EE4011

Semiconductor Devices for RF Design

Introduction to BJT

Why study semiconductor devices?

RF design involves designing circuits that operate at high frequencies from several MHz to several GHz. The semiconductor devices that make up these circuits must themselves be capable of operating at very high speeds so that the whole circuit will function as desired. Thus, a reasonable question to ask of a semiconductor device that you are considering for use in an RF circuits is:

What is the highest frequency at which this device will work?

For many applications this question can be answered by looking at the ***small-signal equivalent circuit*** and using this to determine a ***figure of merit*** known as the ***cut-off frequency***, f_T

A general rule of thumb is that if an RF circuit such as an amplifier is to operate well up to a certain frequency, F, then the devices in the high-frequency signal path should have a cut-off frequency of 10 to 20 times F.

Content and Expectations

1. The DC operation of various devices will be reviewed and some DC equations will be revised. This is to “fill-in” the background. The small-signal behaviour will then be reviewed and finally the RF operation will be covered.

2. For each device you should be able to (where discussed in the course):
    1. Draw the cross-section of an “ideal” device
    2. Draw the cross-section of a real device showing where parasitic resistances and capacitances/charge-storage occur.
    3. Describe the main physical effects which make the device work.
    4. Describe the general I-V behaviour including different operating regions.
    5. Remember the “first-order” equations for DC current.
    6. Use the “first-order” equations to derive small-signal quantities such as input or output resistance, transconductance and the capacitance elements.
    5. Draw the small-signal equivalent circuit.
    6. Use the small-signal circuit to derive the cut-off frequency and to determine the two-port parameters of the device such as y-, h-, z- or s-parameters.
    7. List the main “second-order” effects which cause the device to deviate from its ideal behaviour.

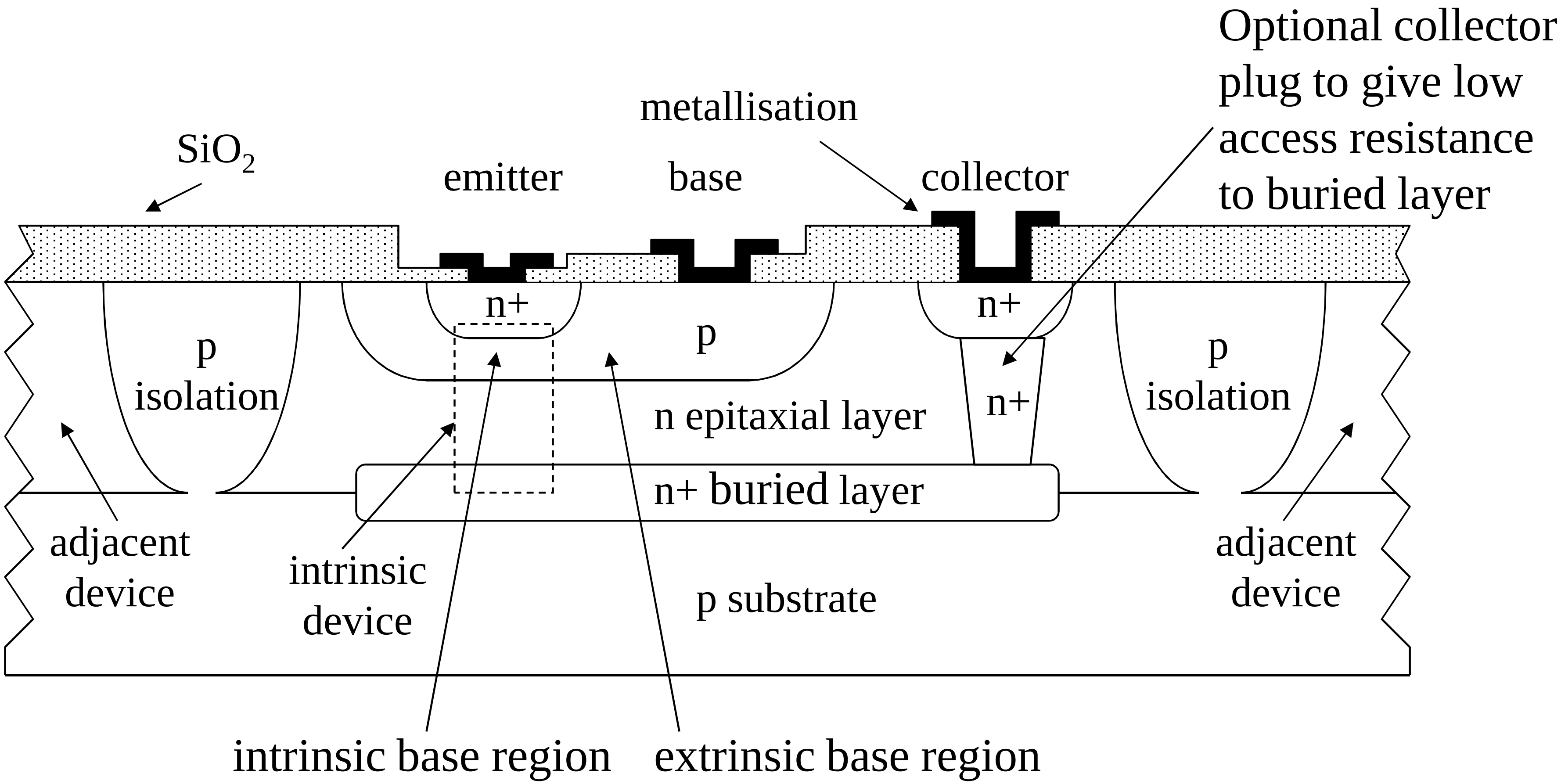
PS: This is a potential checklist to test your knowledge of a device for interviews!

