THE SEMICONDUCTOR

PART 4. SIMPLE CIRCUIT DESIGN

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LAST MONTH we proved for ourselves that there is no difficulty about achieving a voltage gain with a transistor. Now look at Fig. 4.1.

One thing you should notice about the circuit is that the emitter is connected to ground and is common to both base and collector circuits. Because of this a transistor connected in this way is said to be connected in the common or grounded emitter configuration. If we accept the analogy between emitter and cathode, this corresponds to a normal triode amplifier which could be called a grounded cathode triode.

If this was a valve amplifier, we could calculate the gain of the stage provided we knew the amplification factor and anode characteristic of the valve. As the input impedance of a valve approaches infinity it throws little or no load on the signal circuit if it is properly biased, and no current flows in the grid-cathode circuit.

But a transistor depends for its operation not on a voltage applied to the input but on the current flowing through it. As a voltage is actually applied, the input current will depend on the input impedance. Consequently, this parameter has an important bearing on stage gain and must be taken into consideration.

CHARACTERISTICS

So, out of the bewildering array of parameters to be found on a complete transistor data sheet, this gives us three characteristics to consider when we calculate gain. These are the current gain (known as β or α')

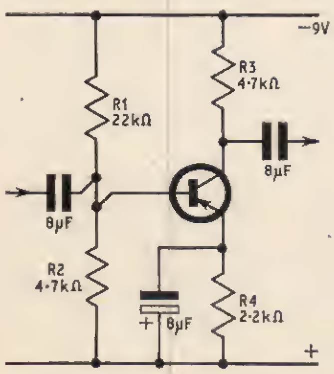

Fig. 4.1. Grounded emitter, or common emitter, connection

the input impedance, Z_{in}, and the output impedance, Z_{out}. For an a.f. transistor the listed data are usually measured at 1,000 c/s with the device working well within its normal range at a temperature of 25°C ambient. They are called the "small-signal" characteristics and should be used for normal calculations. A full transistor data sheet will also contain "large-signal" or d.c. characteristics, maximum ratings, cut-off frequency, average or design centre characteristics and quite a lot more information including a few set of curves, but we need only consider the small-signal characteristics.

COMMON EMITTER

Now let us see how we can use them. The output impedance for a transistor in the common emitter configuration is usually well above 10,000 ohms, often in the region of a megohm. This is useful because the load, R_L is, so far as the signal is concerned, connected in parallel across the output from the collector. As the load is usually much smaller than the output impedance its connection in parallel shunts this and we can say

$$Z_{out} = R_L$$

The output signal voltage will of course be given by

$$v_{out} = I_c R_L$$

where I_c is the collector signal current.

The signal input v_{in} will produce a base current i_b.

$$i_b = \frac{v_{in}}{Z_{in}}$$

If we write this the other way round we get:

$$v_{in} = i_b Z_{in}$$

So voltage gain,

$$\frac{v_{out}}{v_{in}} = \frac{i_c R_L}{i_b Z_{in}}$$

But i_c/i_b (the ratio of output current to input current) is of course β, the current gain of the transistor. So we get

$$\text{Gain} = \beta \frac{R_L}{Z_{in}}$$

Not very complicated really, is it? This is an approximation of course, since it assumes that the output impedance of the transistor itself is so high compared with the load, that it need not be taken into consideration. But it gives the voltage gain within 20 per cent which, as many of the components in the average circuit have a 20 per cent tolerance, is as much as we can expect if we base our calculations on face values.

You may remember that all transistors made by the same process are very much alike in beta and input impedance. The average low-power germanium transistor in use today has a beta of about 50 and an input impedance of between 700 and 2,000 ohms, giving an average of 1,300 ohms.

The listed characteristics of an OC71 are: beta = 47; Z_{in} in common emitter configuration = 800 ohms; Z_{out} = 12,500 ohms.

You should have noticed that the values of the coupling capacitors are very much higher than those in a valve circuit doing the same job. This is because a transistor operates as a low impedance device, hence the value of the capacitor needs to be higher to pass low frequency currents.

STABILISATION

The resistor in the emitter circuit is very important. It is intended to give an automatic bias in the same way as it would if it were in the cathode of a valve, but it serves another important purpose, i.e., limiting the current through the transistors. The number of current carriers, holes or electrons, in a semiconductor increases with temperature because heat tends to disturb the stability of the electron orbits. The effect of heating the transistor is to set free extra current carriers, so increasing the current and raising the temperature. This sets free yet more carriers and creates a snowball process which causes the current to grow so rapidly that the transistor can be destroyed in a moment.

All this current must flow through the emitter resistance, producing a voltage drop which increases with current. This drop is of course a bias tending to cut off the transistor. So the current is held stable and the transistor does not tend to run away with itself. The resistor by itself would produce negative feedback, so it is by-passed by a large capacitor which takes the signal straight to ground without interfering with the d.c. action of the resistor.

How can we make provision for an input bias current? We could do this by connecting the base via a suitable resistance to the collector supply, but usually a potential divider as shown in Fig. 4.1 is used. This helps to hold the base voltage at a constant d.c. level, and so introduces a further measure of stability. The calculation of these values is complicated, but those given will answer for almost any low power a.f. transistor. If you are making up circuits there is no harm in experimenting, provided that you start with a low bias current and watch the emitter current carefully. Once you get used to them, transistors lend themsleves to experiment even more readily than valves.

