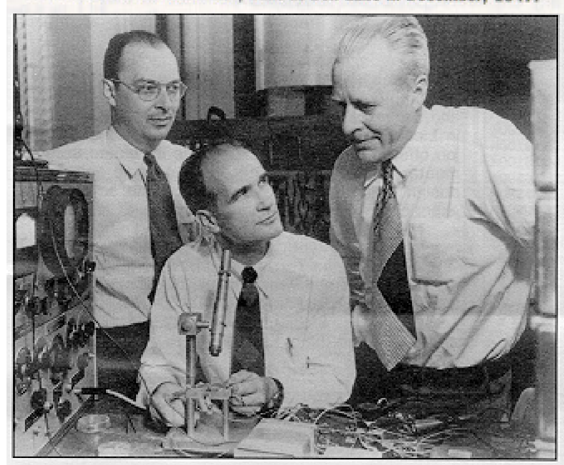
BJT - BIPOLAR JUNCTION TRANSISTOR



Emitter
Base
Collector

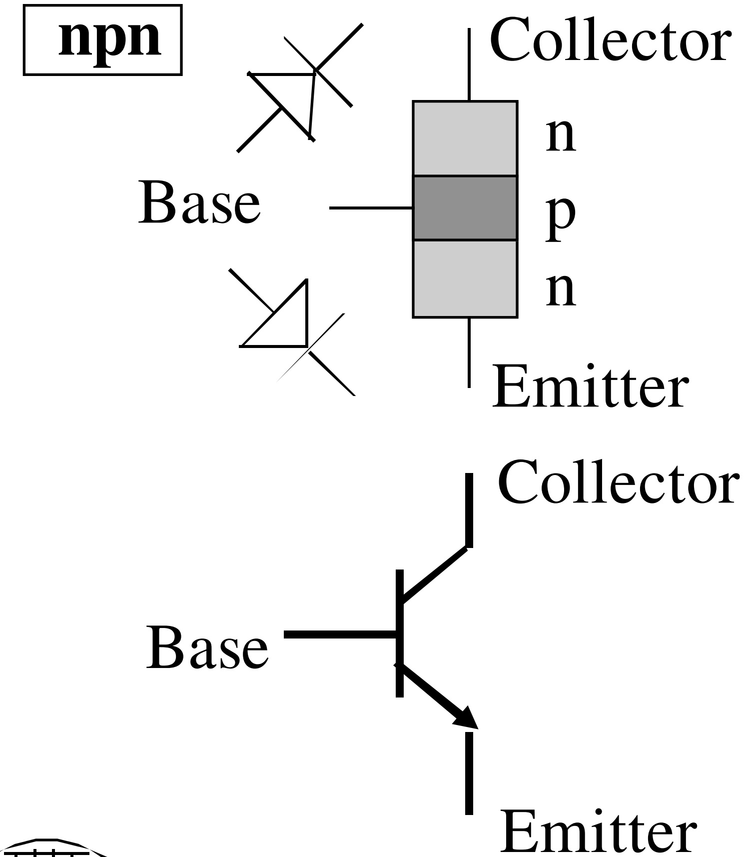


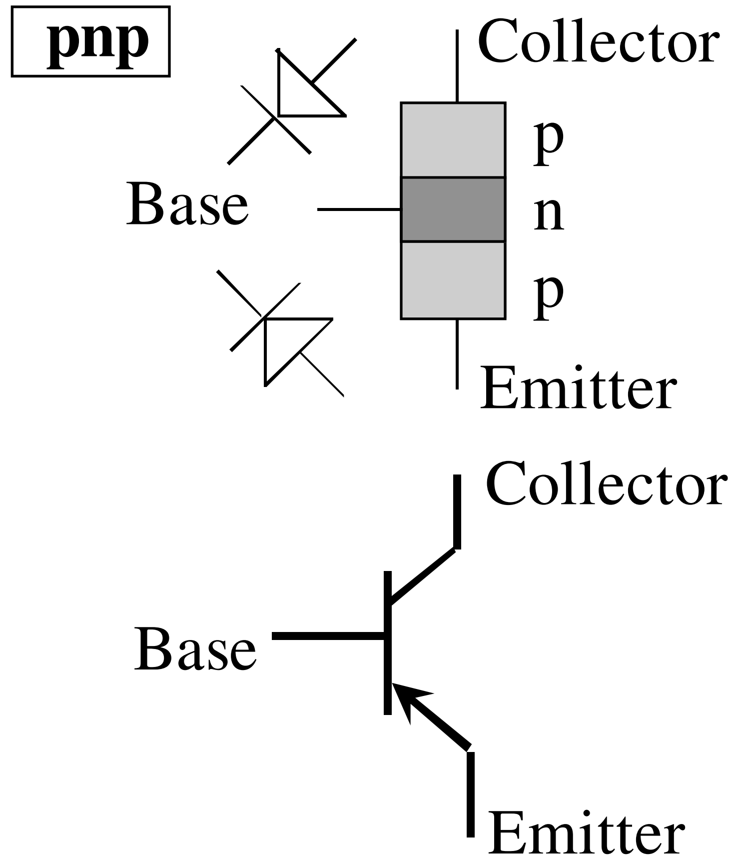
The world's first transistor, built at Bell Labs in December, 1947.



Transistor inventors (from left), Dr. Walter Brattain, Dr. William Shockley, and Dr. John Bardeen.

