EEE118: Electronic Devices and Circuits

Lecture X

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Review

- Introduced the idea of small signals and large signals.
- Introduced the idea of a dynamic resistance or small signal resistance.
- Compared the voltage source model and thévenin model of a diode.
- Considered how capacitors can be used to block quiescent conditions (DC) but pass signals (AC).
- Introduced the idea of a small signal equivalent circuit - How the signal "sees" the circuit.
- Used the device (diode) characteristic to examine the operating point and linearity of a circuit.

Outline

Transistor Definition

Definition

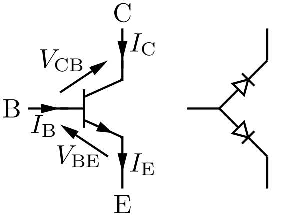
A transistor is a three terminal semiconductor electronic device which is capable of power amplification.

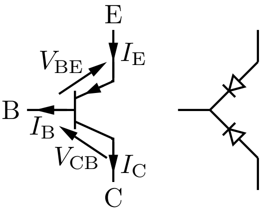
Different from a transformer or resonant circuit which can only increase the amplitude of current *or* voltage. Several different kinds of transistor exist (BJT, MOSFET, JFET) and Valves.

- BJT is the most common small signal amplifier.
- MOSFETs are more common in large signal applications such as switching power supplies.
- MOSFETs also find use in integrated circuits (producing them on a semiconductor wafer is easy c.f BJT).
- JFETs are found in ICs but are also used as discrete devices.
- Thermionic valves are limited to specialist applications (e.g. high power microwave generation, radio and RADAR transmission, specialist audio applications.)

Bipolar Junction Transistor

The bipolar transistor[1] was invented by John Bardeen, Walter Brattain and William Shockley in the late 1940s at Bell Labs. Read: `http://dx.doi.org/10.1109/5.658752`. They shared the 1956 Nobel Prize. The BJT is a semiconductor device composed of three semiconductor regions N-P-N or P-N-P named Emitter (E), Base (B) and Collector (C). The NPN can be thought of as two diodes with their anodes connected together. The PNP, two cathodes connected.





Why can't two diodes be used to make a transistor?

[1] from "transfer-resistor"

JEDEC Numbering System

At least three numbering systems exist but not all part numbers apply the rules, JIS, Pro Electron and JEDEC.

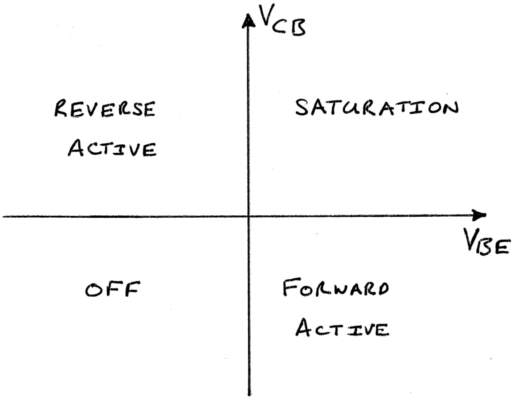
- JEDEC the The Joint Electron Devices Engineering Council was formed in 1958 as a part of the Electronic Industries Association (EIA).
- It standardises semiconductor part numbers used in the USA.
- The code is [Number] ‘N’ [Serial Number] [Suffix Optional].
- Where, 1 - Diode, 2 -Transistor, 3 - Dual-Gate, 4 - Optocoupler (LED + photo diodes), 5 - Optocoupler (LED + Transistor).
- The suffix is optional and is A - low gain, B - medium gain and C - high gain.
- e.g. 2N3904 and 2N2222 are transistors. 1N4148 and 1N4007 are diodes.

Pro Electron Numbering Systems

- European Numbering or “Pro Electron” system. Designated by the European Electronic Component Manufacturers Association of which Pro Electron has been a part since 1983.
- The code is [Letter] [Letter] [Serial Number]
- First letter is A, B, C or R - depends on band-gap
- Second letter indicates device function or application.
- Serial number is an identifier for the device
- e.g. BC182 (Silicon, low power audio frequency transistor) BZX55C4V7 (Zener Diode)
- See handout for full details.

