current and this is known as the AVALANCHE effect. These breakdown effects are exploited in VOLTAGE REGULATOR DIODES (sometimes called zener diodes). These diodes make use of the fact that once the breakdown voltage has been reached the characteristic is almost parallel to the I axis and thus they can be used in voltage regulated power supplies. The voltage at which breakdown occurs is determined by impurity levels and other physical factors.

Diode Applications

Like the thermionic diode, the semiconductor device is commonly used for rectification, modulation and demodulation. It is also used a great deal in logic circuits. In the rectifier circuit, fig. 16(a), the diode passes current only during positive half cycles of the input so that the load voltage is a half-wave rectified signal. This can be smoothed to obtain a steady direct voltage. Other possibilities are full-wave rectifier and voltage doubler circuits.

The function of the demodulator, fig. 16(b), is to abstract the wanted audio frequency signal content from the unwanted radio frequency carrier. The diode permits only the positive going half-cycles of the carrier to reach the load. The average value of the load voltage is the wanted audio frequency signal, the unwanted radio frequency being bypassed through the capacitor whose reactance is chosen to be low at the radio frequency.

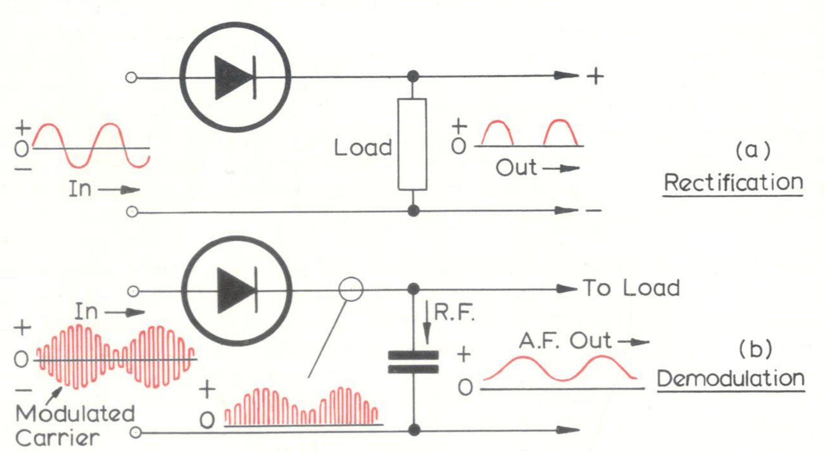

Fig. 16 Diode Applications

SECTION 3 — THE TRANSISTOR

Introduction

The conventional transistor is a two-junction, three-layer semiconductor device capable of current, voltage and power amplification. Clearly there are two possible configurations: p-n-p and n-p-n, fig. 17. There are three electrodes: the BASE (b), EMITTER (e) and COLLECTOR (c). Note that the arrow in the symbol for the p-n-p device points towards the base whereas in the n-p-n transistor it points away from it. The arrow indicates the direction in which 'conventional' current would normally flow in the device, electron flow is in the opposite direction to the arrows.

Transistor Action

Figures 18 and 19 illustrate current amplification in an n-p-n silicon transistor The base-emitter junction forms a diode which is forward biased by the 600mV supply (remember that for forward bias the p-type is connected to the positive terminal of the supply). On the other hand the collector is 5.4 volts (i.e. 6-0.6) positive with respect to the base (taking the emitter as datum =0 volts and ignoring the meter resistances). Hence the base-collector junction is reverse biased.

