VCE Physics – Electronics and Photonics

The n-p-n transistor voltage amplifier

1. Introduction

There is a significant change in the content of the electronics component of the VCE Physics, Unit 3, *Electronics & Photonics*, and this concerns the dropping of the operational amplifier and the inclusion of (amongst other items) the n-p-n transistor in a voltage amplifier circuit. While this is a relatively small part of the overall Unit 3, it is not an easy topic. These notes are provided as additional support and resource material to assist students and their teachers as they study this transistor topic.

It is assumed that you are reasonably familiar with the diode. If a diode is forward biased the p-type material (the anode) is at a higher potential (voltage) than the n-type material (the cathode), and in this situation a significant current can flow through the diode. If the p-n junction is reverse biased then effectively no current flows. It is also assumed that you are fairly confident in using Kirchhoff's voltage and current laws and Ohm's law, and understand the way resistors and capacitors act in a circuit.

2. Definitions

The n-p-n transistor could be viewed as two p-n diodes joined back-to-back with a common anode (p-type semiconductor material) region as the base of the transistor, as depicted in Figure 1. This is not really valid, but for the base, B, and emitter, E, regions (the lower part of the transistor as it is normally drawn) this diode-like behaviour may be assumed to a fair approximation. In this way, when forward biased, the base-emitter, B-E, junction will have a voltage across it approximating the silicon diode cut-in voltage, V_γ , so $V_{BE} = V_\gamma = 0.7$ V.

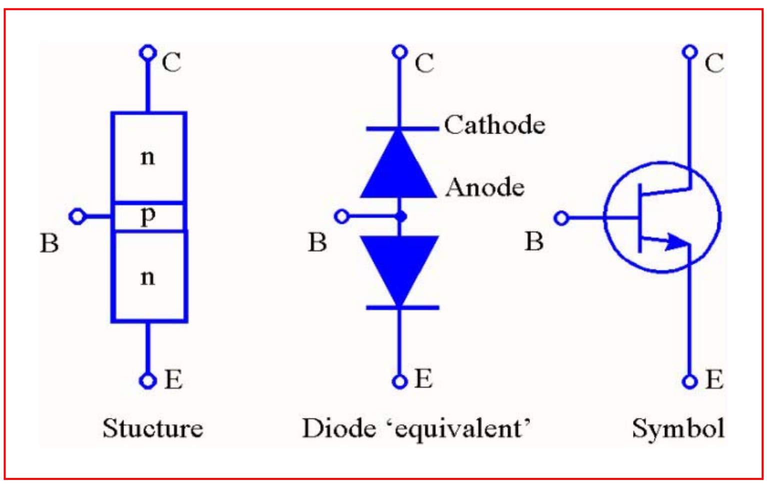

Figure 1: The n-p-n transistor structure and symbol.

Note that in Figure 1 for this bi-polar junction transistor, BJT, the arrow on the emitter part of the symbol indicates the direction of conventional current flow when the B-E junction is forward biased; thus coinciding with the arrow head direction on the normal diode symbol.

To construct and analyse a voltage amplifier based around an n-p-n BJT is not particularly straightforward so a few basic concepts and definitions are in order.

- The intrinsic behaviour of a BJT is that of a current amplifier where, when correctly biased, the collector current, I_C, is an amplified version of the base current, I_B. The current amplification factor is represented by β (sometimes also denoted by h_{fe}) such that $I_C = \beta I_B$, with β typically in the range 50 to 200 depending on the transistor make/model. We shall choose β = 100 for the purposes of this discussion (β is always positive).

- Voltage amplification arises by taking account of the fact that a current, I, passing through a resistor of resistance R (the collector resistor, R_C, is pertinent here) provides a voltage across the resistor of V = IR (Ohm's law).

- The BJT transistor amplifier required in the VCE Physics Unit 3 is in the so-called common emitter (CE) configuration where the input voltage, V_{IN}, is between the base and the emitter side, and the output voltage, V_{OUT}, is between the collector and the emitter side. The emitter side of the transistor is thus common to both voltages.

- The n-p-n BJT CE amplifier in normal operation has the base-emitter, B-E, junction forward biased and the collector-base, C-B, junction reverse biased.

- The n-p-n BJT CE voltage amplifier is an inverting amplifier where the time–varying, AC, output voltage, v_{OUT}, is 180° out of phase (or inverted) with respect to the time-varying AC input voltage, v_{IN}. From this we can write that $v_{OUT} = -A_V \, v_{IN}$, where A_V is the gain (amplification magnitude) of the amplifier; the subscript V simply indicate that we are talking about voltage amplification.