BJT Modes of Operation

There are four possible modes of operation where each of the two junctions is either forward or reverse biased.

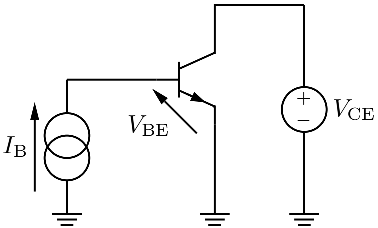


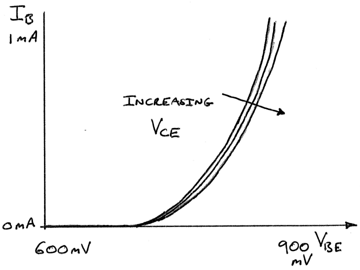
BJT Modes of Operation II

- The forward active region provides amplification of voltage and/or current (both means power amplification ($P = IV$)).
- In the saturation region the transistor appears like a switch which is turned on.
- In the 'off' region the transistor appears like a switch which is turned off.
- The reverse active region is used when the BE and CB junctions are accidentally exchanged (transistor in the circuit backwards). Performance is poor c.f forward active region as transistor designers adjust doping densities and region widths to optimise performance in other regions.

Note: some transistors are designed for amplification (linear) use others are designed for switching use. All transistors can perform both functions but the design of "switching" transistors is optimised for switching applications. Likewise for "amplifier transistors".

Input Characteristics



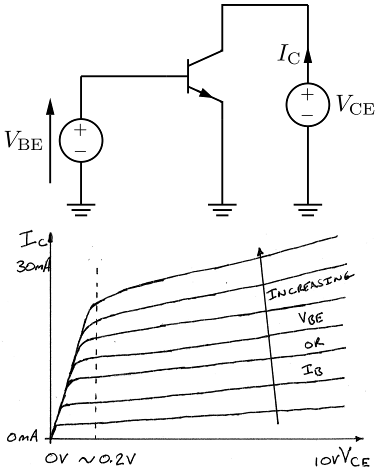


Shape of characteristics essentially governed by the diode equation when $V_{\mathrm{CE}} \approx 0$.

$$I_{\mathrm{B}} = I_S \left(exp \left(-\frac{q\, V_{\mathrm{BE}}}{k\, T} \right) - 1 \right)$$

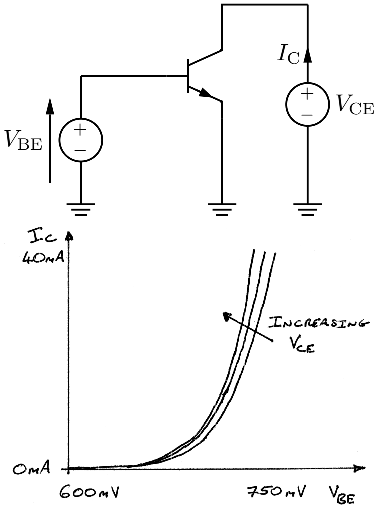
Increasing V_{CE} with constant V_{BE} decreases the base width, slightly decreasing the recombination of minority carriers in the base region. Note, the base current is incidental, it is the base emitter voltage that is controlling the transistor. But like the compressor from Lecture 9, V_{BE} will rise to whatever is necessary to admit the desired current I_B

Output Characteristics



A family of curves showing effect on the output V_{CE} and I_{C} as a function of the input V_{BE} (or I_{B}). When V_{CE} is small the transistor is in saturation both BE and CB junctions forward biased (transistor switched "on") (left of graph). While V_{BE} is too small to cause I_{C} to rise above the leakage current level, the transistor is off ($y \approx 0$ on the graph). Forward active region is indicated by nearly parallel characteristics.