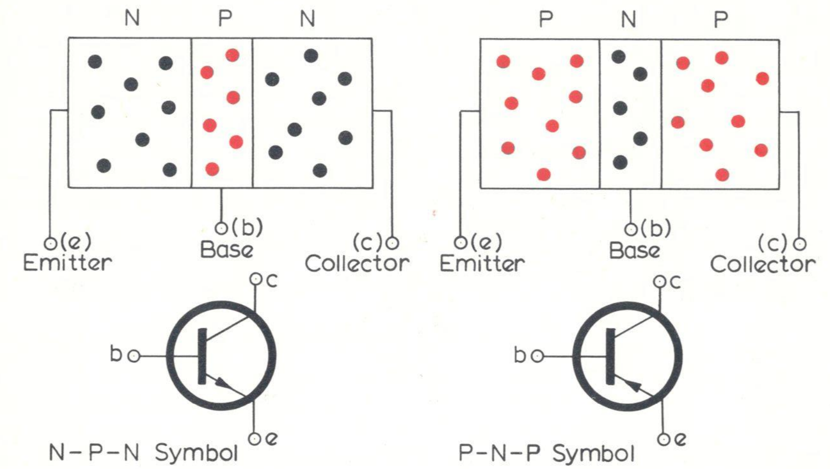

Fig. 17 N-P-N and P-N-P Transistors

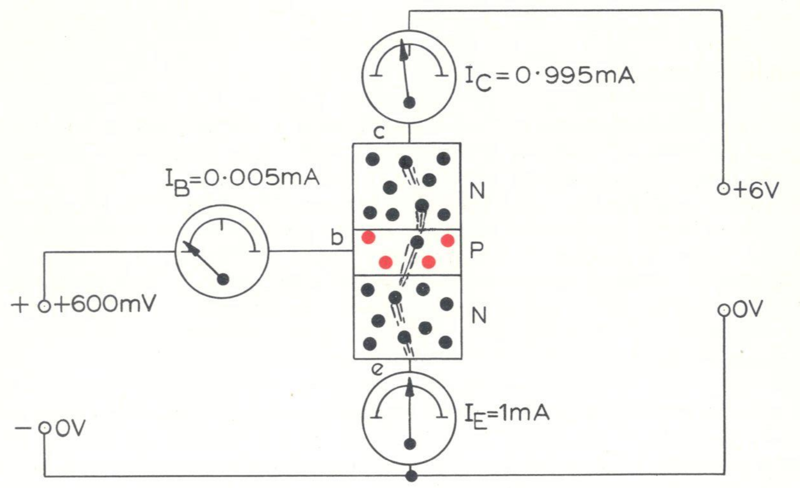

Fig. 18 N-P-N Transistor Action (i)

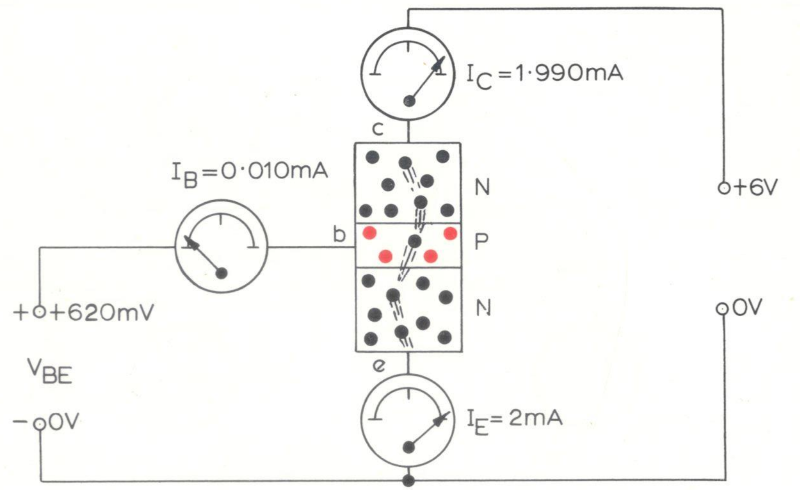

Fig. 19 N-P-N Transistor Action (ii)

A large number of electrons enters the emitter n-region under the influence of the forward biased base-emitter junction. The base region is designed to be very thin and the attractive force due to the positive collector potential is very strong, and so most of the electrons from the emitter pass straight through the base into the collector. Of course the occasional electron meets a hole in the base and combines with it and this gives rise to a small base current. For a typical silicon transistor with an emitter current (I_E) of 1mA, the collector current (I_C) might be 0.995mA and the base current (I_B) only 0.005mA (1 - 0.995).

Now suppose the base voltage is increased sufficiently to cause the emitter current to be doubled to 2mA, fig. 19. Referring back to the diode characteristic in fig. 15, it will be remembered that a large increase in forward current can be achieved by just a few millivolts change in forward voltage. Thus, in a typical case, an increase in base voltage from about 600mV to 620mV would produce the change in emitter current from 1mA to 2mA. The collector current doubles to 1.990mA and the base current to 0.010mA since now there are twice as many electrons (per second) entering the emitter, twice as many passing through to the collector and twice as many electron-hole combinations in the base.

