EEE225: Analogue and Digital Electronics

Lecture I

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This Lecture

Aims & Objectives

To continue our description of the operation of analogue circuits.

These lectures cover three topics,

1. Introduction to some common analogue building blocks
2. Frequency dependence in operational amplifier circuits
3. Introduction to electronic noise in circuits

Approximately 4-5 lectures on each topic.

Many things not included: (C)MOS, second & higher order circuits, translinear circuits, oscillators, full discussion of feedback, SFDs, current mode circuits, practical considerations (board or IC layout) etc. etc.

How is this different from the other parts of EEE225?

Neil Powell's part of the course develops a description of digital building blocks and design techniques.

John David's part of the course continues the description of semiconductor devices.

In this part of the course the objective is

to broaden our understanding of how to make electronic devices work in circuits especially in integrated circuits.

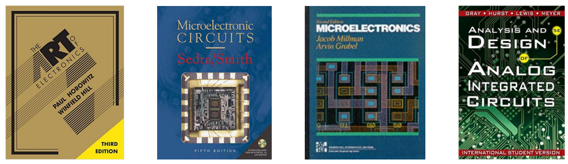
Can I use what I know about electron device operation and circuit design to analyze and design ICs and discrete circuits.

What to expect...

- Slides
- Handouts in lectures
- Handouts available on-line
- Videos of the lectures available on-line
- Biscuits (sometimes)
- Problem sheets & classes, Wednesday 1200 – 1300
- Going to the Library...
- Still need Help? Email Me.

I'm assuming familiarity with the content of EEE117 and EEE118 and mathmatics modules. If you've not seen EEE118 or need a refresher look for the videos on YouTube `https://goo.gl/FK5Ded`.

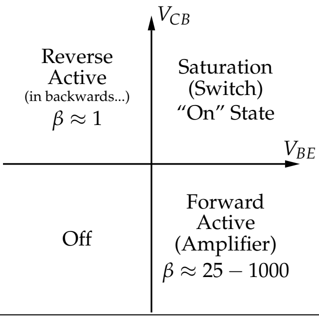
Books



- Horowitz, P. and Hill, W., "The Art of Electronics", Cambridge University Press, 3rd ed., 2015.
- Sedra, A. S., and Smith, K. C., "Microelectronics", Oxford University Press, 5th ed., 2006.
- Millman, J., and Grabel, A., "Microelectronics", McGraw-Hill Higher Education, 2nd ed. 1988.
- Grey, P. *et al.*, "Analysis and Design of Analog Integrated Circuits", John Wiley & Sons, 5th ed. 2009.

BJT Modes of Operation

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



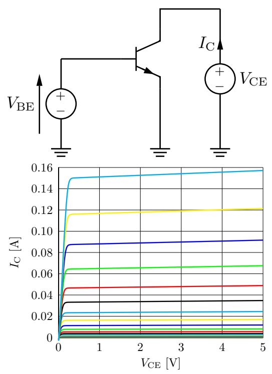
- Forward active is used for amplification B-E forward biased, C-B reverse biased.
- Saturation is a "switch" in the on state B-E and C-B forward biased.
- Off ... All reverse biased
- Reverse active is not used but could make a poor amplifier C-B and B-E junctions exchanged.

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.

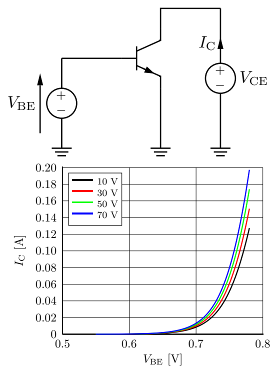
Note: some transistors are designed for amplification (linear) use others are designed for switching use. All transistors can perform both functions but the design of "switching" transistors is optimised for switching applications. Likewise for "amplifier transistors".

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). When 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.

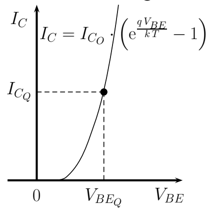
Transfer Characteristics



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 EEE118). 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.