The BJT

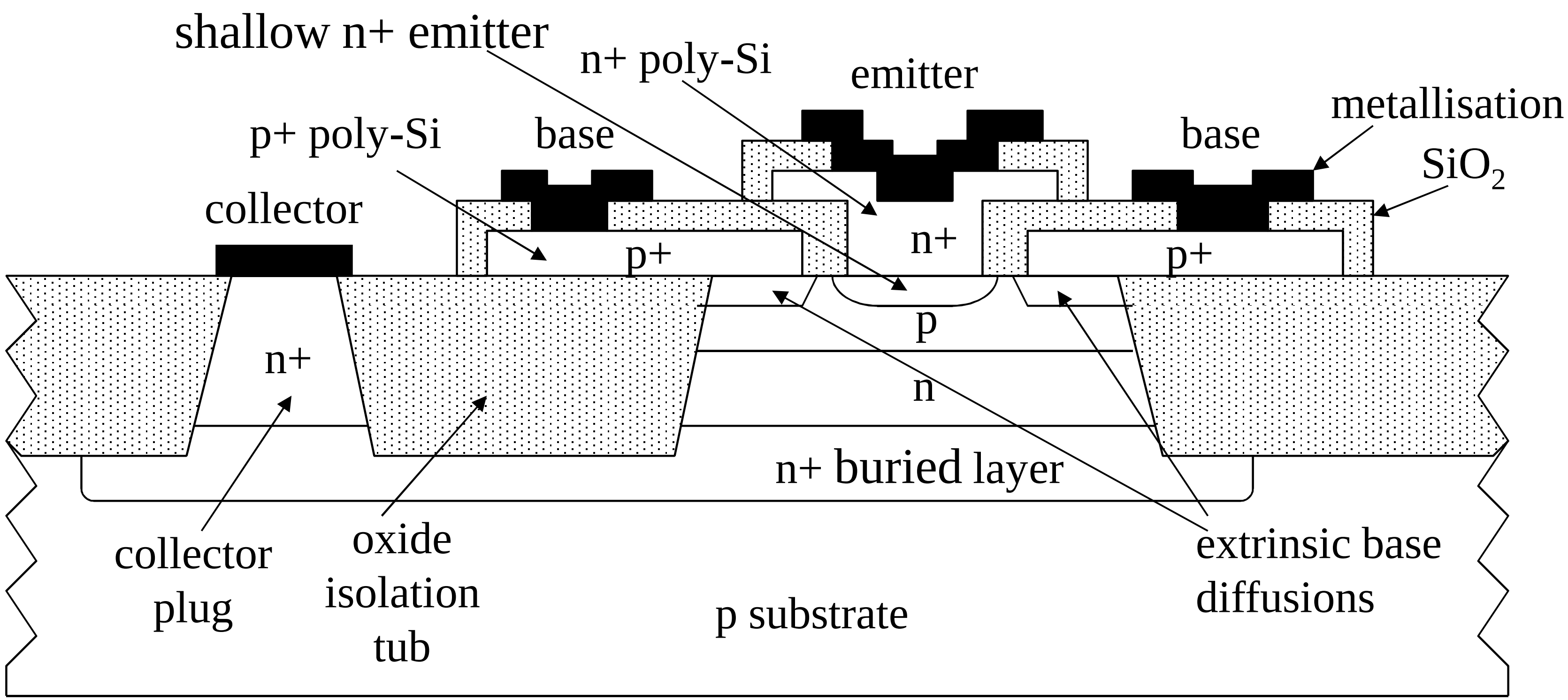
Bipolar Junction Transistors (BJTs) are used widely for RF circuits, especially a modern variant known as the Heterojunction Bipolar Transistor (HBT). BJTs and HBTs can be fabricated in both silicon and compound semiconductor technologies.