GROUNDED BASE

The common emitter configuration is not the only way in which a transistor can be used. In a grounded grid triode circuit, the grid can be connected to ground and the signal applied to the cathode. There seems no reason why the same kind of thing could not be done with a transistor. Fig. 4.2 is the basic circuit of a grounded-base amplifier.

As you can see, it corresponds closely to the grounded grid triode so far as the connections are concerned. The transistor though needs some slightly different mathematics.

To start with, the beta current gain no longer applies. We have seen that only one in fifty of the current carriers from the emitter flow into the base circuit. The remainder cross this thin layer to the collector giving us our β of about fifty. But in the grounded-base configuration all the transistor current must flow in the base circuit instead of in the emitter circuit. And this current must be shared by collector and emitter. If you look carefully at the circuit diagram you will see that this is the only way in which current can flow.

As the current carrying capacities of base-emitter and base-collector circuits are the same, we have only changed the connections, not the transistor. About one carrier in every fifty will flow in the emitter circuit and the rest will go to the collector. So if the base current was, say, 1mA, the collector current could be only about 0·98mA. The ratio of the two currents is called the alpha (α) or current gain of the transistor. Since the current gain is really a small loss, it appears that this connection will not give a voltage amplification.

But if we apply the same reasoning to this as we did to the common-emitter circuit we get:

$$\frac{v_{out}}{v_{in}} = \frac{i_{out} R_L}{i_{in} Z_{in}}$$

But the ratio of input to output is now the alpha current gain,

$$\text{Gain} = \frac{\alpha R_L}{Z_{in}}$$

The input impedance of a transistor in the common-base configuration is much lower than that of the common emitter, but the output impedance is higher. This is logical, since the emitter, into which the signal is fed in a common base amplifier, carries the entire transistor current and must offer a lower impedance than the base. The collector, on the other hand, is separated from the emitter by the grounded base so that its potential can have little effect on transistor current. So the approximation $Z_{out} = R_L$ becomes much more accurate.

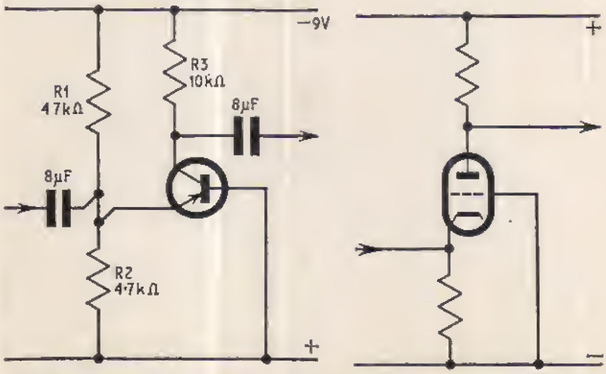

Fig. 4.2. Grounded base transistor and grounded grid triode

On this basis, assuming an input impedance of say 50 ohms, load of 4,700 ohms and α of 0·98, we can calculate the gain of a common-base amplifier.

$$\text{Gain} = \alpha\frac{R_L}{Z_{in}} = \frac{0{\cdot}98 \times 4{,}700}{50} = 90$$

This, for a small load, is a high gain, but the high output impedance of the common-base configuration makes the use of a higher load convenient. Also, we can get a very close approximation by calling alpha unity. So a 10,000 ohm load would give a voltage gain of 200. The secret of course is the ratio of output to input impedance. The output current is very nearly as great as the input current, and so must produce a much greater voltage drop across the high collector load.

The common-base circuit has a more stable gain than the common emitter and is less likely to run away with itself. But its low input impedance is a serious drawback. Imagine connecting 50 ohms across a sharply tuned circuit! So for normal purposes the common-emitter amplifier is more popular.

EMITTER FOLLOWER

The final transistor configuration is the grounded collector circuit, which is sometimes called an emitter follower. It is drawn in Fig. 4.3 with its valve analogy, the cathode follower. Its characteristics differ from those of the grounded emitter and grounded base circuits. The collector, although it is taken to the collector supply line, is of course grounded so far as the a.c. signal is concerned.

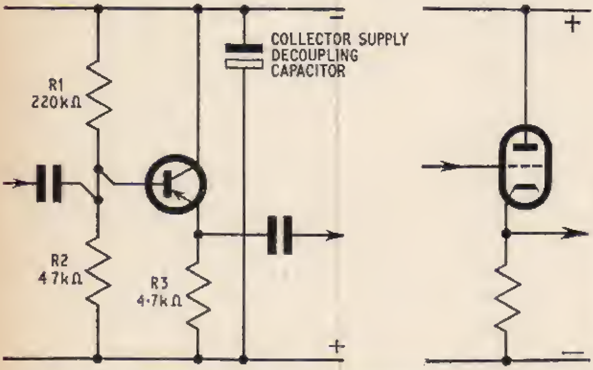

Fig. 4.3. Grounded collector transistor (emitter follower); and grounded anode triode (cathode follower)

As the signal is applied to the collector, which has the highest impedance of all the transistor segments, the input impedance must be high. Conversely, the output is taken from the lowest impedance, the emitter, so the output impedance must be low. The common collector circuit gives a large current gain but its voltage gain is slightly less than unity but, unlike the cathode follower, it does not invert the phase of the signal.

All of this has just scratched the edges of a complex subject, but it is a start. However, readers who have been following this short series will probably have more confidence in making an amplifier. If you made up the diode receiver described in the second article of this series, there is no reason why you should not add a stage of a.f. amplification, using the headphones as collector load.

With a little practice you will find that transistors are just as easy to experiment with as valves. ★