

TRANSISTOR AUDIO AND RADIO CIRCUITS

Mollard

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# **TRANSISTOR AUDIO AND RADIO CIRCUITS**

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The bulk of the information contained in this book is based on material supplied by W. D. Benson, D. R. Hyde and R. Osborne of the Mullard Central Application Laboratory. Other contributors include K. C. Warner of the Mullard Consumer Electronics Division and engineers of the Central Application Laboratory. The material has been edited by Miss A. Peters of Mullard Central Technical Services.

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## FOREWORD

'Transistor Audio and Radio Circuits' is intended as a manual of established and practical circuits for use by receiver and equipment manufacturers, radio and audio service engineers, university and college students, and do-it-yourself home constructors and hi-fi enthusiasts. A wide range of circuits is presented, extending from portable radio receivers to f.m. tuners and audio amplifiers capable of the highest standards of reception and reproduction.

The circuits presented can often be used in a variety of combinations to give a wide range of equipment. For example, various pairings are possible of the h.f. and a.f. stages designed for radiograms and portable radios. And again, in the hi-fi realm, either of the f.m. tuners can be used with either of the audio amplifiers and each resulting line-up can be used with or without a stereo reception facility, and can be combined with disc and tape input sources.

Details of the practical circuits are complete, but because of the wide range of possible combinations of circuits, no attempt has been made to present precise layout and constructional information. Some general guidance is given for hi-fi amplifiers, and a chapter is devoted to some simple test equipment and its use in effectively commissioning and maintaining audio circuits. But because of the need for rather complex equipment for aligning r.f. and i.f. circuits, similar information has not been given for such stages: it is envisaged that it will be those who have access to specialised knowledge and equipment—amateur enthusiasts, beginners under expert tutelage, or professionals—who attempt to build these h.f. circuits.

'Transistor Audio and Radio Circuits' is the latest of a number of Mullard books aimed at those whose interest lies in the audio and radio fields. It reflects the advances in electronic science since the earlier books were published, both in terms of devices and circuit techniques.

## AVAILABILITY OF COMPONENTS

All the Mullard devices mentioned in this book can be obtained through the usual trade channels. Other components, including meters and transformers, not marketed by Mullard are also readily obtainable; suitable components are manufactured by:—

### *Transformers*

Colne Electric Limited, Rickmansworth, Herts.  
Drake Transformers Limited, Billericay, Essex.  
Gardners Transformers Limited, Christchurch, Hants.  
Parmeko Limited, Aylestone Park, Leicester.

### *Meters*

Sifam Electrical Instrument Company Limited, Woodland Road, Torquay, Devon.  
Taylor Electrical Instruments Limited, Montrose Avenue, Slough, Bucks.

Printed-wiring boards for some of the audio circuits described in this book may be obtained from Bribond Printed Circuits Limited, Terminus Road, Chichester, Sussex.

## DATA ON MULLARD DEVICES

Abridged data on most of the Mullard devices mentioned in this book are given in the current edition of the Mullard 'Pocket' Data Book (U.K. edition).

Data on the few devices not included in the 'Pocket' Data Book can be obtained free of charge from Central Technical Services, Mullard Limited.

Complete data on all current Mullard devices are given in the Mullard Technical Handbook. Details of the Handbook can be obtained from Central Technical Services, Mullard Limited.

The circuits in this book are proven designs and it must be stressed that Mullard cannot undertake to answer queries arising from the information presented.

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## CHAPTER 1

# SILICON AND GERMANIUM TRANSISTORS

Most transistors are made from either silicon or germanium. The early transistors were made from germanium because silicon presented many manufacturing problems, but these problems have been largely overcome by the development of the planar process. Silicon and germanium transistors are now produced concurrently, and there are applications for which each is the more suitable.

Certain characteristics of germanium semiconductor material limit the operating junction temperature of germanium transistors to below  $100^{\circ}\text{C}$ , while silicon devices can operate at temperatures in excess of  $150^{\circ}\text{C}$ . However, germanium transistors still have the advantage of a low value of forward base-emitter voltage and bottoming voltage and, since these two represent voltage losses in the circuit, germanium devices are particularly suitable for the lower-voltage type of a.f. output stage. Another advantage of germanium transistors is that they are easily matched in complementary (p-n-p/n-p-n) pairs, thus facilitating their use in complementary-pair push-pull output stages.