Simple equations are very successful at representing the operation of the BJT device, even as technology scales, so we’ll look at that device in most detail to see how a small-signal model is built up.

Cross Section Through NPN of Standard Bipolar Process



Cross Section Through NPN of Advanced Bipolar Process



Features of Advanced Bipolar Devices

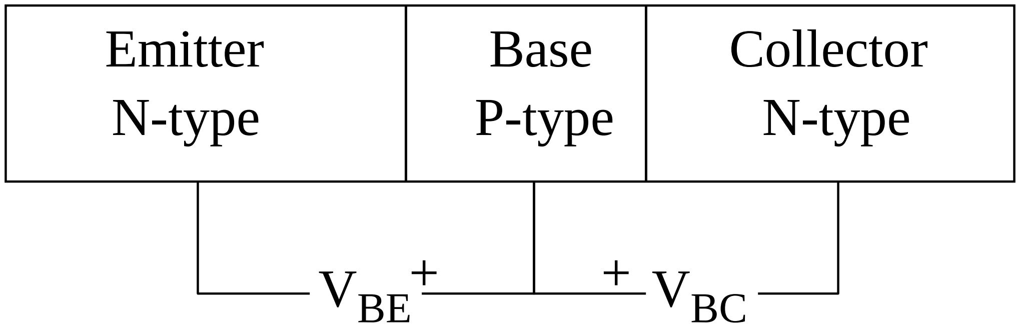
A modern advanced BJT may have:

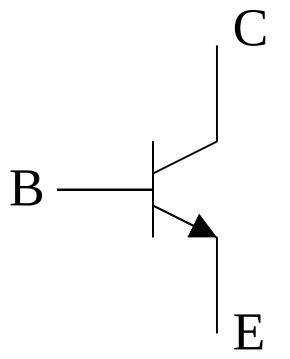
1. Collector plugs to reduce collector resistance.
2. Oxide isolation for decreased parasitic capacitance and leakage currents.
3. The emitter and extrinsic base formed by carrier diffusion from highly doped polysilicon regions. The resulting emitter can be made very shallow and highly doped while the extrinsic base regions reduce the parasitic base resistance.
4. Many processes form the devices completely on top of an oxide substrate which further improves device isolation and reduces parasitics.

Doping and contacting the emitter and base regions from the polysilicon layers allow the emitter and base contacts to be automatically aligned to the underlying diffusions so that small devices can be created without being constrained by the alignment tolerances of lithography equipment. This and the higher emitter and extrinsic base dopings which can be achieved allowed a large improvement in BJT performance from about the mid 1980’s.

