EEE118: Electronic Devices and Circuits

Lecture XI

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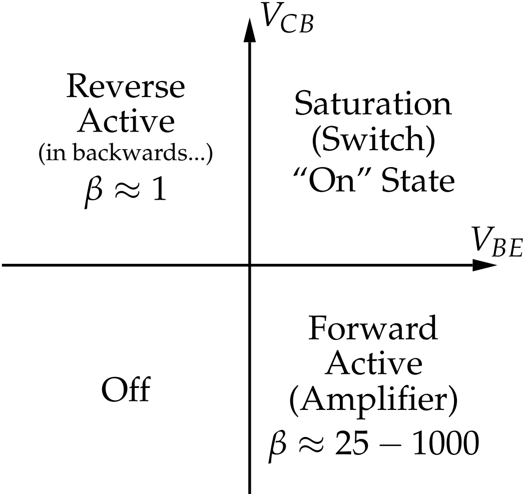
Review

- 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.
- Introduced the bipolar transistor.
- Briefly discussed two numbering systems for active devices.

Outline

BJT Modes of Operation

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

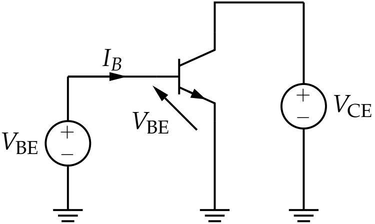


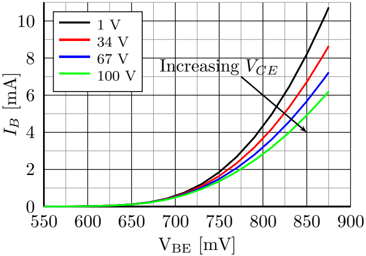
BJT Modes of Operation II

- 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



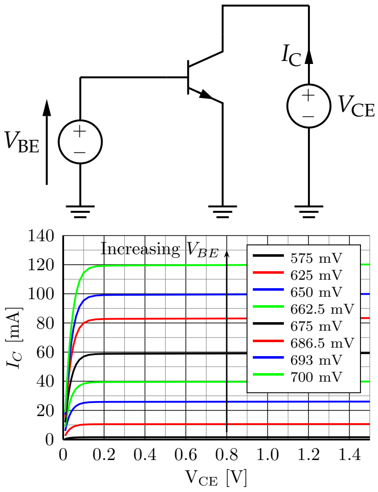


Shape of characteristics essentially governed by the diode equation when $V_{CE} \approx 0$.

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

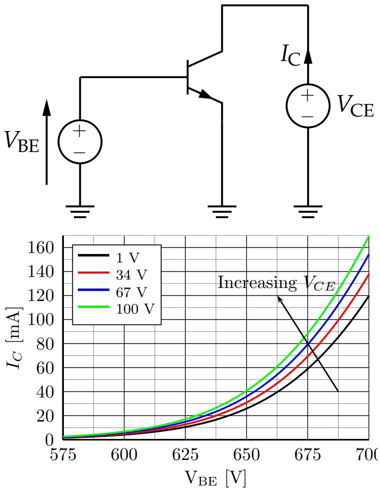
Increasing V_{CE} with constant V_{BE} decreases the base width, slightly decreasing the recombination of minority carriers in the base region. Note, the base current is incidental, it is the base emitter voltage that is controlling the transistor. But like the compressor from Lecture 9, V_{BE} will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

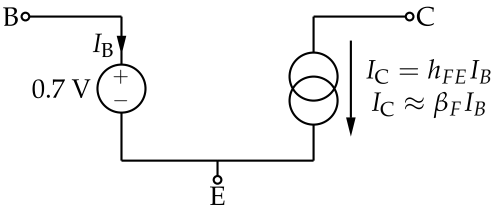
Transfer Characteristics



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

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}[1]) $I_C = h_{FE}\, I_B$.[2]



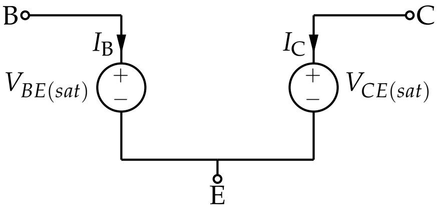
[1] note capital F and capital E means large signal parameters

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

- V_{BE} is the controlling variable and I_C is the controlled variable and I_B is incidental (MOSFETs have no equivalent, I_G). However, in the large signal model V_{BE} is fixed at 0.7 V. How can it be the controlling variable if it is fixed?
- In switching applications we want the transistor to change from conducting to non-conducting (and back) as quickly as possible. The load (whatever the collector is connected to) defines the maximum value of I_C.
- The designer 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. This makes the exact value of V_{BE} and I_B less important.
- In this way the dependence of the circuit operation on h_{FE} is lessened. This is desirable because h_{FE} varies a great deal even between transistors of the same type.

Large signal BJT model: Saturation (i.e. Switched "On")

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}, $V_{\mathrm{CE(sat)}}$, $V_{\mathrm{BE(sat)}}$

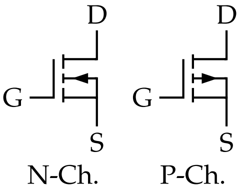
The following parameters of the Large Signal Model may be found on a transistor datasheet.

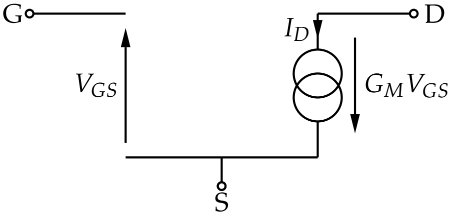
- h_{FE} - the large signal (capital subscript letters) forward active mode relationship between I_C and I_B.
- $V_{\mathrm{CE(sat)}}$ the saturation voltage between collector and emitter.
- $V_{\mathrm{BE(sat)}}$ the saturation voltage between base and emitter

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 $V_{\mathrm{BE(sat)}}$ have also be ignored, but in real design situations (project work etc.) these dependencies should not be forgotten.