Small Signal Model

In EEE118 small signal models were developed for a diode and for a transistor acting as an amplifier. The fundamental mechanism underpinning "transistor action" is the transconductance - a small change in input voltage elicits a larger change in output current. For small signals it is the slope of the transconductance characteristic that is significant.



$$I_C = I_{C_O}\left(\exp^{\left(\frac{q\,V_{BE}}{k\,T}\right)} - 1\right) \quad (1)$$

the slope is,

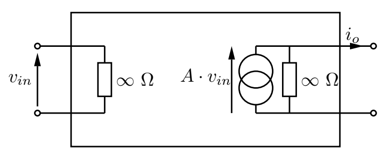
$$\frac{d\,I_C}{d\,V_{BE}} = I_{C_O}\,\frac{q}{k\,T}\,\exp^{\left(\frac{q\,V_{BE}}{k\,T}\right)} \quad (2)$$

For a conducting diode, $\exp^{\left(\frac{q\,V_{BE}}{k\,T}\right)} >> 1$ so,

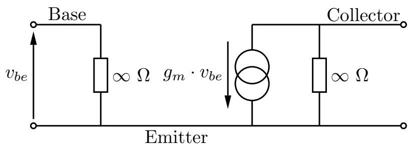
$$I_C = I_{C_O}\left(\exp^{\left(\frac{q\,V_{BE}}{k\,T}\right)} - 1\right) \approx I_C = \left[I_{C_O}\,\exp^{\left(\frac{q\,V_{BE}}{k\,T}\right)}\right] \quad (3)$$

$$\therefore\ \frac{d\,I_C}{d\,V_{BE}} = \frac{q}{k\,T}\cdot\left[I_{C_O}\,\exp^{\left(\frac{q\,V_{BE}}{k\,T}\right)}\right] = \frac{q\,I_C}{k\,T} \quad (4)$$

$g_m = \frac{q\,I_C}{k\,T}$ is a fundamental relationship which holds over more than nine orders of magnitude of I_C. Remember it! Looking back at EEE118 lecture 13, the generalised transconductance amplifier is,



But, the transistor only has three terminals. For the circuits in this course the emitter terminal is common to both the input and output networks. The small signal model of a transistor reduces to,



this is a good low frequency model for JFETs, MOSFETs and Valves. The BJT is special however because there is recombination of carriers in the base region, a base current flows. As a result the resistance looking into the base towards the emitter must be finite (by Ohm's law). The characteristics can be used indirectly to yield the small signal base emitter resistance, r_{be}.

$$r_{be} = \frac{d\,V_{BE}}{d\,I_B} = \frac{d\,I_C}{d\,I_B} \cdot \frac{d\,V_{BE}}{d\,I_C} \quad (5)$$

$$\frac{d\,I_C}{d\,I_B} = \beta = \text{ small signal current gain (see datasheet)} \quad (6)$$

$$\frac{d\,V_{BE}}{d\,I_C} = \frac{1}{g_m} \quad (7)$$

$$\therefore r_{be} = \frac{\beta}{g_m} \quad (8)$$

This is another vital BJT relationship. $d\,V_{BE}$, $d\,I_C$ and $d\,IB$ are the small changes in the bias conditions and may be represented as small signal quantities, v_{be}, i_b and i_c.

$$r_{be} = \frac{\beta}{g_m} = \frac{d\,V_{BE}}{d\,I_B} = \frac{v_{be}}{i_b} \quad (9)$$

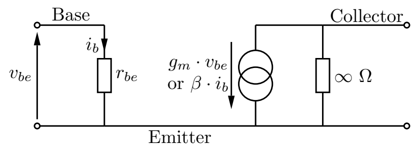
$$r_{be} = \frac{\beta}{g_m} = \frac{v_{be}}{i_b} \quad (10)$$

multiplying through yields,

$$g_m\,v_{be} = \beta\,i_b \quad (11)$$

This means that the BJT can be thought of as a device which accepts an input voltage and outputs a current (transconductance amplifier) or a device that accepts an input current and outputs a current (current amplifier). The choice of how one should think about it depends on the situation. Some circuits are easier to solve if the transistor is thought about in terms of a current amplifier and other circuits are solved more simply by considering the transistor a transconductance device. Only BJTs have the option of two avenues of thought. MOSFETs, JFETS and Valves can only be thought about in terms of transconductance.

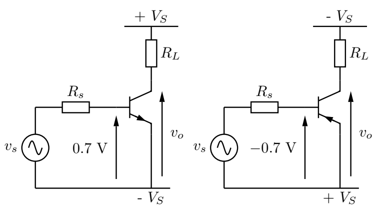
Including the effect of a finite r_{be} in the small signal model yields,



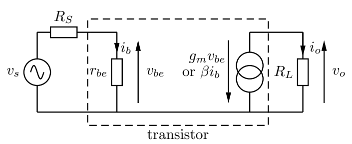
- Usually $\beta \neq h_{FE}$. β is a small signal parameter and h_{FE} is a large signal parameter.
- β is sometimes called h_{fe} (notice the lower case subscripts). h_{FE} and β can be assumed equal at low frequencies
- Other circuit elements can be added to more accurately reflect real device performance e.g. the infinite reistance in parallel with the $g_m \cdot v_{be}$ generator is finite and is responsible for the gentle slope of the output characteristics in the forward active region.