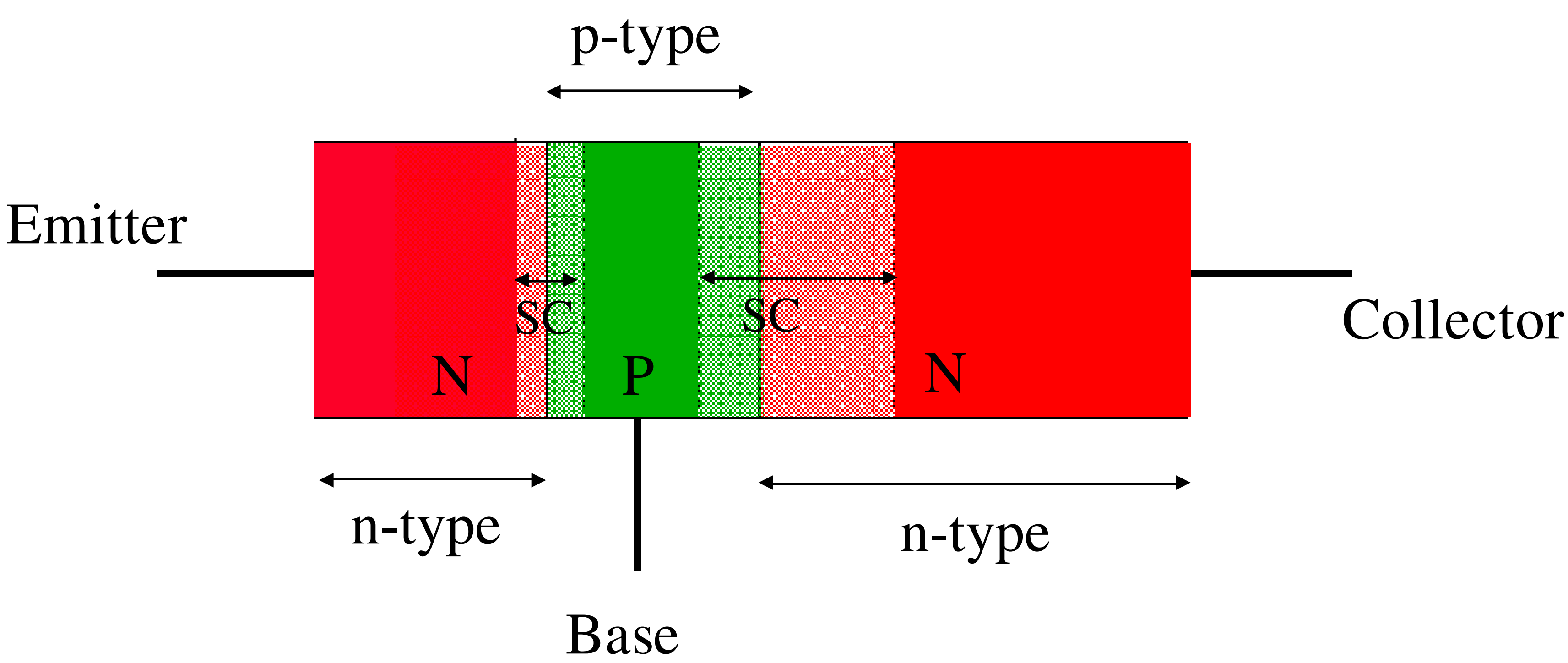
SCHEMATIC SYMBOLS



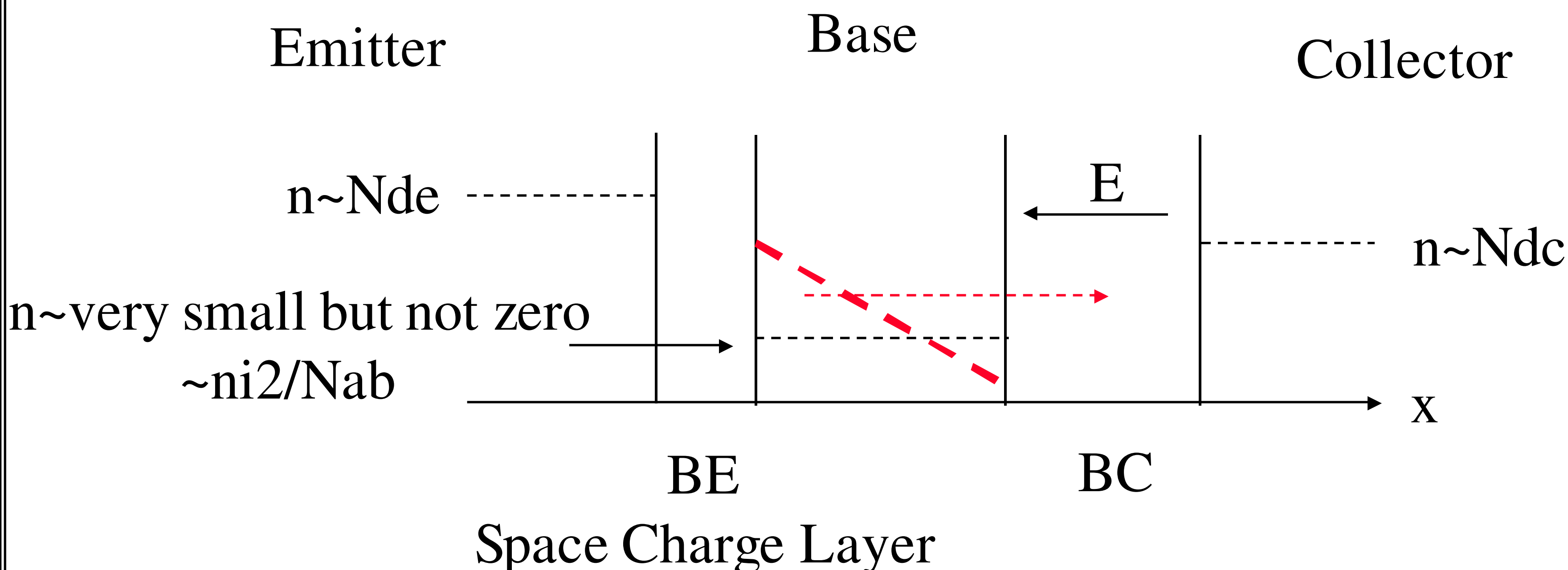


The arrow on the emitter is in the direction that current will flow in the Base Emitter pn junction