Current Amplification

Comparing figures 18 and 19 it can be seen that a change of 0.005mA in I_B caused a change of 0.995mA in I_C, a current gain or amplification of $\frac{0.995 \text{ (change in } I_C)}{0.005 \text{ (change in } I_B)} \simeq 200$. In practice approximately the same figure is obtained by taking the ratio of *static* values of I_B and I_C. The ratio is defined by the British Standards Institution as the STATIC VALUE OF THE SHORT-CIRCUIT FORWARD CURRENT TRANSFER RATIO (symbol h_{FE}, h_{FB} or h_{FC}, see section 5).* This is the ratio between the continuous output current, in our case I_C, and the continuous input current, in our case I_B, the output voltage being held constant. Thus when I_B is 0.010mA and I_C is 1.990mA the ratio is $\frac{1.990}{0.010} \simeq 200$. In published data the ratio is always quoted for a specified value of I_C, 1mA for example.

Voltage and Power Amplification

In order to obtain a voltage output a load resistor (R_L) must be added. The base-collector junction is reverse biased and therefore its resistance is of the order tens of thousands of ohms (in practice it varies with I_C). A load resistor of the order hundreds of ohms can therefore be added in series with the collector without changing the values of I_C very much. In fig. 20 then, a 1kΩ load has been added. The voltage developed by this is the

* *The current amplification factor, symbol α, is no longer recommended.*

output (V_{OUT}). We have seen that in a typical case when the base-emitter voltage (V_{BE}) is changed by 20mV, I_C changes by 0.995mA and so, assuming that the presence of R_L does not significantly alter I_C, V_{OUT} changes by: $0.995mA \times 1k\Omega \simeq 1$ volt. The change in V_{OUT} is therefore about 50 times $(=\frac{1}{0.020})$ the change in V_{BE}; a voltage gain of 50. In fig. 20 the initial conditions are indicated in black and the final conditions in red.

The change in input power is $(620 \times 0{\cdot}010 - 600 \times 0{\cdot}005)\ \mu W \simeq 0{\cdot}003mW$. The corresponding change in output power is approximately $(4 \times 2 - 5 \times 1) = 3mW$. The power gain is therefore about 1000.

A.C. Amplification

Fig. 21 is the basic circuit for an a.c. amplifier. The a.c. input signal of 20mV peak to peak is applied, through d.c. blocking capacitor C1, to the base. The input signal is superimposed on the 610mV d.c. base bias. Assuming that the same current transfer ratio applies as in fig. 20, the a.c. output waveform has a peak-to-peak value of 1 volt. In practice the a.c. gain, or to be precise the SMALL-SIGNAL SHORT-CIRCUIT FORWARD CURRENT TRANSFER RATIO (h_{fe}, h_{fb} or h_{fc}, see section 5), is slightly larger than the static ratio. It should also be noted that the output signal is in antiphase with the input.

The principle of operation of p-n-p transistors is similar to that for n-p-n devices and can be described in terms of hole flow from emitter to collector (rather than electron flow as in the case of n-p-n). It is also important that the base-emitter and collector-emitter supplies are reversed. It should also be noted that the forward base-emitter bias voltage necessary for germanium transistors is far less than for silicon devices. This is indicated by the diode characteristic, fig. 15. In fig. 22, which is the circuit for a basic p-n-p transistor a.c. amplifier, the differences between the n-p-n and p-n-p circuits are indicated in red. From the user's point of view n-p-n and p-n-p transistors are equally useful and it may be asked why semiconductor manufacturers bother to make both types. The short answer is that it is easier to mass produce silicon n-p-n devices than silicon p-n-p types, but, on the other hand, it is easier to mass produce germanium p-n-p types than n-p-n types. Thus in view of the current preference for silicon transistors, there is a preponderance of n-p-n devices. Also it is often advantageous to have both n-p-n and p-n-p types together in a circuit, for example a complementary transformerless push-pull amplifier.