Because silicon has an extremely high intrinsic resistivity the leakage currents of silicon transistors are far smaller than those of germanium transistors. This advantage, together with the higher permissible junction temperature mentioned above, and the high voltage ratings available with silicon transistors, makes them ideal for a wide variety of audio applications, especially at high output powers where high voltages are necessary. Silicon planar transistors can be manufactured with high switching speeds, making these devices suitable for use at high frequencies, for example in the r.f. stages of radio receivers.

### TRANSISTOR MANUFACTURE

The manufacturing processes of germanium and silicon transistors both start with the production of a crystal of the doped semiconductor material. The crystal is then cut into thin slices and it is from this point on that the manufacturing processes differ.

## Germanium Transistors

Germanium transistors can be made by either of two methods—the alloy-junction method or the alloy-diffusion method. In the manufacture of a p-n-p transistor by the alloy-junction method, an emitter pellet of p-type material is fused to one side of the n-type slice and a collector pellet of p-type material is fused to the other side. In the alloy-diffusion method, a p-n-p transistor is made by depositing a layer of n-type material on one surface of the p-type slice and placing two pellets close together on the n-type layer. One of the pellets, which eventually forms the base connection of the transistor, contains n-type additives only, and the other pellet, which will form the emitter, contains p-type and n-type additives. The assembly is heated and the additives diffuse into the p-type germanium beyond the prediffusion layer. In this way a transistor is made in which the collector is formed by the original slice, and all diffusion has been effected on one side. The processes used in the manufacture of germanium transistors are now well known and will not be elaborated upon in the present book. The manufacture of a germanium alloy-junction transistor is summarised in Fig. 1.

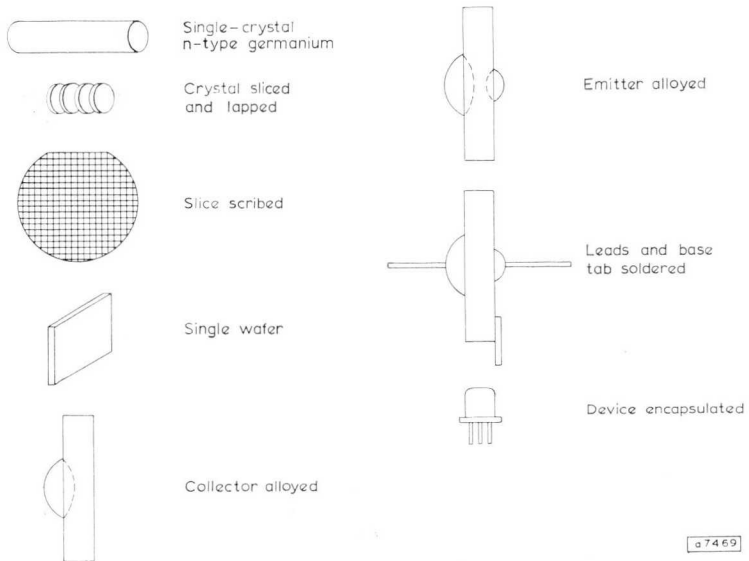


Fig. 1—Stages in the manufacture of germanium alloy-junction transistors

## Silicon Transistors

A process now widely used in the manufacture of silicon transistors is the planar process illustrated in Fig. 2. A slice of n-type silicon is cleaned under very stringent conditions and is then heated in oxygen so that a layer of silicon oxide is formed all over it. The oxidised slice is attached to the middle of a high-speed spinner, and a drop of photosensitive etchant-resistant material, or photoresist, is placed on it. When the spinner revolves, the photoresist spreads out in a thin, even coating. Some transistors, such as power transistors, need a thicker layer than others; in high-frequency transistors where well-defined edges are needed, a thin layer of photoresist is used. Hence, the spinning speed for power transistors is less than that for high-frequency transistors.