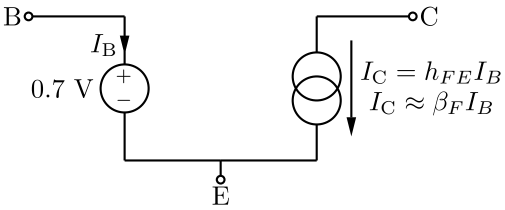
Transfer Characteristics



The transfer characteristic relates the controlling voltage (V_{BE}) to the controlled parameter I_C. V_{BE} is related to I_C for a BJT by $I_C = I_S\left(exp\left(\frac{q\,V_{BE}}{k\,T}\right) - 1\right)$ and by square law expressions for FETs (see handouts). This expression holds over many orders of magnitude while the relationship between base current and collector current changes considerably (h_{FE} not constant). See Horowitz and Hill, second Ed. pp 79 - 81 section 2.10 for full details.

Large signal BJT model: Forward Active

Large signals deal with active devices moving through large *non-linear* regions of their characteristics. A suitable large signal model for the forward active region of a BJT is to replace the base emitter junction with a 0.7 V source (it is a diode after all...) and to replace the reverse biased collector base junction with a current source where the current is controlled by the base current (the two are linked by the large signal current gain h_{FE}[2]) $I_C = h_{FE}\, I_B$.[3]



[2] note capital F and capital E means large signal parameters

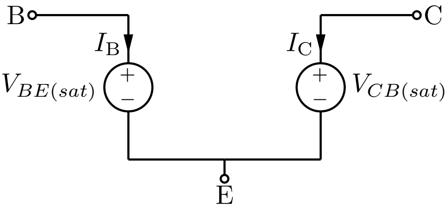
[3] h_{FE} **h**ybrid model **F**orward, **E**mitter common. Also “Ebers-Moll transistor model”, Millman and Grabel second ed. pp. 87 - 114.

Earlier it was said that V_{BE} was the controlling variable and I_C was the controlled variable and that I_B was incidental (MOSFETs have no equivalent, I_G). However, in the large signal model V_{BE} is fixed at 0.7 V. Making it the controlling variable would make answering questions hard!

In switching applications the concern is often to cause the transistor to change from conducting to non-conducting (and back) as quickly as possible. The circuit designer aims to allow the load (whatever the collector is connected to) to define the maximum value of I_C. The designer then ensures that the input to the transistor (whatever the base is connected to) is able to supply whatever base current (I_B) is required to cause the transistor to switch. By approaching the problem in this way the designer can lessen the dependence of the circuit operation on h_{FE}. This is desirable because h_{FE} varies a great deal even between transistors of the same type.

Large signal BJT model: Saturation

A large signal model for the saturation mode of the BJT is two voltage sources representing the saturation voltage between the base and emitter and the collector and emitter. These are given on switching transistor datasheets (e.g. ZTX653 note not Pro E or JEDEC) or the exam question...



In saturation $I_C = h_{FE}\, I_B$ *does not apply*. A model for the transistor when it is off is open circuit between B, C and E. In practice very small leakage currents flow, which are defined on the transistor datasheet.

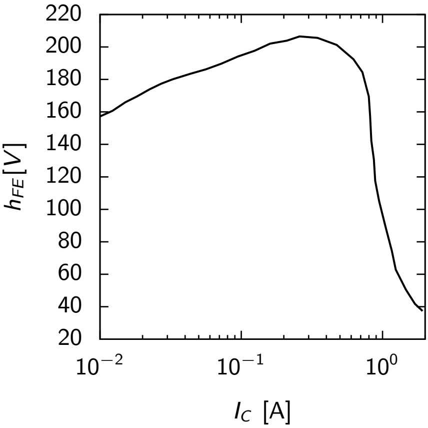
Finding a Value for h_{FE}, $V_{\mathrm{CE(sat)}}$, $V_{\mathrm{BE(sat)}}$

The following parameters of the Large Signal Model may be found on a transistor datasheet.