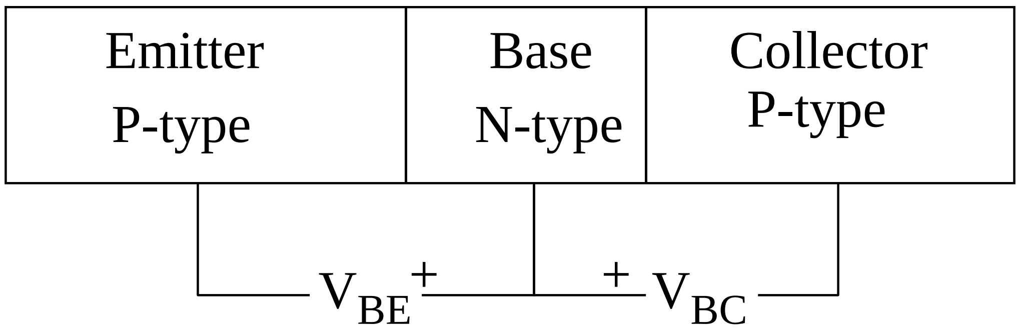
Simplified Structures and Circuit Symbols

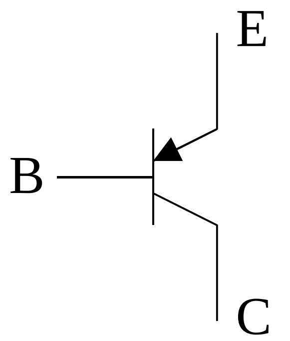
NPN:





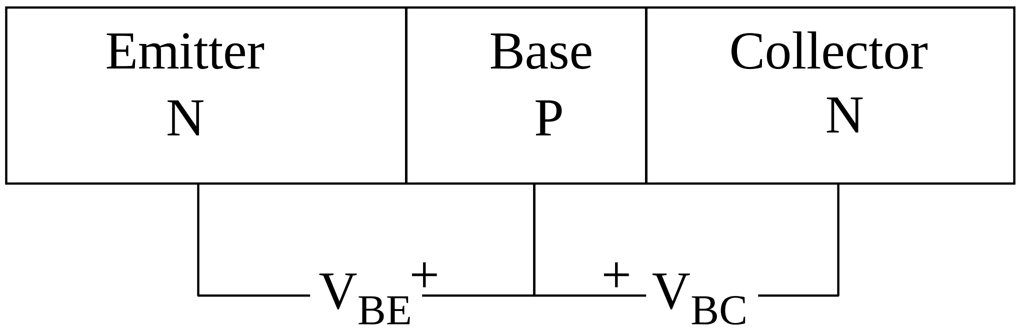
PNP:





For modeling and CAD purposes the devices are usually considered to be biased by means of a base-emitter voltage, V_{BE} and a base-collector voltage, V_{BC} although for circuit design the bias voltages are usually considered to be V_{BE} and V_{CE}.

Different Operating Regions of BJT (1)



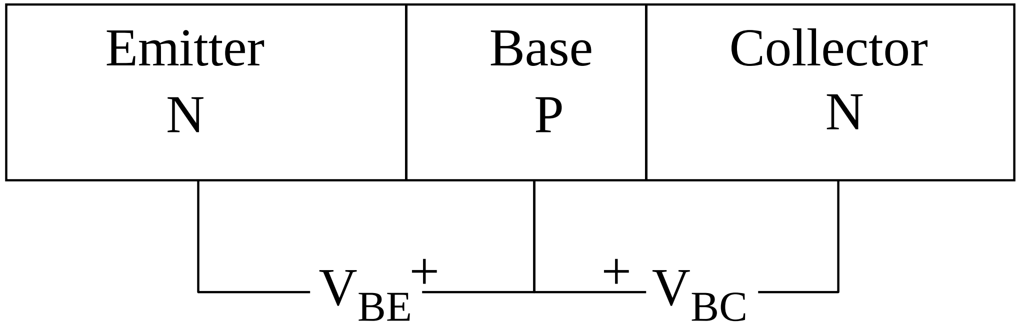
<u>Forward Active Region</u>

Base-Emitter forward biased, Base-Collector reverse biased.
This is the most-widely used configuration.
For NPN: $V_{BE} > 0 \quad V_{BC} \leq 0$

<u>Reverse Active Region</u>

Base-Emitter reverse biased, Base-Collector forward biased.
Sometimes used for digital logic. Nearly always avoided for analogue/RF circuits and may even damage modern devices.
For NPN: $V_{BE} \leq 0 \quad V_{BC} > 0$

Different Operating Regions of BJT (2)



Off

Base-Emitter reverse biased, Base-Collector reverse biased.