Practical Amplifier Circuits

Fig. 23 illustrates typical practical amplifier circuits for p-n-p and n-p-n transistors. The differences are illustrated in red. The standing base current

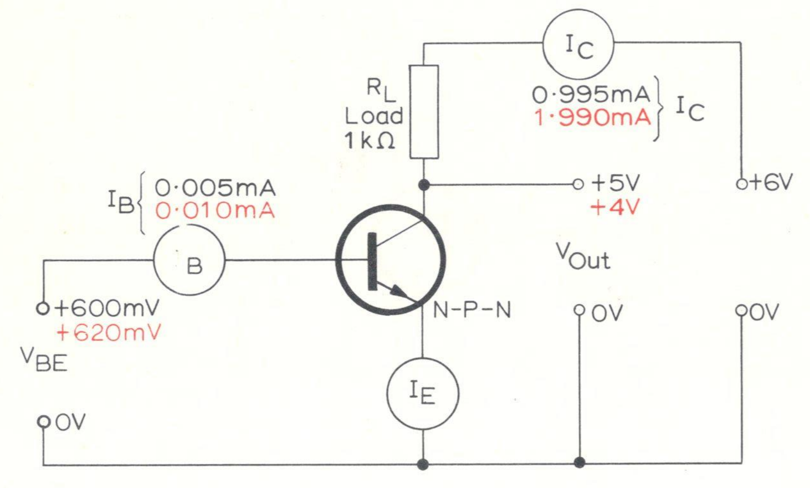

Fig. 20 Voltage Amplification

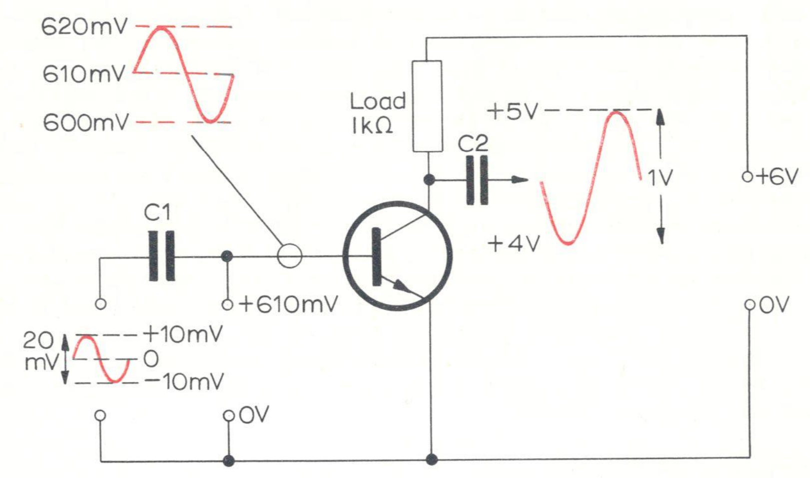

Fig. 21 A.C. Amplification

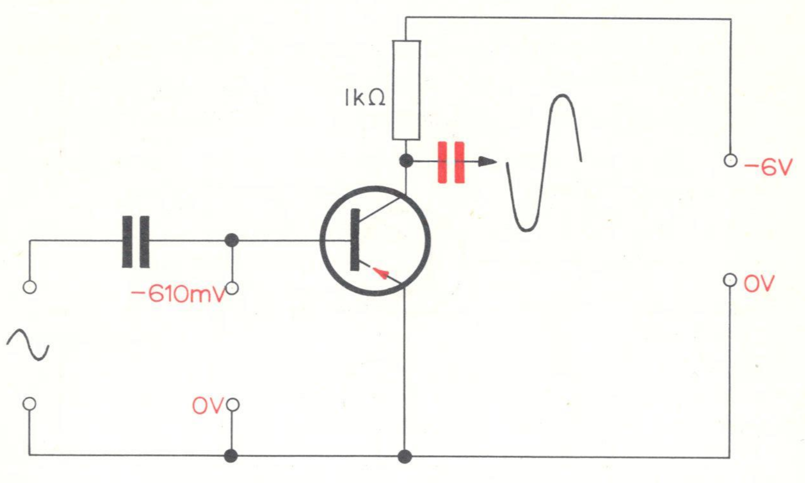

Fig. 22 P-N-P A.C. Amplifier

is provided by potential divider resistors R1 and R2, so that the circuit may be powered by a single battery. Resistor R4 is included to minimise the effects of temperature changes on collector current. Due to minority carriers there is always a small temperature dependent leakage current flowing between emitter and collector even when the base is open circuited. The leakage current causes a small voltage drop across R4 which raises the emitter potential and backs-off the emitter-base junction, thus any change in temperature is largely compensated for by a proportional change in base-emitter bias. R4 also provides a degree of negative feedback for wanted