- h_{FE} - the large signal (capital subscript letters) forward active mode relationship between I_C and I_B.
- $V_{\mathrm{CE(sat)}}$ the saturation voltage between collector and emitter.
- $V_{\mathrm{BE(sat)}}$ the saturation voltage between base and emitter

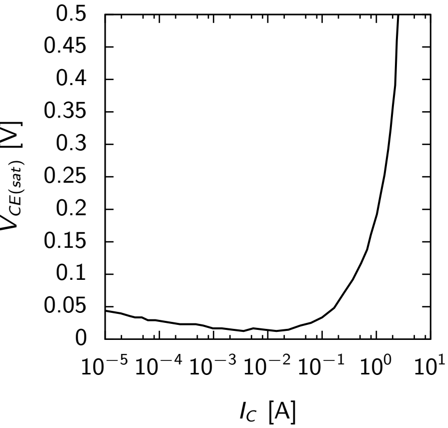
All of these parameters are functions of I_C. For the purposes of this course $h_{FE} = 100$ may be assumed if no value is given. The dependence of $V_{\mathrm{CE(sat)}}$ and $V_{\mathrm{BE(sat)}}$ may also be ignored, but in real design situations (project work etc.) these dependencies should not be forgotten.

ZTX653 h_{FE} as a function of I_C



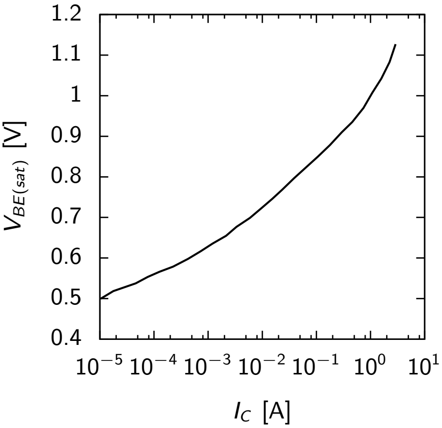
The ZTX653 is a standard 'switching' transistor for low power applications. Observe the wide variation of h_{FE} as a function of I_C. Also note that as the transistor switches on, the base current demand will increase (h_{FE} ultimately falls with increasing I_C). h_{FE} is also a function of temperature. $V_{CE} = 2\ V$ for this plot. h_{FE} measured in saturation is sometimes called the "forced β".

ZTX653 $V_{CE(sat)}$ as a function of I_C



$V_{CE(sat)}$ is also a function of collector current. In the large signal model is constant for a particular problem with values in the range 0.1 V – 1 V depending on the current and voltage rating of the BJT in the question. Note that $V_{CE(sat)}$ increases with I_C, this is unfortunate as the product of $V_{CE(sat)}$ and I_C yields the "on state power loss" (more on this next week).

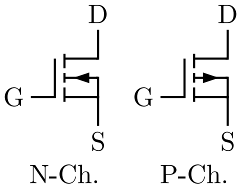
ZTX653 $V_{BE(sat)}$ as a function of I_C

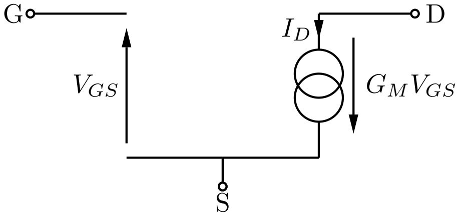


V_{BE} *is* the controlling variable and I_C *is* the controlled variable. However in switching situations the maximum I_C is defined by the load (whatever is connected to the collector) and the input circuit (whatever is connected to the base) must supply the V_{BE} and I_B required to make the transistor "go". If it can't, the transistor may not behave as expected. In the large signal model we assume V_{BE} is 0.7 V irrespective of I_C.

MOSFET Large Signal Model "Saturation" Region

The MOSFET is a three terminal amplifying device like the BJT but the collector has become the drain, base is now gate and emitter changes to source. Also the meaning of saturation is different in BJTs and MOS transistors. Saturation in BJT = "Linear Region" in MOS. Forward Active in BJT = "Saturation" in MOS! For the N-Ch device to be in saturation V_{GS} must be positive and V_{DG} must be negative. For the P-Ch device to be in saturation V_{GS} must be negative and V_{DG} must be positive.