For NPN: $V_{BE} \leq 0 \quad V_{BC} \leq 0$

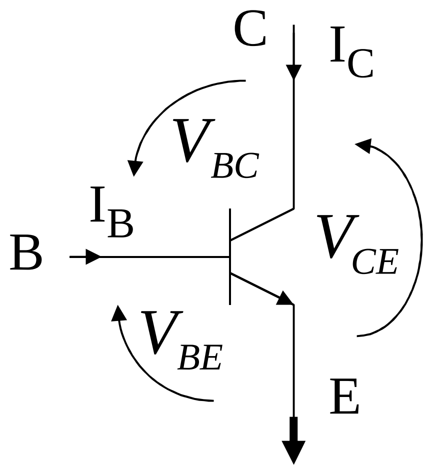
Saturation

Base-Emitter forward biased, Base-Collector forward biased.

For NPN: $V_{BE} > 0 \quad V_{BC} > 0$

Saturation occurs during switching in TTL circuits but it slows down switching so it is prevented in many cases by connecting a Schottky diode between the base and the collector. This region is nearly always avoided for analogue/RF circuits as the gain is low in this region.

BJT Common-Emitter Bias Arrangement



The "normal" biasing setup for a common-emitter amplifier is to consider the emitter as the reference point or ground and to apply V_{BE} to the base and V_{CE} to the collector. In this case:

$$V_{BC} = V_B - V_C = V_{BE} - V_{CE}$$

The collector and base currents can be described approximately by:

$$I_C = I_S\left(e^{\frac{qV_{BE}}{kT}} - 1\right)\left(1 + \frac{V_{CE}}{V_A}\right) \qquad I_B = \frac{I_C}{\beta}$$

I_S is the saturation current.
V_A is the Early voltage.
β is the current gain of the transistor.
kT/q is the thermal voltage (approximately 25mV at room temperature).