### *Base and Emitter Diffusion*

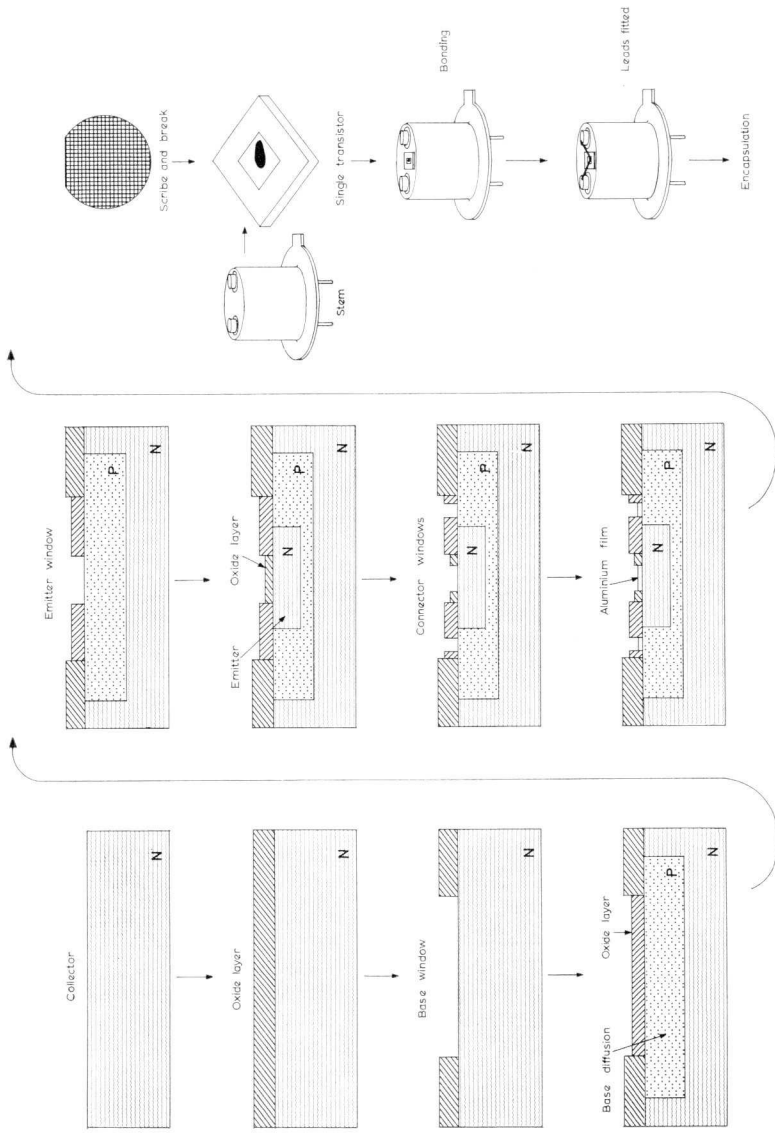
When the slice has been coated with the photoresist, it is covered with the base mask and exposed to ultraviolet light. The base mask is a photographic negative which carries a pattern formed by the proposed positions of the bases of the transistors that will be made from the slice.

The parts of the photoresist exposed to ultraviolet light change to a hard material which cannot easily be washed off, while the unexposed parts are easily removed. Therefore, after washing, there are many small windows in the photoresist, through which the silicon oxide is exposed. These windows are in the positions of the transistor bases.

The remaining photoresist is further hardened by baking the slice, which is then treated with acid to etch away the oxide exposed through the windows and reveal the silicon. The rest of the photoresist is then removed and the slice is ready for base diffusion.

When all the photoresist has been removed, the slice is again cleaned and placed in an oven with a little of the required p-type doping additive (usually boron). The additive evaporates and some of it settles in the windows. The slice is then transferred to a hotter oven filled with oxygen. In this oven, the additive is driven into the silicon to the required depth. At the same time, another oxide layer is formed all over the slice, including the windows. The base of each transistor in the slice has now been formed.