- It is possible to have two types of BJT CE voltage amplifiers; one based on an n-p-n transistor and the other based on a p-n-p transistor. The n-p-n transistor is preferred here at an introductory level as all the important DC currents and DC voltages in the analysis end up being sensibly defined as positive quantities (they are negative in the p-n-n case).

- The BJT CE voltage amplifier will only amplify time-varying input voltage signals above a certain frequency; they are not able to amplify DC voltages like an operational amplifier, and because of this we need to distinguish carefully between the AC and DC components of all relevant currents and voltages. This tends to be a troublesome issue for many, but we get around this here by using the following convention: upper case I and V for DC (time invariant, constant) currents and voltages, and lower case i and v for AC (time-varying, and in general we shall only consider sinusoidal) currents and voltages. To these symbols we shall add subscripts that describe the point at which the current or voltage exists (as we have already done above in some instances).

- There are a few simple texts that discuss this type of amplifier and many start with the specific transistor current-voltage characteristics, but this approach is expressly denied in the VCE Physics Study Design. These texts then often move on to measuring the transistor characteristics using two DC batteries or power supplies, and then on to practical circuits. The notes here treat a real n-p-n BJT CE voltage amplifier, commencing with a realistic circuit and analyse this using simple models of diodes, resistors and capacitors that you should be familiar with.

3. Amplifier circuit

We start with the complete amplifier circuit shown in Figure 2, where all the relevant DC currents and are indicated using a sensible convention as to direction and polarity. So all currents, I_B, I_E and I_C, go in a direction towards the common/ground connection. All voltages are measured with respect to this common/ground line at the foot of the circuit diagram.

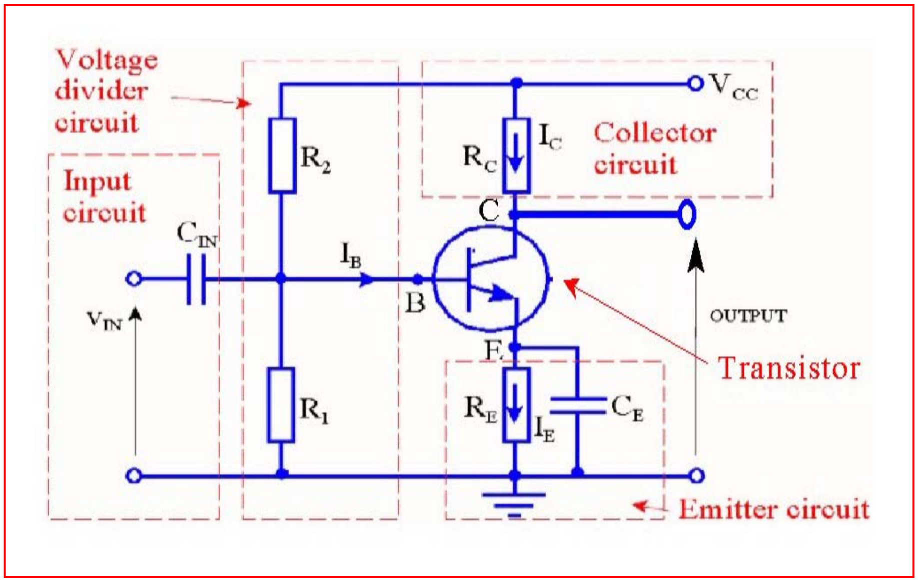

Figure 2: The basic n-p-n CE voltage amplifier circuit.

Typical component values are as follows, and the circuit will work if you use these: R_1 = 5 kΩ, R_2 = 25 kΩ, R_C = 4 kΩ, R_E = 1 kΩ, C_{IN} = 10 μF, C_E = 47 μF, while the DC power supply is V_{CC} = 20 V.

We will now analyse this circuit in as simple a way as possible, section-by-section, using only the model parameters defined along with Kirchhoff's laws and Ohm's law. In doing this we will see how the AC voltage input, v_{IN}, is amplified to the AC voltage output, v_{OUT}. However, to do this we will analyse the circuit in two stages; first by only considering the DC currents and voltages to set up the conditions for amplification, then second, by considering just the AC current and voltage time-varying fluctuations. We shall look at each circuit area indicated in Figure 1

4. The input circuit

This section comprises only the AC input voltage, v_{IN}, and the input capacitor, C_{IN} (see Figure 2). The rest of the circuit can be represented by a single resistor we will denote by R_B (you will have to take my word for this!) with $R_B \approx 1$ kΩ.