IDEALIZED STRUCTURE



ELECTRON CONCENTRATIONS IN AN NPN BJT

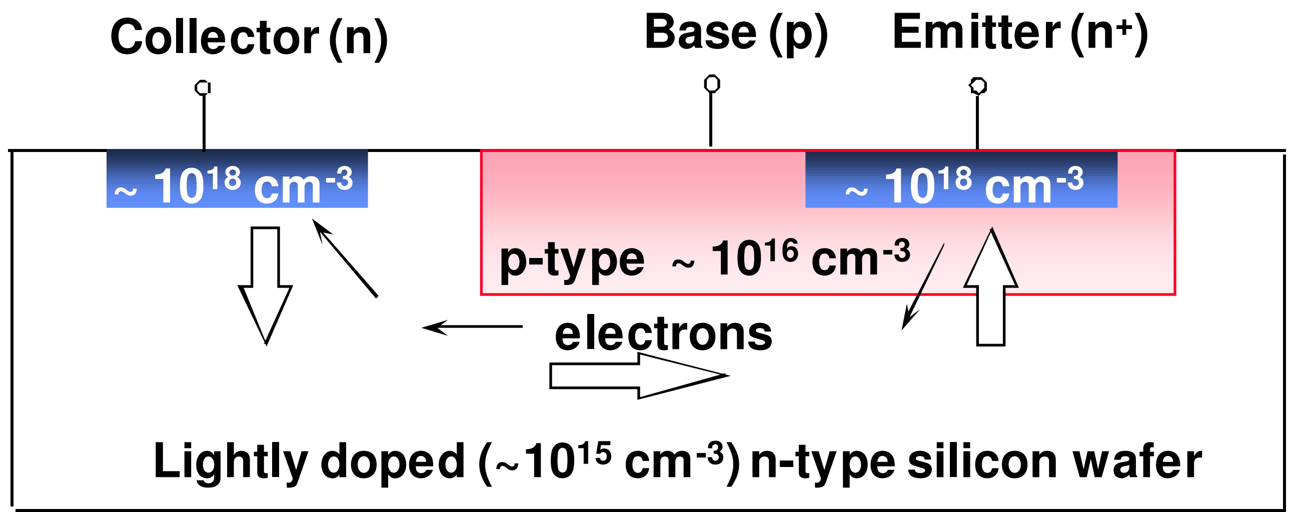


With the B-E junction forward biased, and B-C junction reverse biased. There is a concentration gradient in the base that forces electrons to flow toward the collector.

COMMENTS

1. The concentration of electrons in n-type silicon is ~ doping concentration in that region.
2. In p-type silicon the number of electrons is almost zero
3. A forward biased pn junction means more carriers of both types can cross the potential barrier. So a forward biased base-emitter junction (in an npn BJT) means more electrons on the base side than in equilibrium (no bias).
4. A reverse biased pn junction means less carriers of both types can cross the potential barrier. So a reverse biased base-collector junction (in an npn BJT) means less electrons on the base side than in equilibrium (no bias). Even closer to zero electrons in p-type base at the edge of the B-C space charge layer.
5. The base is so narrow that few electrons are lost as they diffuse across the base width. Diffusion is driven by a concentration gradient. So electrons move towards the collector and current flows in the opposite direction.

INTEGRATED BJT STRUCTURE



Since the emitter is more heavily doped compared to the base than the collector, the emitter-base junction has a lower breakdown voltage than the base-collector junction.

n^+ means heavily doped n-type
n^- means lightly doped n-type
p^+ means heavily doped p-type
p^- means lightly doped p-type

BJT TERMINAL CURRENTS

From device physics

$IE = I_{SE}\, e^{V_{BE}/V_T}$

where $I_{SE} = AqDni2/N_AW$ and $V_T = KT/q$

$IC = \alpha\, IE$ where α represents the fraction of carriers from the emitter that make it to the collector

$IC = \beta\, IB$ where β represents the ratio of collector current to base current

We can show that $\beta = \alpha/(1-\alpha)$ or $\alpha = \beta\, /\, (\beta+1)$

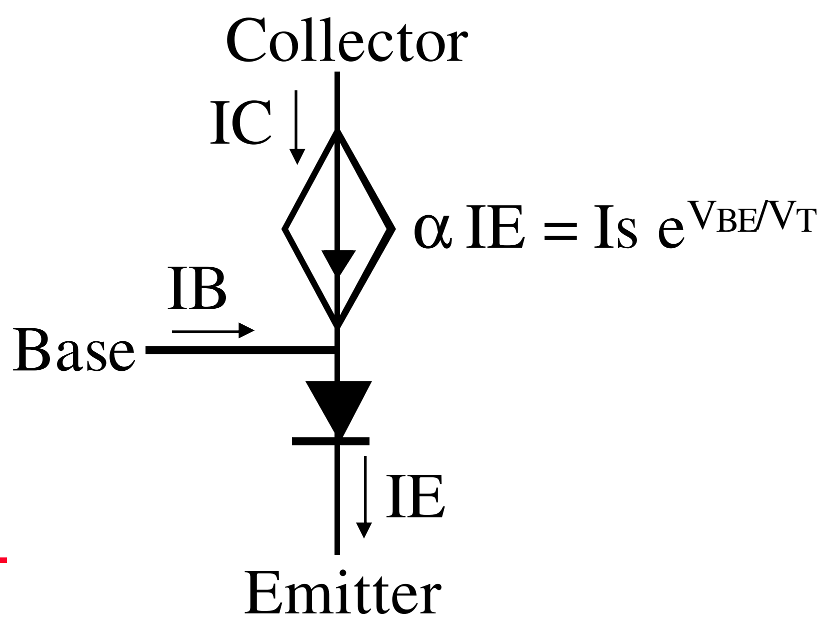
With the B-E junction forward biased, and B-C junction reverse biased.

LARGE SIGNAL MODEL IN FORWARD ACTIVE MODE

Modes

	Base/Emitter	Base/Collector
Cutoff	Reverse	Reverse
Active	Forward	Reverse
Inverse	Reverse	Forward
Saturation	Forward	Forward

With the B-E junction forward biased, and B-C junction reverse biased.