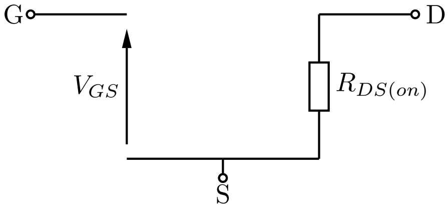




G_M is the large signal transconductance. It is rarely necessary to know it's value, but it can be found on datasheets.

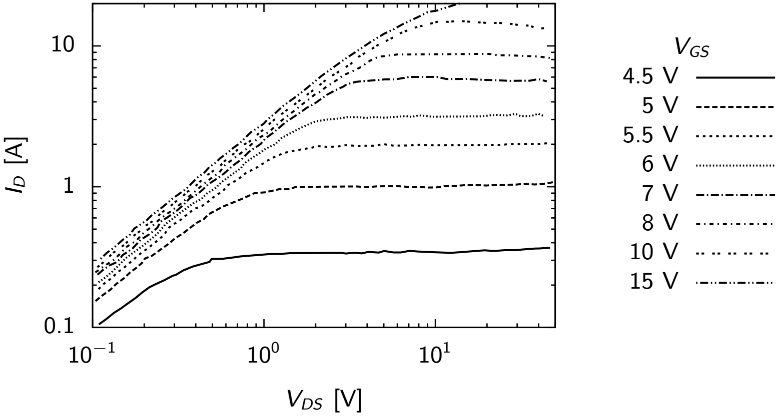
MOSFET Large Signal Model "Linear Region"

Linear because at a constant value of V_{GS} a slight increase in V_{DS} will bring about an *approximately* linear increase in I_D. This is most easily understood by looking at the output characteristics.



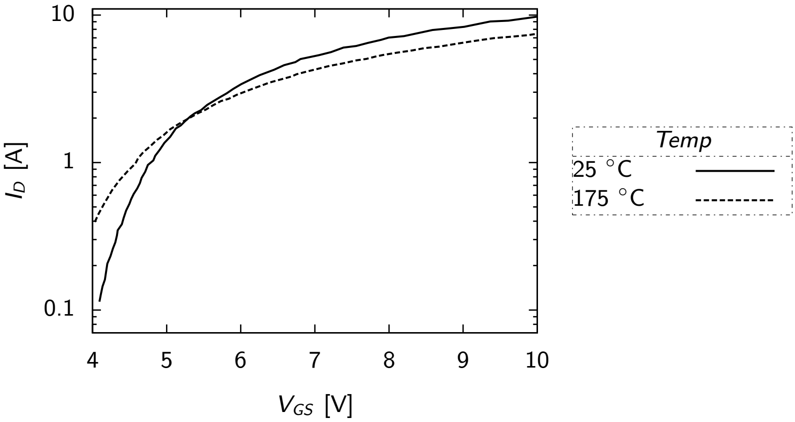
In the linear region the MOSFET behaves like a resistance, $R_{DS(on)}$. The value of $R_{DS(on)}$ is sensitive to temperature (increasing temperature increases $R_{DS(on)}$ however in saturation the dependence is somewhat more complex, based on both the kind of MOSFET (lateral or vertical) and the region of the characteristics it is being operated over.

IRF510 Output Characteristics



Notice V_{GS} is much greater than in the BJT case. In the linear region (left) all of the curves are parallel, $R_{DS(on)} \approx$ constant. These characteristics at 25 °C. Very generally, often,

IRF510 Transfer Characteristics



The characteristics of MOSFETs are often found in datahseets, because the transconductance depends on device geometry. In BJTs an expression exists independent of device dimensions.

Review

- Introduced the bipolar transistor.
- Briefly discussed two numbering systems for active devices.
- Considered the four modes of operation of a BJT.
- Looked at examples of the input, output and transfer characteristics of a BJT.
- Developed a large signal model for a BJT which can be used to solve switching problems.
- Noted some of the limitations of the model in the saturation
  - h_{FE} dependent on I_C
  - $V_{BE(sat)}$ dependent on I_C
  - $V_{CE(sat)}$ dependent on I_C
- Developed a large signal model of a MOSFET.
- Briefly observed some differences between MOSFET and BJT characteristics.