The slice is again covered with the photoresist and another pattern of windows produced as described above. This time, however, a different negative—the emitter mask—is used, and the windows are in the positions of the transistor emitters. The cleaning, diffusion and oxidation processes are repeated to form the transistor emitters. The doping additive used in this diffusion process, however, is not boron but phosphorus—an n-type substance.



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Fig. 2—Stages in the manufacture of silicon planar transistors

### *Lead Connections*

By means of the photoresist and a third negative, windows are produced over the base and emitter areas. The slice is placed in a vacuum and a fine layer of aluminium deposited all over it. The slice is removed from the vacuum and, by means of a fourth mask and another etching process, the aluminium is removed from all areas except where it is needed to provide contacts to the bases and emitters. The remaining aluminium is lightly alloyed to the bases and emitters to form non-rectifying contacts. At a later stage, fine gold or aluminium wires will connect the aluminium layer to the transistor leads or pins.

The oxide layer is now removed from the collector side of the slice, and the thickness of the slice is reduced by etching to lower the thermal resistance and improve the knee characteristic of the transistors.

The slice now contains between 200 and 6000 transistors, depending on the type of transistor, to which no leads have been attached. Each transistor is tested for breakdown voltage and small-signal current gain by means of a special probing machine connected to a test set. A photograph of this machine is given in Fig. 3. Transistors which fail any of these tests are marked and rejected at a later stage in manufacture.

After these tests, the slice is scribed with a diamond and broken into dice, each containing one transistor. At this stage, the marked transistors are rejected.

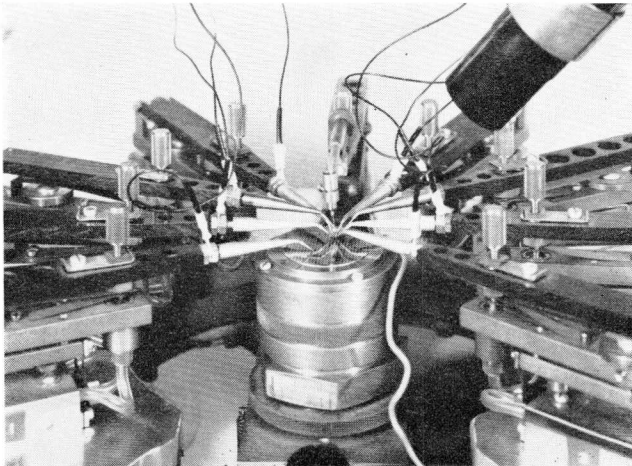


Fig. 3—Probing machine checking breakdown voltage and current gain of transistors

Each good transistor is soldered or bonded, collector side down, on the gold-plated stem or header. This operation is performed automatically on a dice bonder which fixes the transistor to the header by a silicon-gold eutectic.

The wires connecting the base and emitter to their leadout wires are usually of gold or aluminium, and are attached to the aluminium film on the transistor by means of a suitable bonder. When the leads have been attached, the transistors are encapsulated.

#### *Lockfit Encapsulation*

The familiar metal-can encapsulation requires no further description. However, a more modern encapsulation is epoxy resin, which is used on the range of Lockfit transistors. The coating of epoxy material provides the semiconductor wafer with complete environmental protection, and the junction-to-ambient thermal conductivity of the material is superior to that obtained with most metal encapsulations. The transistor leads take the form of flat pins which are designed to snap into printed-wiring board as shown in Fig. 4.

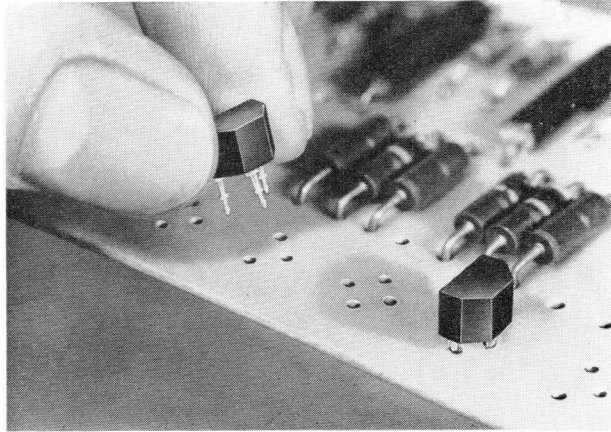


Fig. 4—Insertion of Lockfit transistors in printed-wiring board

The encapsulated transistors are subjected to a temperature cycling test, a drop test and a test to detect pinholes in the encapsulation.