EBERS-MOLL MODEL OF NPN BJT

This type of model works in all four regions of operation

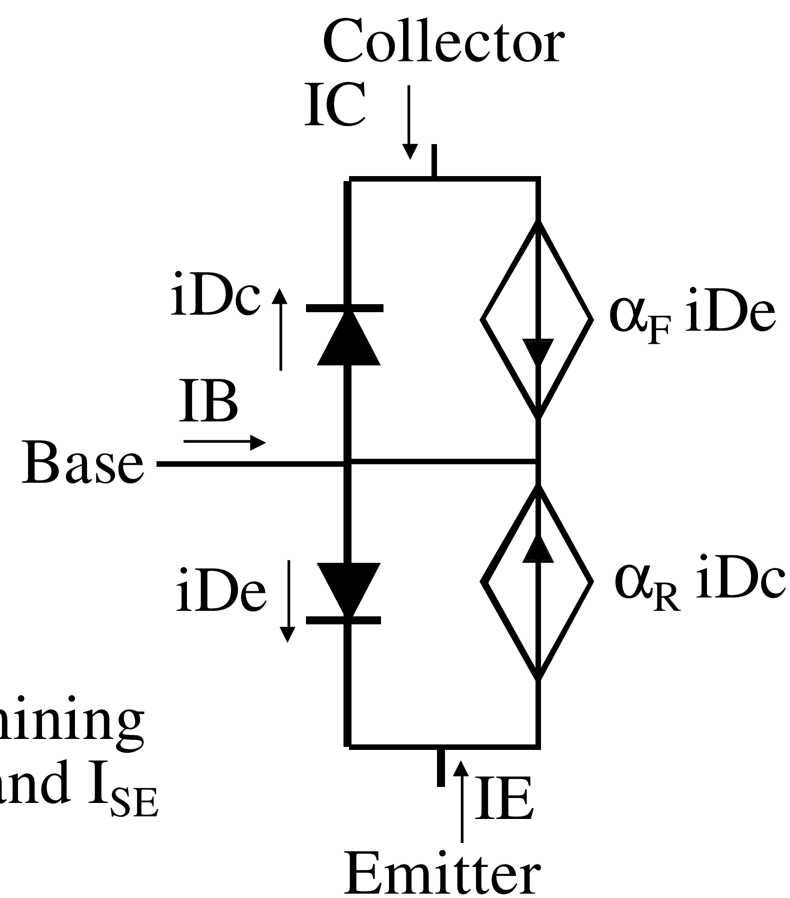
$IC = \alpha_F\, iDe - iDc$

$IE = -iDe + \alpha_R\, iDc$

The diode currents are:

$iDc = I_{SC}\,(e^{Vbc/VT} - 1)$

$iDe = I_{SE}\,(e^{Vbe/VT} - 1)$



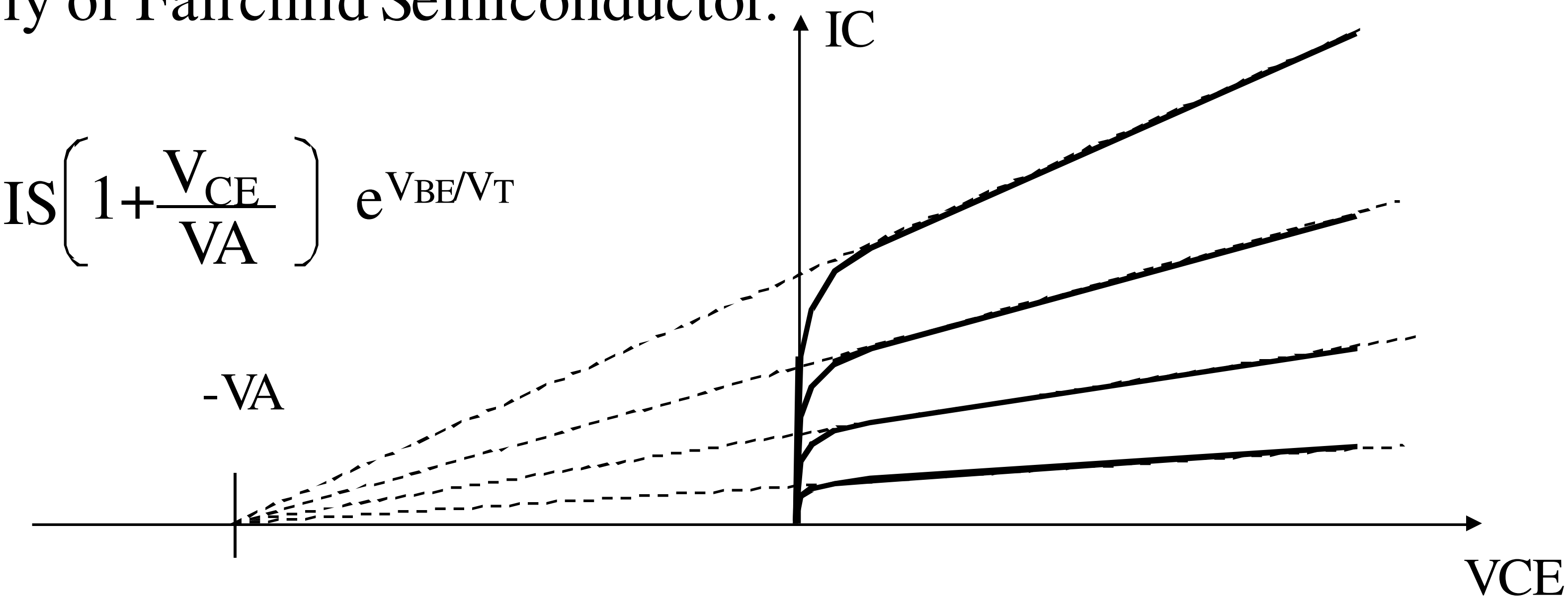
Transistors are modeled by determining appropriate values of: α_F, α_R, I_{SC} and I_{SE}

Note: β is often given instead of α but $\alpha = \beta/(1+\beta)$

EARLY VOLTAGE

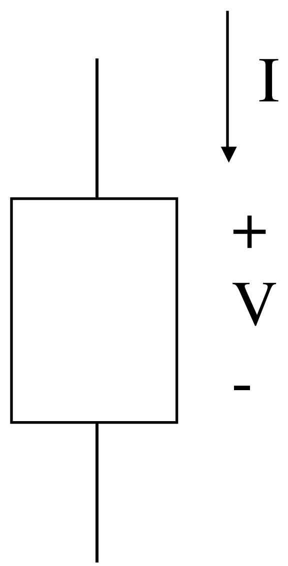
Increasing VCE increases the reverse bias on the BC junction increasing the width of the BC space charge layer resulting in a decrease in the base width and increase in concentration gradient and an increase in collector current. To account for this the equation relating the collector current to the V_{BE} can be modified slightly as shown: VA is the Early voltage after Dr. Jim Early of Fairchild Semiconductor.