MOSFET Large Signal Model

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/Forward Active” in MOS. “Linear Region/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.

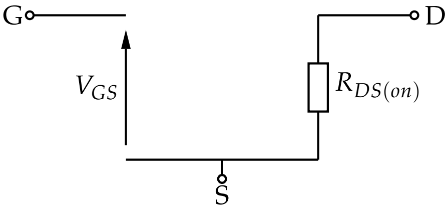




G_M is the large signal transconductance. It is rarely used.

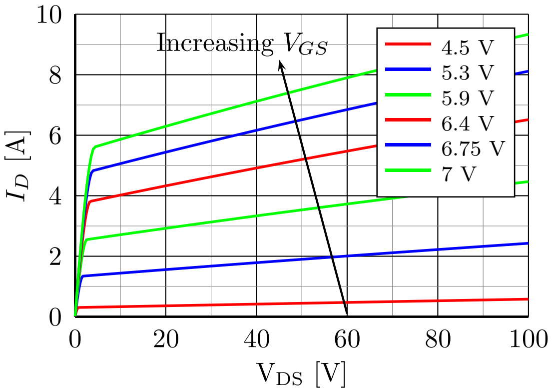
MOSFET Large Signal Model: Switched "On"

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.



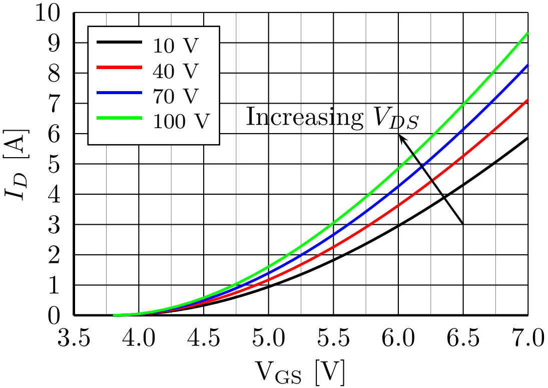
In the linear region the MOSFET behaves like a resistance, $R_{DS(on)}$. The value of $R_{DS(on)}$ is sensitive to temperature (increasing temperature increases $R_{DS(on)}$ however in saturation the dependence is somewhat more complex, based on both the kind of MOSFET (lateral or vertical) and the region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

IRF510 Output Characteristics



Notice V_{GS} is much greater than in the BJT case. In the switching region (left) the curves can be assumed parallel, $R_{DS(on)} \approx$ constant. These characteristics at 25 °C. Very generally speaking $V_{DS(on)} < V_{CE(sat)}$.

IRF510 Transfer Characteristics



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

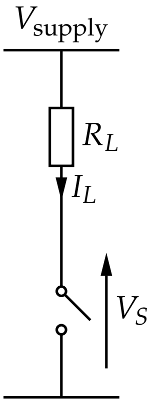
An Ideal Switch

When "on" $I_L = \frac{V_{supply}}{R_L}$

When "off" $I_L = 0$

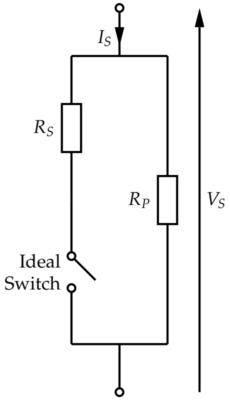
When "on" $V_S = 0$

When "off" $V_S = V_{supply}$



The product of V_S and I_L is zero in both switch states so no power is dissipated in the switch. I_L - the on state current - is determined by the external circuit not the switch.

A Real Switch

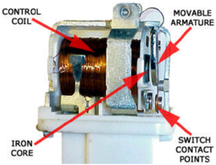


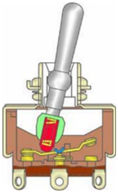
Real switches have some series resistance and some leakage current in the "off state" In most cases, R_P, which represents the "off" state leakage can be neglected. R_S usually has to be considered because it is responsible for the power loss ($I^2 R$) in the switch. For a real switch,

$$I_S = \frac{V_{supply}}{R_L + R_S} \tag{1}$$

Mechanical Switches

- Mechanical force brings together two metal contacts.
- Easily designed for currents in the range 10^{-3} to 10^{7} A
- Very low contact resistance (R_S)
- Very low leakage (high R_P)
- Requires the application of mechanical for to operate. Elasticity and inertia limits the switching rate to a few hundred Hz.
- The need for mechanical force requires some kind of linkage between the switch and the operator.





Electro-Mechanical Switches

- Similar to mechanical switches except that the mechanical force is provided by an electro-magnet.
- Electro-magnet drive scheme offers possibility of remote operation.
- Advantages of mechanical contacts are maintained i.e. low loss.
- Most small toggle switches are rated for $\sim 10^5$ mechanical operations and 10^6 electrical operations but it depends on the application. A particular kilovac[3] carrying 500 A at 600 V has a *rated* lifetime is about 25 switching cycles. Switching no current it is rated fro 10^6 cycles.

Note that in both theses switch types the switch contacts are usually insulated from the control linkages or electromagnet.

[3] P/N: EV200AAANA see `http://relays.te.com/` or Farnell: 9913971

Review

- 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
- Developed a large signal model of a MOSFET.
- Briefly observed some differences between MOSFET and BJT characteristics.
- Discussed an ideal switch
- Considered the non-idealities of a switch
- Discussed the properties of two classes of 'switch': Mechanical and Electro-Mechanical.