a.c. signals and, if such feedback is not required, bypass capacitor C2 is included in the circuit. Thermal effects are more of a problem in germanium than in silicon devices. With silicon devices the inclusion of R4 is often unnecessary. At high collector currents, if precautions are not taken, the heat generated can cause many minority carriers to be liberated. These carriers add to the collector current generating still more heat. If this cumulative build-up, called 'thermal runaway', is allowed to continue it can result in destruction of the device. Therefore it is sometimes necessary to mount the transistor on a carefully designed heatsink.

Circuit Configurations

The amplifier circuits so far considered have been of the 'common emitter' type, so called because, as far as a.c. is concerned, the emitter is common

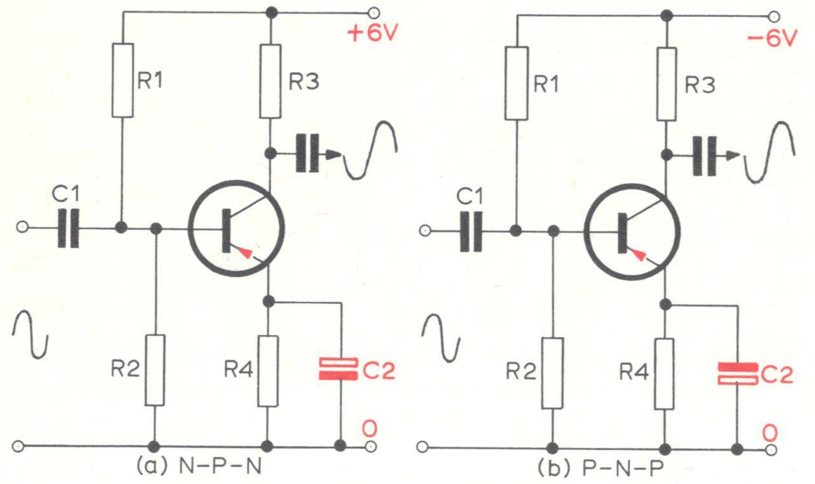

Fig. 23 Practical Amplifier Circuits

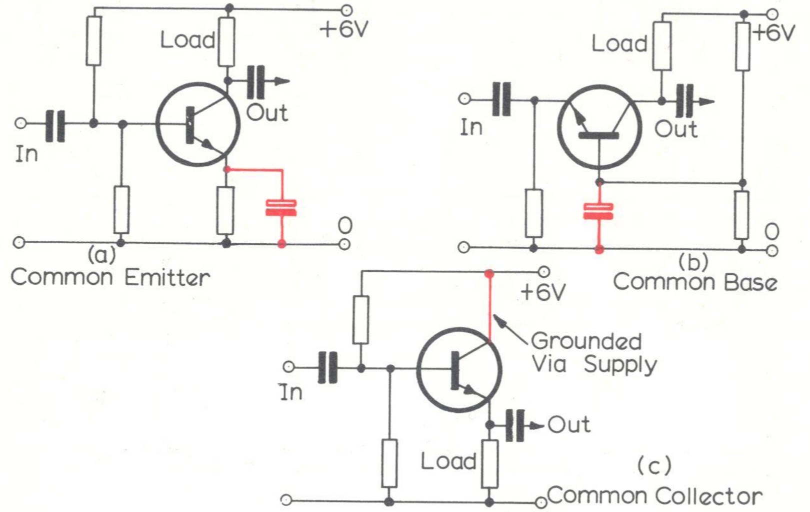

Fig. 24 Basic Circuit Configurations

ERRATUM

The red arrow in fig. 23(a) should point away from the base.