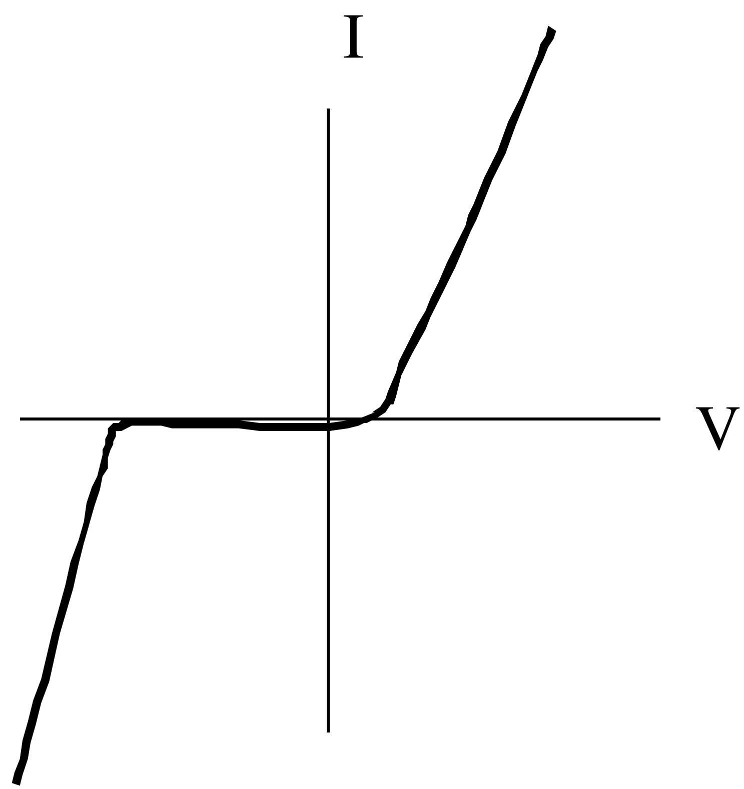
$$IC = IS\left(1+\frac{V_{CE}}{VA}\right) e^{V_{BE}/V_T}$$



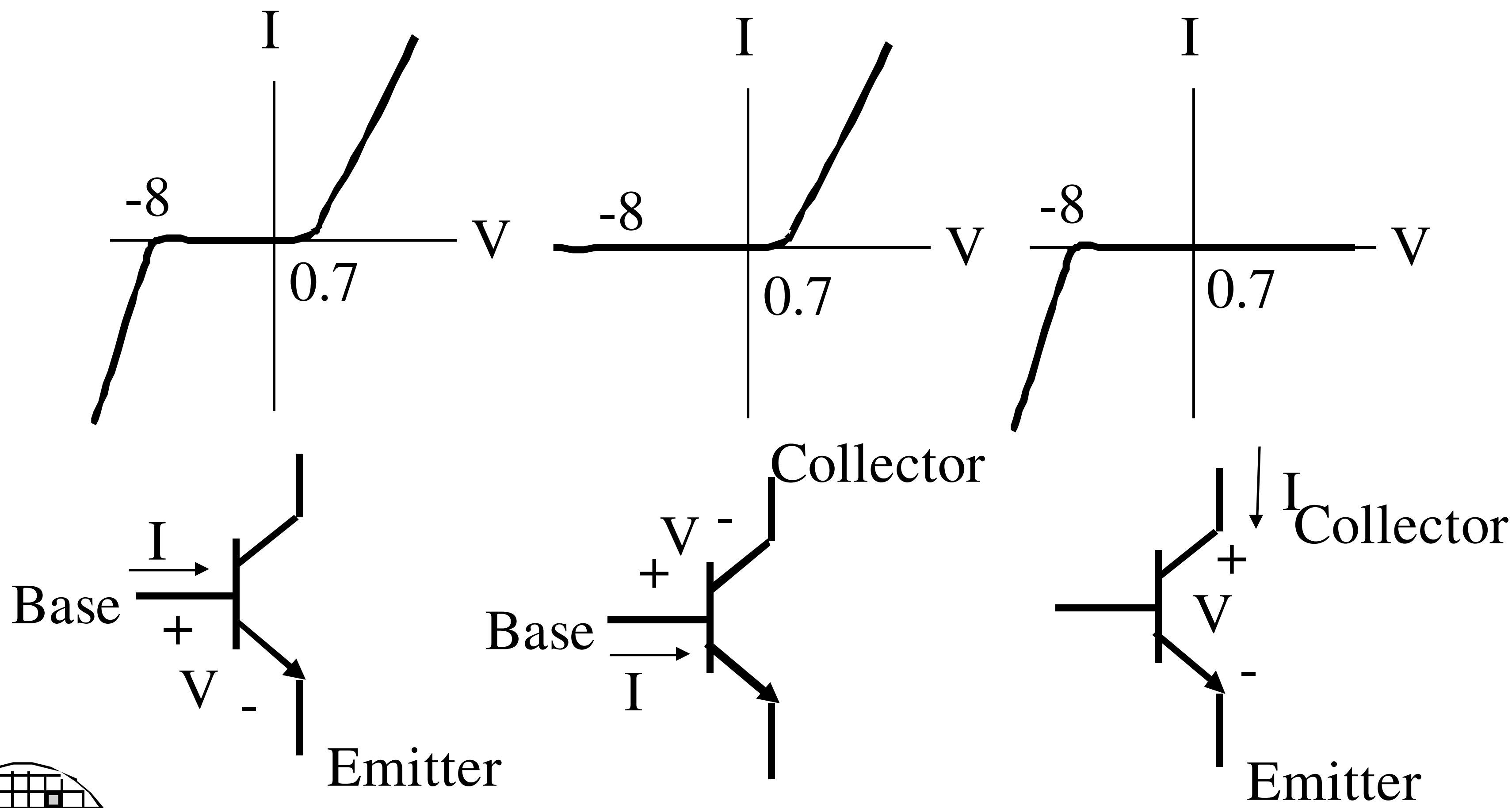
This is one of the many modifications to make the BJT models more accurate. Other modifications include resistors to account for series resistance in the collector, base and emitter.