## Epitaxy

When special types of silicon planar transistor are required, the procedure is modified slightly. When, for example, transistors are required for r.f. and i.f. applications, the silicon substrate is more heavily doped than in other transistors, and it undergoes further treatment in the crystal-growing chamber before being cleaned and covered with the first coat of photoresist. Consequently, the slice is covered with a thin layer—5 to 20 micrometres thick—of lightly-doped silicon. This layer has the same crystal orientation as the original slice and is therefore known as the epitaxial layer. The subsequent treatment of the slice with the epitaxial layer is the same as previously described. In the epitaxial type, however, the transistor is essentially within the thin layer, and the substrate is really a low-resistance back contact which provides a convenient thickness for handling. With the non-epitaxial type, the transistor is within the substrate.

## Field-effect Transistors

Despite the differences in materials and methods of manufacture, the transistors described in the earlier sections of this chapter all have essentially the same construction and principle of operation. They all consist of emitter, base and collector regions, and their properties are all largely a consequence of the movement of electrons and holes across the junctions between these regions or of the existence of the junctions themselves. The field-effect transistor, however, has a structure and characteristics differing from the conventional junction transistor.

### Structure and Operation

Fig. 5 is a schematic diagram of a field-effect transistor. It will be seen that a channel of n-type semiconductor material is enclosed for part of

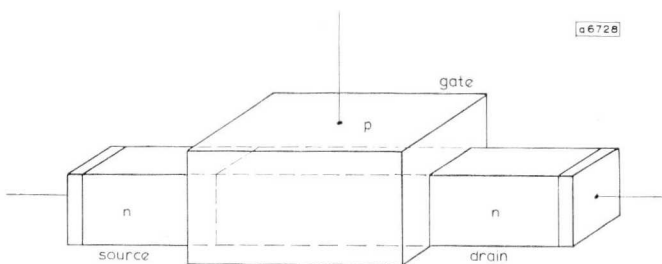


Fig. 5—Schematic diagram of a field-effect transistor

its length by a collar of p-type material. One end of the n-type channel is called the source, and the other end is called the drain. The collar of p-type material is the gate.

If a voltage is applied across the length of the n-channel so that the source is positive with respect to the drain, electrons will flow from the drain to the source; that is, current will flow conventionally from the source to the drain.

If a voltage is applied to the gate so that the gate is negative with respect to the source, the p-n junction formed between the gate and channel will be reverse-biased. No current flows across the junction, but the recombination of holes and electrons that migrate across the junction forms a region in the n-channel depleted of free electrons.

This non-conductive depletion region narrows the conductive n-channel, and thus reduces the current flowing from source to drain. Varying the gate bias voltage will thus vary the source-drain current. The action is analogous to the control of anode-cathode current in a triode valve by means of a negative bias voltage applied to the grid of the valve.

In the field-effect transistor, as in the triode valve, a comparatively small bias voltage will control a large current. Therefore amplification of a signal is possible with the field-effect transistor.

Since the gate-channel junction is reverse-biased during operation, the field-effect transistor is essentially voltage driven, and it therefore has a high input impedance. The device has a low noise figure and good high-frequency performance. For these reasons, field-effect transistors are ideal for use in such applications as the r.f. stages of high-quality f.m. tuners.

### *Manufacture*

The structure of an n-channel field-effect transistor is shown in Fig. 6. The planar process is employed in the manufacture of these transistors.