“Conventional” NPN I-V (Output) Characteristics

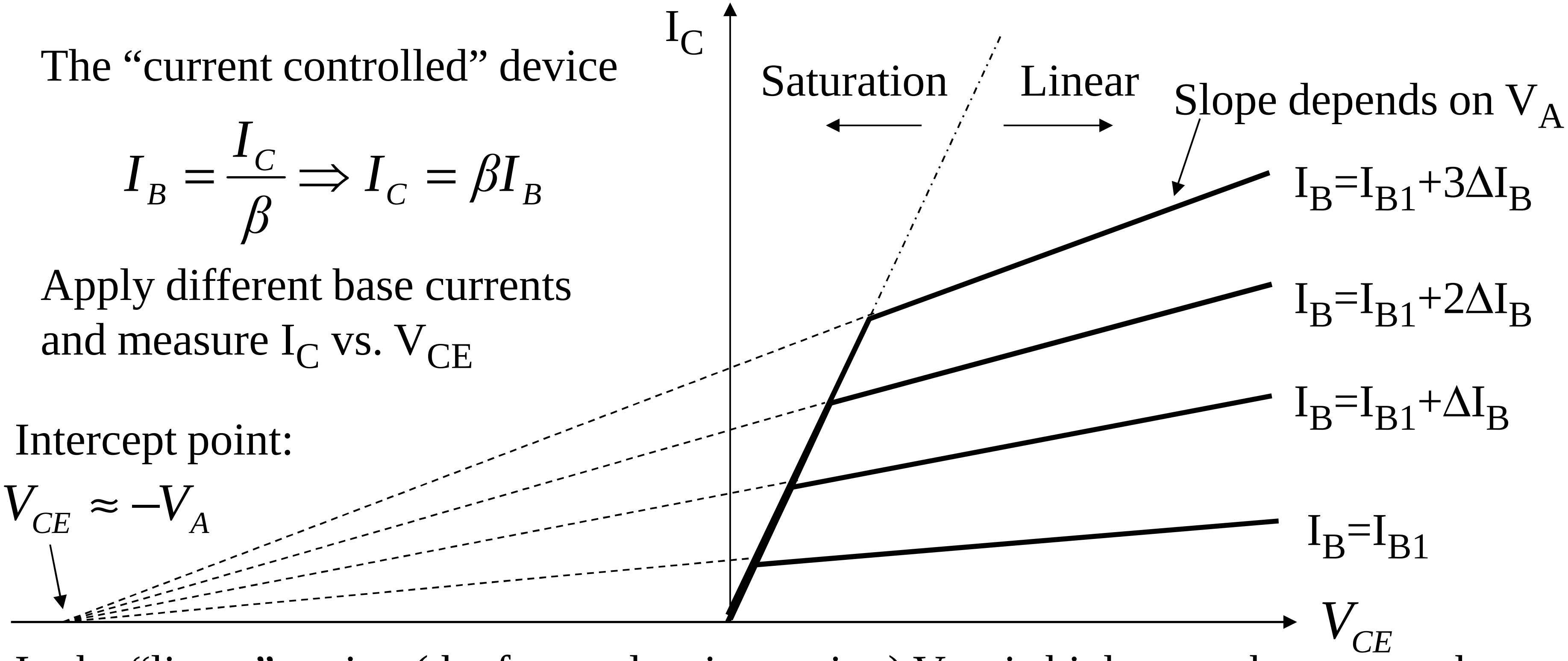
The “current controlled” device

$$I_B = \frac{I_C}{\beta} \Rightarrow I_C = \beta I_B$$

Apply different base currents and measure I_C vs. V_{CE}

Intercept point:

$$V_{CE} \approx -V_A$$



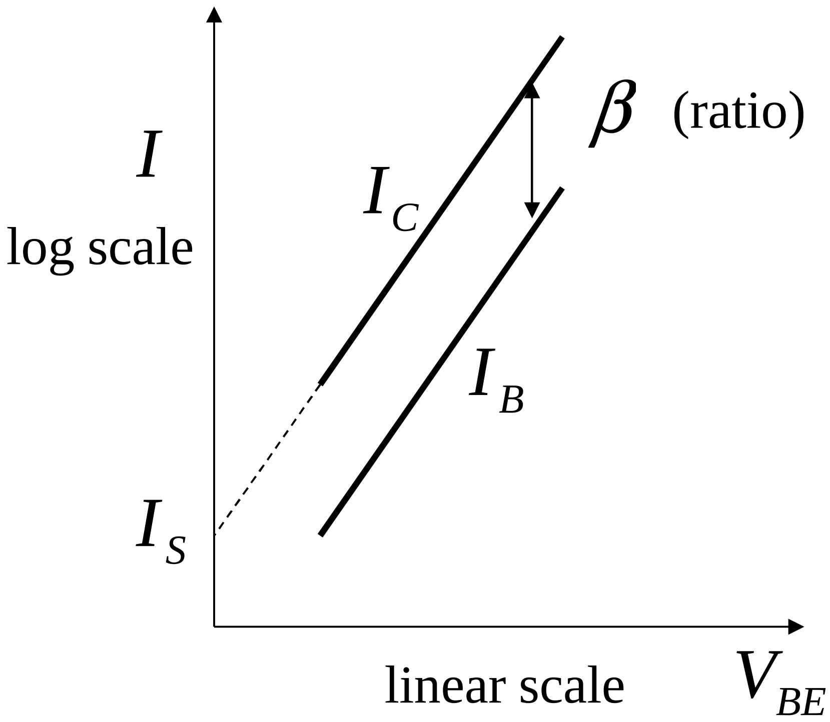
In the “linear” region (the forward active region) V_{CE} is high enough to cause the base/collector junction to be reverse biased and there is a linear relationship between I_C and I_B. In “saturation” V_{CE} is low so the base/collector junction is forward biased as well as the base/emitter junction. The base region is “saturated” with minority carriers and the linear relationship between I_C and I_B breaks down.

V_A can be determined from this type of plot.

The Gummel Plot

The “voltage controlled” device

$$I_C = I_S\left(e^{\frac{qV_{BE}}{kT}} - 1\right)\left(1 + \frac{V_{CE}}{V_A}\right) \qquad I_B = \frac{I_C}{\beta}$$



Set V_{CE} to a constant value high enough to keep the device in the forward active (linear) region, vary V_{BE}, measure I_C and I_B and plot the currents on a log scale vs. V_{BE} on a linear scale.

This type of plot is called a “Gummel Plot” and can be used to determine I_S and β.
For a “proper” Gummel plot it is V_{BC} which should be kept constant, not V_{CE}.