CHARACTERISTICS OF TWO TERMINAL DEVICES

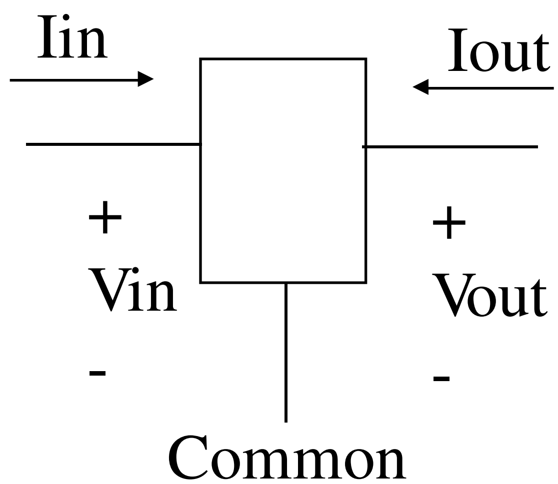


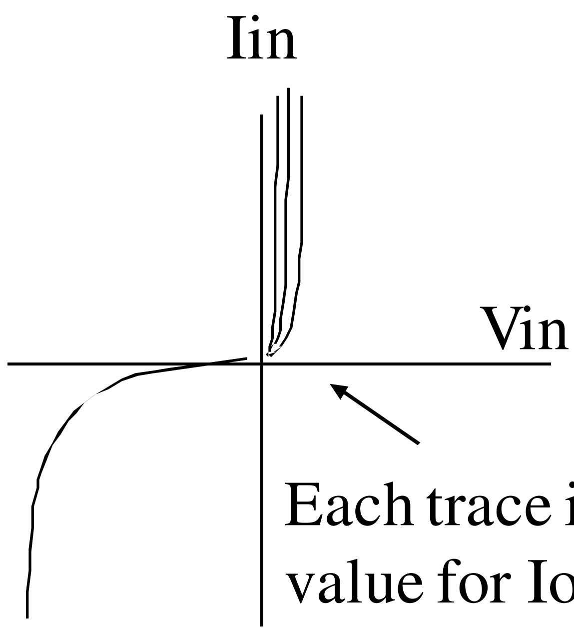


BE JUNCTION, BC JUNCTION, CE

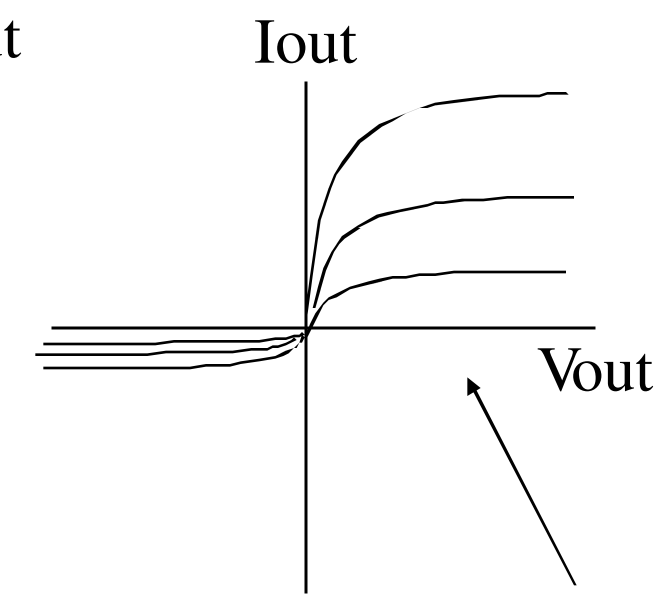


CHARACTERISTICS OF THREE TERMINAL DEVICES



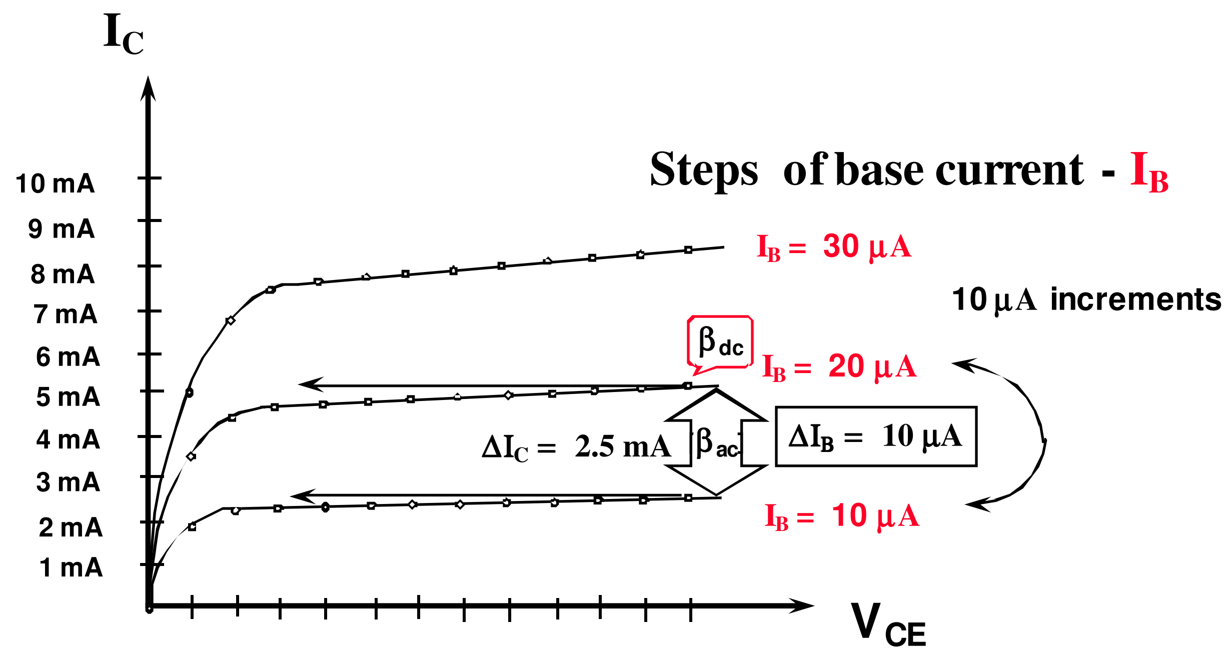


Each trace is for a different value for Iout or Vout



Each trace is for a different value for Iin or Vin

BJT IC-VCE FAMILY OF CURVES



$$\text{Beta } (\beta_{ac}) = \frac{\Delta I_C}{\Delta I_B} = \frac{2.5\times10^{-3}}{10\times10^{-6}} = 250$$

$$\text{Beta } (\beta_{dc}) = \frac{I_C}{I_B} = \frac{5.0\times10^{-3}}{20\times10^{-6}} = 250$$