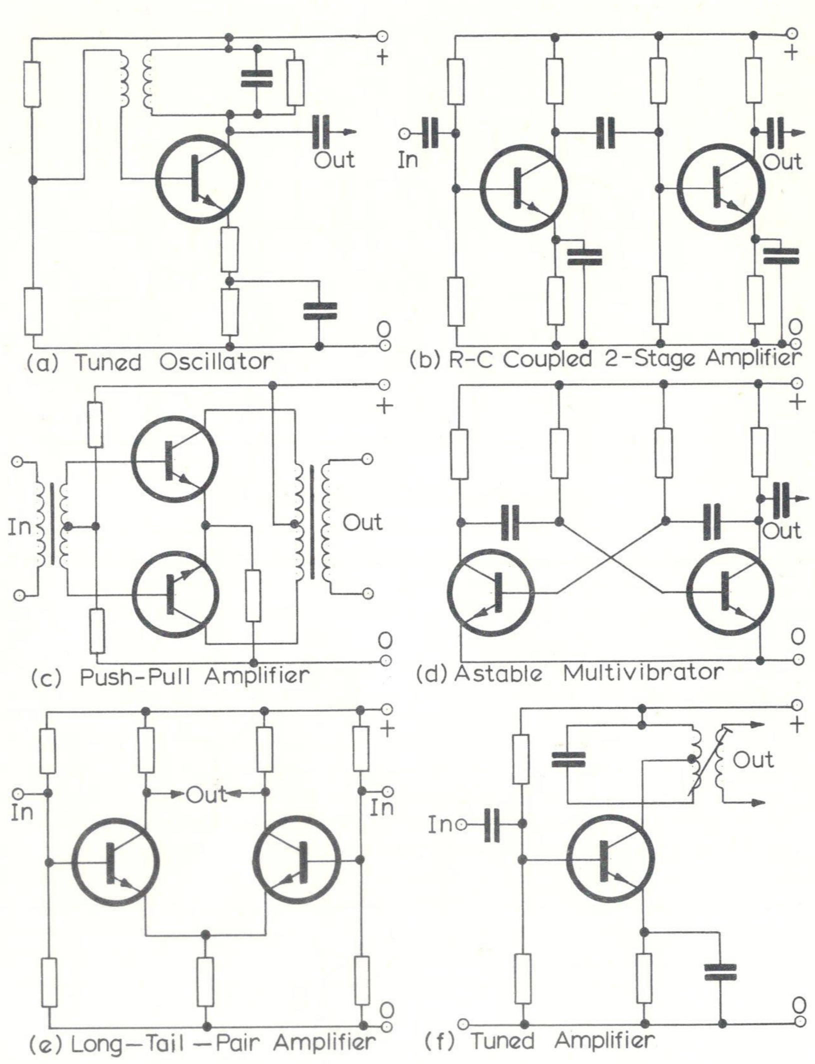

Fig. 25 Typical Circuit Applications

to both input and output terminals. Whilst the common or 'grounded' emitter circuit is by far the most frequently used, there are applications for which the 'common base' and 'common collector' configurations are useful. Fig. 24 illustrates the three configurations. The paths by which the relevant electrodes are commoned are indicated in red. An important consideration when choosing a circuit is the input and output impedance requirements. Some important features of the three circuits are illustrated in the following table.

	Common Base	Common Emitter	Common Collector
Current gain	about 1	High	High
Voltage gain	High	High	about 1
Input impedance	Low	Medium	High
Output impedance	High	Medium	Low
Power gain	Medium	High	Low
180° phase inversion (output w.r.t input)	No	Yes	No

Basic Transistor Circuits

Fig. 25 illustrates some typical basic transistor circuits. In the tuned oscillator, fig. 25(a), oscillations in the collector tuned circuit are maintained by the positive feedback introduced by the inductive coupling between base and collector. Fig. 25(b) shows a method of coupling two amplifier stages to obtain greater overall gain. The push-pull amplifier, fig. 25 (c), is commonly used as an audio output stage, the output being fed to a loudspeaker. In a (class B) push-pull amplifier each transistor conducts during alternate half-cycles, one conducting whilst the other one is non-conducting. Fig. 25(d) is a free-running square wave oscillator frequently used as a pulse generator. The long-tail-pair amplifier, fig. 25(e), is a differential amplifier, the output being a measure of the difference between the two inputs. The tuned amplifier shown in fig. 25(f) has a tuned circuit for its collector load and has a high gain at the resonant frequency. It is typical of the stages used for intermediate frequency amplifiers in radio receivers.