You know that a capacitor will not pass DC current (it is an open circuit), but may pass AC current depending on the current frequency and the time constant, τ, of the resistor-capacitor (here R_B and C_{IN}) combination. The time constant is given by $\tau = R_B C_{IN}$. The circuit design has to ensure that C_{IN} is chosen so that the time constant is comparable to the lowest period, T, of a sinusoidal input voltage signal that you wish to amplify. So, for example, if you wish to amplify voltages with frequencies above 500 Hz (so T < 2 ms) we use the condition $\tau = 5 R_B C_{IN} = 0.01$ s, and with R_B = 1 kΩ we end up with C_{IN} = 10 μF as suggested in the previous section. The factor of 5 in the time constant expression is to allows the full smoothing effect of the R-C combination.

The capacitor, C_{IN}, has another very important function and that is to block any DC current component from v_{IN} from disturbing the DC set-up of the overall circuit. The only change to the base current we want is from the AC input signal. This current is given by $i_B = v_{IN}/R_B$.

5. Voltage divider circuit

This part of the circuit comprises the two resistors R_1 and R_2 and the DC power supply, so we are only interested in the DC currents and voltages at this stage. The purpose of this voltage divider is to set the DC voltage of the base, B, of the transistor to ensure the B-E junction is forward biased. If the transistor were to be removed completely then $V_B = (V_{CC} R_1)/(R_1 + R_2)$.

In a practical amplifier circuit this expression for V_B is not correct as the transistor 'loads' the divider circuit, but the result is not too far out, so we would calculate the base voltage to be approximately $V_B = (20 \times 5)/(5 + 25) = 3.3$ V. This DC voltage is adequate to ensure the B-E junction is forward biased and that $V_{BE} = 0.7$ V (approximately). We have already said that the transistor can be thought to present a resistance of around $R_B = 1$ kΩ so there now will be a DC and an AC component of the base current, I_B and i_B respectively. The effect of the R_E-C_E parallel combination will be covered in a moment, but we can now calculate the emitter DC voltage as $V_E = 3.3 - 0.7 = 2.6$ V (or thereabouts). Given all this, you can now calculate the DC emitter current as $I_E = V_E/R_E = 2.6/1000$ A $= 2.6$ mA. This emitter DC current, I_E, exists only through the resistor R_E, not through C_E (see section 7).

6. The collector circuit

Again, the collector side of the circuit has to be analysed in two parts; first with the DC currents and voltages, and then second with the AC currents and voltages. Let's look at the DC situation first. This part of the circuit comprises the DC power supply, $V_{CC} = 20$ V, and the collector resistor, R_C. At the start of this discussion we mentioned that the collector current is simply β times the base current, $I_C = \beta I_B$, so the DC voltage drop across R_C is just $I_C R_C = \beta I_B R_C$. At this point we do not know what I_B is so we will just assume some value for this voltage across the collector resistor (that I know is realistic!).

Say the voltage across the collector resistor is 8 V, As V_{CC} is known to be 20 V this means that the DC voltage at the collector is $V_C = 20 - 8 = 12$ V by simple application of Kirchhoff's voltage law. The output of the transistor amplifier is always taken between the collector and ground, so the DC output voltage is $V_{OUT} = V_C = 12$ V.

Now to the AC analysis. As there is an AC base current component, i_B, there is an AC collector current $i_C = \beta\, i_B = 100\, i_B$. From this we can calculate the AC output voltage, and this always causes problems! As far as AC currents are concerned all capacitors and the DC power supply can be taken to be short circuits (zero resistance). This means that we can re-draw the actual circuit as an AC equivalent circuit with which to analyse the AC signals. This AC equivalent circuit is shown in Figure 3 and it takes a while to be comfortable with this 'new' circuit. But you will now notice that R_E is removed as it is shorted by C_E (think of parallel resistances), and that R_1 and R_2 are gone as they play no role in the AC analysis. Also removed is the DC power supply; it acts as a short to common/ground for the AC current as stated above.

We can now see that the output AC voltage is identical to the voltage across R_C (but with the opposite polarity) so $v_{OUT} = -(I_C R_C) = -(\beta I_B R_C)$. As we can write $i_B = v_{IN}/R_B$ we have the final expression we require for the voltage amplification: $v_{OUT}/v_{IN} = -(\beta R_C/R_B)$. Using the approximate values for $\beta = 100$ and $R_B = 1$ kΩ, then we arrive at $A_V = (100/1000) R_C = 0.1 R_C$ with R_C in ohms. Thus we have a voltage amplifier, in this example, with a voltage gain of $A_V = 400$ (but an inverting amplifier, remember).