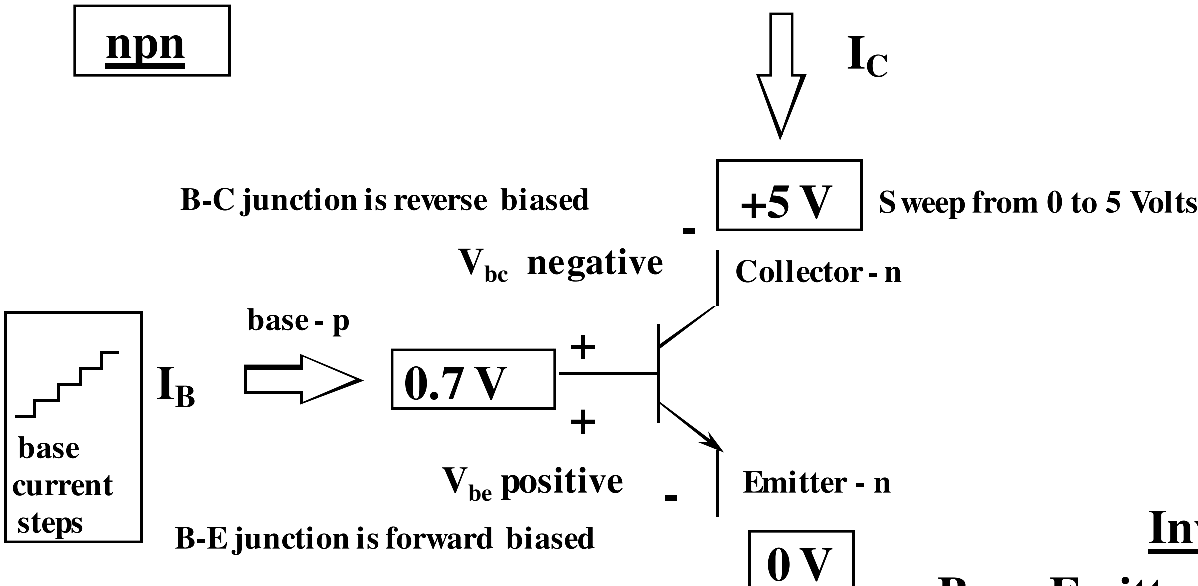
The two Beta values are not always the same!

NPN COMMON EMITTER IC-VCE CHARACTERISTICS

Forward Active Mode

Base-Emitter junction is forward biased
Base-Collector junction is reverse biased

V_a > 0 is a forward biased junction
V_a < 0 is a reverse biased junction
Va is defined as the voltage from p to n

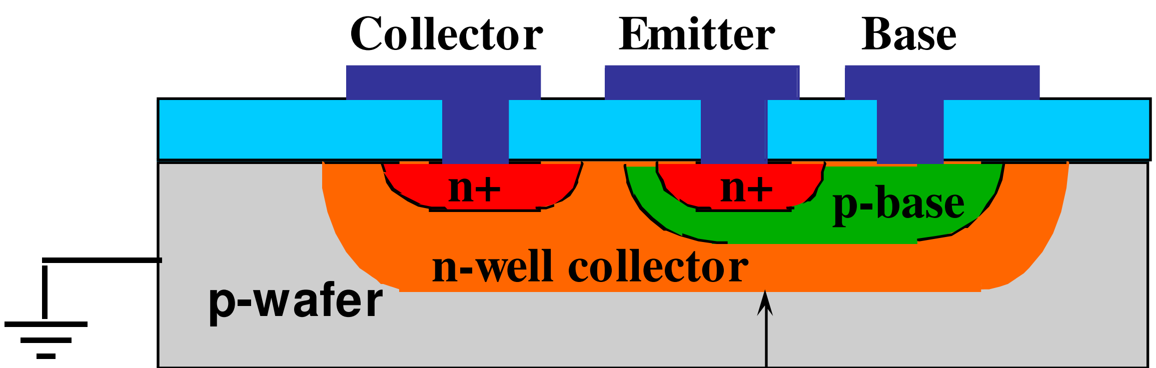


Inverse Active Mode

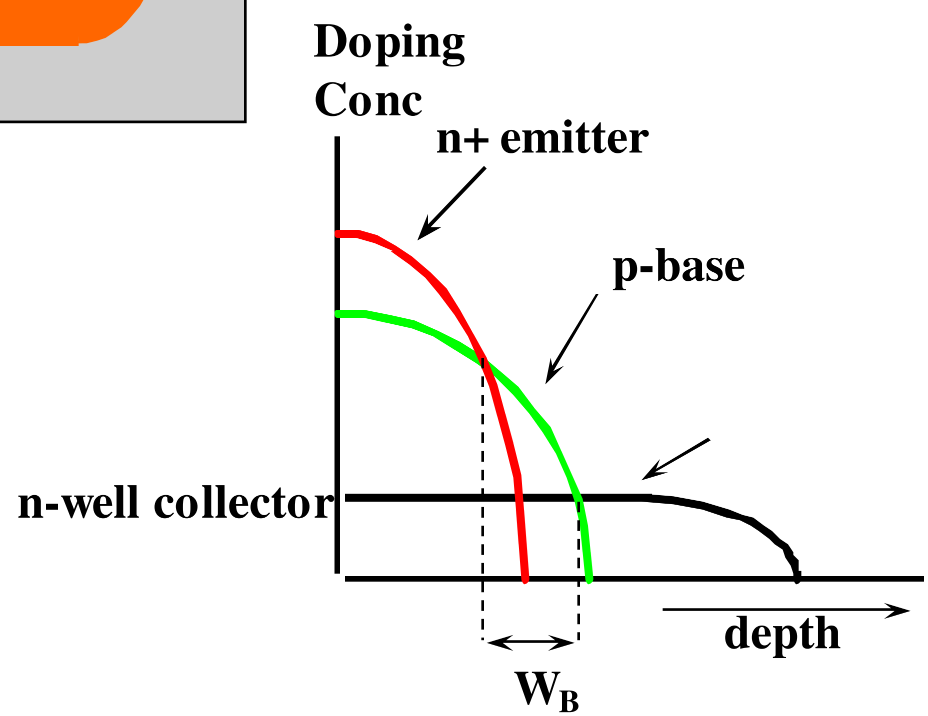
Base-Emitter junction is reverse biased
Base-Collector junction is forward biased