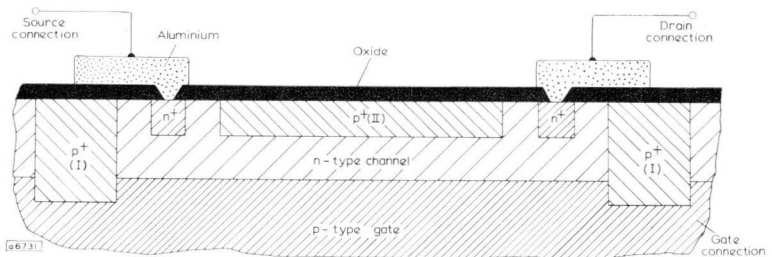


Fig. 6—Structure of a field-effect transistor

An n-type epitaxial layer which eventually will form the n-channel is grown on a substrate of high-conductivity p-type material, which will form the gate. After oxidation of the surface of the epitaxial layer, windows are etched in the oxide layer corresponding to the channel-isolating region I. Through these windows is diffused an additive rich in holes, which creates a 'super-p' or  $p^+$  region penetrating through the epitaxial layer to the p-type substrate, and thus isolating the n-channel.

After re-oxidation, a window is etched corresponding to region II, and another  $p^+$  region is created to form the upper part of the p-gate surrounding the n-channel.

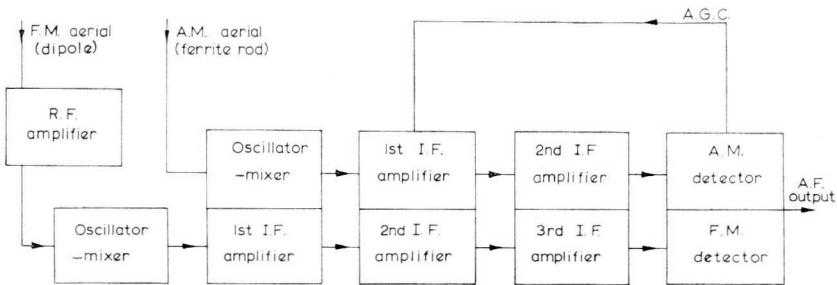
A third diffusion is performed to create 'super-n' or  $n^+$  regions at the ends of the n-channel. Aluminium bonds are deposited on these  $n^+$  regions, and to these are connected the source and drain contact wires. The purpose of the  $n^+$  region is to diminish the series resistance of the source and drain contacts. The gate contact is made to the p-type substrate, and the transistor is encapsulated in a metal envelope.



## CHAPTER 2

# BASIC H.F. CIRCUITS

The block schematic diagram for the high-frequency stages of a typical a.m./f.m. radio receiver is given in Fig. 7. The audio-frequency, or a.f., output is fed to one of several types of a.f. amplifier, which are discussed more fully in Chapter 3. In the present chapter, the operation of each of the circuits named on the block diagram is discussed in general terms, detailed practical circuits being given in later chapters.



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Fig. 7—H.F. stages of a typical a.m./f.m. receiver

### R.F. AMPLIFIER

A typical basic r.f. amplifier circuit is shown in Fig. 8. The transistor is connected in the common-base configuration because this configuration gives the highest gain at frequencies approaching the cut-off frequency. The collector circuit is tuned and is inductively coupled to the self-oscillating mixer circuit.

### MIXER

The mixer, or frequency changer, converts by heterodyne or 'beating' action the wanted frequency of the carrier signal at the aerial to a fixed frequency at the input to the i.f. amplifier. The a.m. carrier frequencies

vary from 160 to 280kHz in the long waveband and from 540 to 1640kHz in the medium waveband. The f.m. carrier frequencies vary from 85 to 100MHz. The intermediate frequency is usually 470kHz for a.m. and 10.7MHz for f.m. The audio-frequency information, carried on the r.f. waveform as modulation of the amplitude or frequency, is transferred from the r.f. carrier signal to the i.f. carrier.

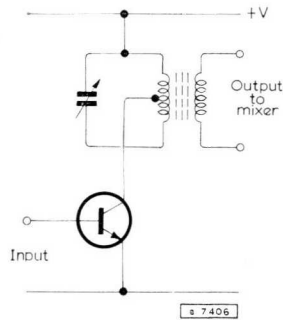


Fig. 8—Basic r.f. amplifier circuit

Heterodyne action is effected by injecting signals of different frequencies into a non-linear element such as the base-emitter diode of a transistor. In a radio receiver, one injected signal is the aerial signal, derived either directly or through an r.f. amplifier, and the other is a signal generated within the receiver by a local oscillator. The signals combine as shown in Fig. 9 to produce a complex waveform. When the waveform is applied between the base and emitter of a transistor, the main components occurring in the collector waveform are the original aerial and oscillator frequencies together with their sum and difference frequencies. The difference frequency (i.f. signal) is preferentially selected by the tuned circuit in the collector of the mixer, and further selectivity is provided by the i.f. amplifier stages. Voltage gain is obtained from the mixer stage in the same manner as the gain obtained from a normal i.f. amplifier, but somewhat reduced in magnitude.