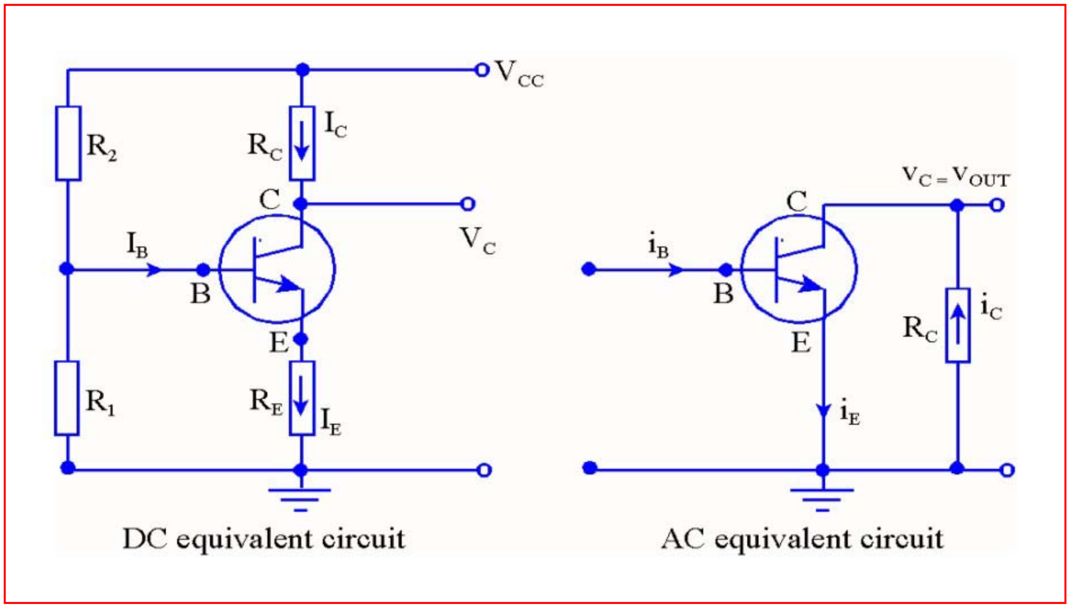

Figure 3: The DC and AC equivalent amplifier circuits.

7. Emitter circuit

For completeness we have to look at the emitter circuit that really only comprises the parallel combination of R_E and C_E. The emitter resistor is required to ensure that the base-emitter voltage in indeed positive (derived from the R_1 and R_2 voltage divider network) and that the B-E junction is forward biased.

Using Kirchhoff's current law at the transistor (thought of as a single point, or node) you have $I_C + I_B = I_E$. But we know that I_B is only about 0.01 of I_C, so we can almost completely neglect I_B in the above equation. The means that $I_E \approx I_C$ and a little arithmetic yields, from the values we started with, $I_E = I_C = 2.6$ mA, so $I_B = 26$ µA.

As in practice there can be a significant AC collector current, i_C, we have to avoid the emitter voltage changing with i_E. With C_E in parallel with R_E, the emitter voltage with respect to common/ground is fixed at $V_E = I_E R_E = 2.6$ V as i_E is directed through C_E, not R_E. Although outside the VCE syllabus it can be shown that for frequencies above 500 Hz, the parallel R_E-C_E combination has a total 'resistance' to AC currents (but not DC currents) of less than 10 Ω which justifies the short depicted in the AC equivalent circuit from emitter to the common/ground line.

8. Sign of the voltage amplification

We will go through the numbers once more for the complete BJT CE n-p-n transistor amplifier of Figure 2 starting with $v_{IN} = 0$ V and using the typical values we defined earlier. Only DC currents and voltage exist and we have calculated these previously as $I_B = 26$ µA and $I_C = I_E = 2.6$ A.

The DC voltage across the 4 kΩ collector resistance is actually $4000 \times 2.6 \times 0.001 = 10.4$ V. This produces a DC collector voltage of $V_C = 20 - 10.4 = 9.6$ V. If we now (somehow) increase the base current we also increase the collector current, but decrease the output collector voltage. A worked example will suffice.