Common Emitter Amplifier

- Large voltage gain.
- Either npn or pnp transistors.
- Both the npn and pnp versions have the same small signal equivalent circuit – next slide.
- The resistors R_S are the Thévenin resistance feeding the base, assume that effects of the biasing circuit are included within R_S.



- R_L represents the total resistance looking from the collector to ground – it is composed of the transistor load resistor, the input resistance of the *next* circuit and the transistor's r_{ce}.



Sum currents at the output,

$$v_o = i_o\,R_L \quad (12)$$

$$= -g_m\,v_{be}\,R_L \quad (13)$$

At the input,

$$v_{be} = v_s \frac{r_{be}}{R_S + r_{be}} \quad (14)$$

Substituting yields,

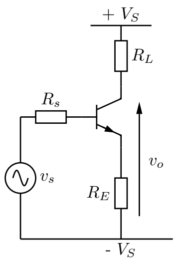
$$\frac{v_o}{v_s} = -g_m\,R_L \frac{r_{be}}{R_S + r_{be}} \quad (15)$$

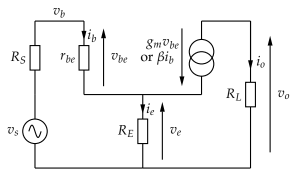
Note:

- The gain is inverting; "–" sign.
- Gain $\propto g_m$ (so large g_ms are attractive).
- Gain $\propto R_L$ (so large R_Ls are attractive).
- Ideally $r_{be} >> R_S$, to avoid attenuation of input.
- resistance looking into input $r_i = r_{be}$.

Common Emitter with Degeneration

- Sometimes CE circuits have a small value of resistance 10s of Ω to low kΩ between the emitter terminal and ground.
- This resistance is called an "emitter degeneration" resistance.
- The small signal equivalent circuit adjusted to add a resistor R_E between the emitter node and ground.
- This complicates the small signal analysis, especially if r_{ce} is included in the analysis, because R_E couples the output circuit to the input circuit.
- We will assume that r_{ce} has a negligible effect.





Summing currents at the emitter,

$$i_e = i_b + g_m\, v_{be} \quad (16)$$

or
$$\frac{v_e}{R_E} = \frac{v_{be}}{r_{be}} + g_m\, v_{be} \quad (17)$$

$$v_e = v_{be}\, R_E \left(\frac{1}{r_{be}} + g_m\right) \approx v_{be}\, R_E\, g_m \quad (18)$$

because $1/r_{be} = g_m/\beta$ and $\beta >> 1$.

For the input loop,

$$v_s = i_b\, R_s + v_{be} + v_e \quad (19)$$

$i_b = v_{be}/r_{be}$ and using (18),

$$v_s = v_{be} \left(1 + \frac{R_S}{r_{be}} + g_m\, R_E\right) \quad (20)$$

Looking at the collector circuit, $v_o = i_o\, R_L$ and $i_o = -g_m\, v_{be}$ and using (20),

$$v_o = -g_m\, R_L\, v_{be}$$
$$= -\frac{g_m\, R_L\, v_s}{\left(1 + \frac{R_S}{r_{be}} + g_m\, R_E\right)} \quad (21)$$

isolating for v_o/v_s,

$$\frac{v_o}{v_s} = \frac{-g_m\, R_L}{\left(1 + \frac{R_S}{r_{be}} + g_m\, R_E\right)} \quad (22)$$
$$= -\frac{R_L}{r_e + \frac{R_S}{\beta} + R_E} \quad (23)$$

where $r_e = 1/g_m$

The important conclusions are:

1. The gain is inverting.
2. The gain is proportional to R_L.
3. R_E reduces the gain.
4. If $R_E >> \frac{1}{g_m}$ and $R_E >> \frac{R_S}{\beta}$ then gain $-\frac{R_L}{R_E}$

The addition of R_E also affects the input resistance of the amplifier. Use node or loop analysis to find v_b/i_b... see handout page 4.

Review

- Stated the Aims and Objectives of the course
  Continue discussion of electronic devices (diodes, transistors *et al.* in circuits)
- Reviewed operating region of transistors. Forward active, saturation, reverse active and off.
- Reviewed output and transfer characteristics as an explanation of transistor operation. Relationship between V_{CE}, I_C and V_{BE}, which describes transistor opperation.
- Re-familliarised ourselves with the idea of small signal models especially in relation to a BJT.
- Reviewed and expanded description of the one transistor common emitter amplifier from EEE118. With and without "degeneration" (negative feedback).