Switch the connections to the emitter and collector leads

TRIPLE DIFFUSED BJT STRUCTURE



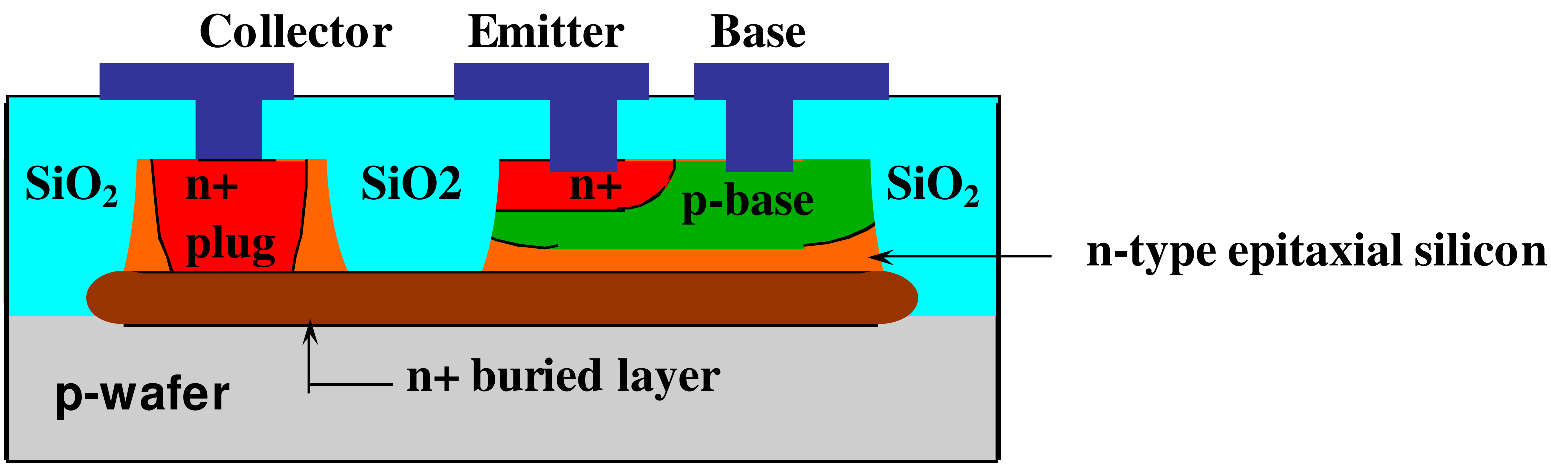
1-D Doping Profile



Base Width $W_B \sim 0.5\mu m$

- **Simple BJT structure**
  - Large collector series resistance
  - Large dimensions
  - Isolation issues

SHALLOW TRENCH ISOLATION



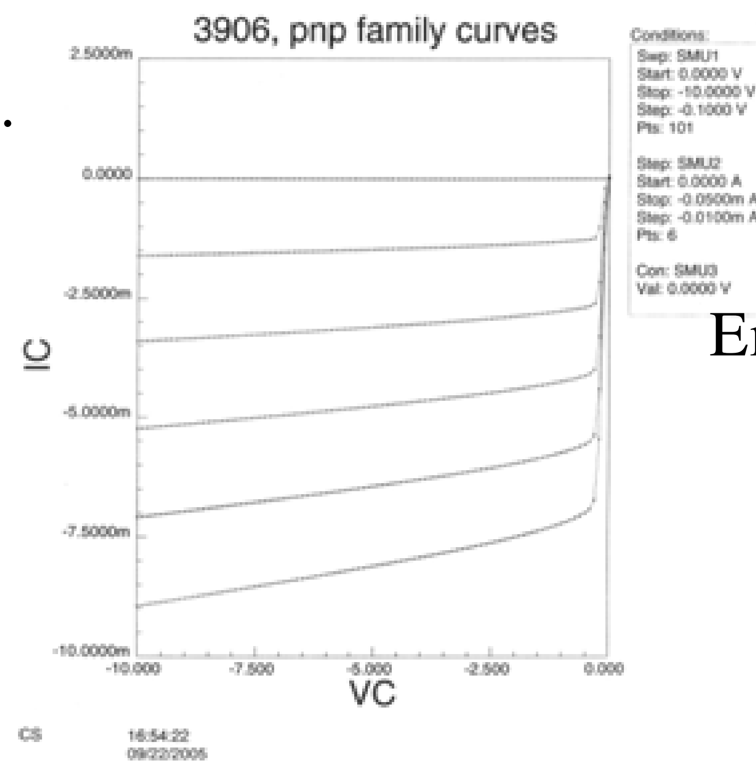
- **Process Enhancements**
  - Oxide-plug isolation
  - Patterned buried sub-collector
  - Epitaxial silicon
- **Performance Improvements**
  - Low collector series resistance
  - Improved collector/emitter isolation
  - smaller geometries

REFERENCES

1. Sedra and Smith, 5.1-5.4
2. Device Electronics for Integrated Circuits, 2nd Edition, Kamins and Muller, John Wiley and Sons, 1986.
3. The Bipolar Junction Transistor, 2nd Edition, Gerald Neudeck, Addison-Wesley, 1989.

HOMEWORK - BJT'S

1. Why won't two back to back diodes behave like a BJT?
2. Sketch a figure like that on page 7 showing the hole concentration for a pnp transistor with B-E junction forward biased and B-C junction reverse biased. Show direction of current flow.
3. The Ic versus Vce family of curves for a 2N3906 BJT is shown. What is the current gain, Beta, β
4. Look up the 2N3906 and see what the typical β is.
5. Look up some information about John Bardeen. Write a few sentences.



Vce

Ib

Emitter