Say we increase the base current from 26 μA to 30 μA, then the voltage across the collector resistor increases from 10.4 V to 12 V. This means the output voltage at the collector decreases from 9.6 V to 8 V. When the amplifier is set up the change in base current, of course, arises from a voltage change in v_{IN}. But when v_{IN} increases, v_{OUT} decreases, and vice-versa; you have an inverting voltage amplifier.

9. Saturation and cut-off

When the n-p-n BJT amplifier circuit of Figure 2 is first wired up you short the input terminals (v_{IN} = 0) and only work on setting up the DC conditions. While we have quoted some typical values above for circuit components, transistors will vary slightly in their characteristics. The way to handle this is to wire the circuit up and then adjust R_1 so that $V_C = ½ V_{CC}$, so about 10 V in this case. This does not have to be very accurate, so between 8 and 12 volts would be fine (½ V_{CC} to within about 20%). This arrangement allows the output voltage at the collector to 'swing' up and down around this initial DC value approximately equally in both directions by the maximum amount.

With the input signal now connected, as v_{IN} increases during the start of a cycle a magnified version will appear at the output but as a decreasing, inverted, voltage signal. The lowest the output voltage can swing down is to the common/ground potential, 0 V, and so eventually if v_{IN} is instantaneously large enough (in a positive sense) the output will be clipped at 0 V. This is referred to a cut-off and gives rise to output signal distortion. On the other hand, if v_{IN} decreases too much then v_{OUT} rises, but is eventually clipped at the maximum positive excursion of the collector voltage which is V_{CC}. This distortion is referred to as saturation.

10. Measuring currents and voltages

If you do wire a circuit like that of Figure 2 up and adjust things so that $V_C = ½ V_{CC}$ the amplifier will almost certainly work satisfactorily. The DC power will probably be provided by a DC power supply (almost certainly not a battery). A DC supply of 20 V is fine (anything between 15 V and 30 V is OK) but if the power supply is earthed you have to be very careful when using an oscilloscope to measure voltages in the circuit.

In this case the earth of the oscilloscope and the earth of the power supply must be common and thus must form the common/ground line depicted in Figure 2. Failure to do this may damage components and will short out some of the circuit!

If you use a cathode ay oscilloscope, CRO, to measure voltages, please realise that all the voltages you measure will be with respect to the common/earth line at earth potential; 0 V. So you can measure the DC voltages V_E and V_B and V_C, but if you want to 'measure' the voltage across the transistor from emitter to collector you will have to calculate this from $V_{CE} = V_C – V_B$; you must not put the CRO across E and C (that is, you must not pull out the CRO earth lead and connect it to the point E).

The input and output time-varying voltages can be measured by having the 'active' CRO lead at B and then C respectively, and having the AC-DC switch on the CRO set to AC to remove the DC voltages from the CRO display.

If you want to determine the current in any resistor, use the CRO to measure, or calculate, the voltage across the resistor (be careful about earths, though!) and divide the voltage measured by the resistance. So to work out the DC current in the collector resistor, first measure V_C and then calculate the voltage across the resistor as $V_{CC} – V_C$, and then divide by R_C.

If you use a non-earthed multi-meter (analog or digital) you do not have all these earth problems to worry about. You can measure a voltage by connecting the meter leads directly across the component of interest. But again, to work out a current, AC or DC, measure the AC or DC voltage across the component and then divide by the known value of the resistance. Do not 'break' the circuit and insert the meter and use the AC/DC current function, as many multi-meters have significant resistance in current mode and this affects the circuit that you are attempting to analyse. Meters used in voltage mode have very large resistances and when placed across components (in parallel with them) do not materially affect the circuit.

11. Summary

Transistor amplifiers are not easy to analyse, but by making some simple assumptions and using the component ideas consistent with other parts of the VCE Physics subject and Kirchhoff's laws and Ohm's law it is not too difficult. The main things to keep in mind are the model parameters of a silicon diode cut-in voltage of 0.7 V for the B-E junction and a current gain of $\beta = 100$ (or whatever the transistor data sheet indicates).

Again, the typical component values listed at the start of this document and a cheap n-p-n BJT transistor like the 2N5368 available form Dick Smiths or similar for about a dollar will give you a working voltage amplifier with a gain of 400 or thereabouts.

12. References

http://www.microelectr.com.hk/datasheet-list/Transistor/2N%20PN/
(May 2005, and click on the link 2N5368)

P. Horowitz and W. Hill, *The Art of Electronics*, Cambridge University Press: Cambridge, 1st edition, 1980.

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