To maintain a constant difference between the aerial and oscillator frequencies, the oscillator frequency must be changed whenever the aerial frequency is changed, that is, the oscillator tuned circuit must 'track' the aerial tuned circuit. Therefore, if the aerial is tuned to 1.5MHz, the local oscillator must be tuned to 1.97MHz, to give a difference frequency of 470kHz, and if the aerial tuning is changed to 1MHz, the oscillator

must be tuned to 1.47MHz. For a.m. reception, the oscillator is usually tuned to frequencies 470kHz above the aerial frequency so that signals in the long waveband, which have frequencies below 470kHz, can be accepted. For f.m. reception the oscillator frequency may be 10.7MHz above or below the aerial frequency dependent upon other design considerations.

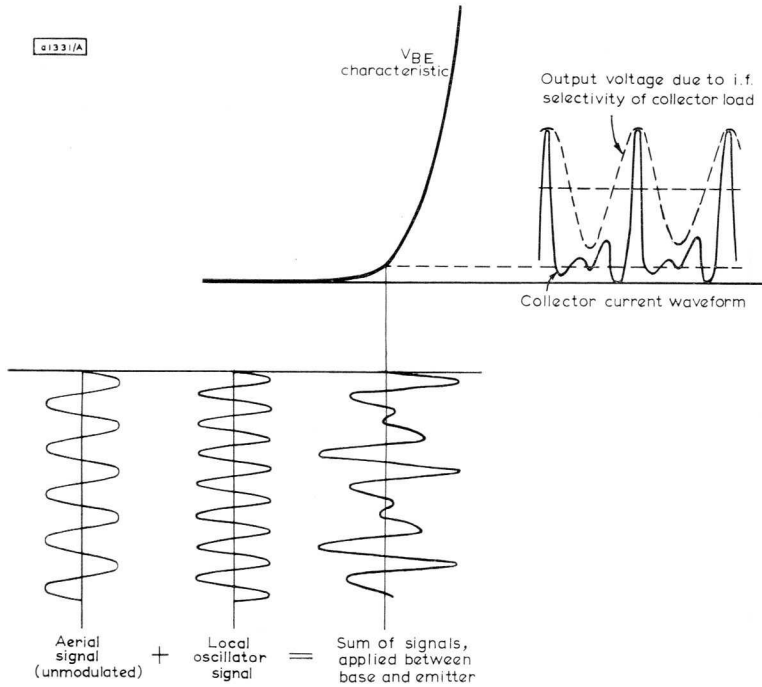


Fig. 9—Diagram illustrating the action of a mixer transistor

### SELF-OSCILLATING MIXER

The local-oscillator signal applied to the mixer may be derived from a separate oscillator transistor in the receiver or one transistor may act as both oscillator and mixer. This latter arrangement is the more common and is known as a self-oscillating mixer.

The basic circuit of a self-oscillating mixer is shown in Fig. 10. At the oscillator frequency, the base of the transistor is effectively connected to earth because the aerial tuned circuit has negligible impedance. The input

electrode for the oscillator action is, therefore, the emitter, which is inductively coupled to the collector of the transistor. Both the emitter winding and the collector winding are closely coupled to the oscillator tuned circuits. Positive feedback is applied from output to input through this coupling, and oscillation occurs at the resonant frequency of the oscillator tuned circuit. The aerial signal is applied from the aerial tuned circuit to the base of the transistor. Both the aerial signal and the oscillator signal are, therefore, in series with the base-emitter diode. The component of the heterodyne output signal having the required intermediate frequency is extracted by the i.f. bandpass filter or transformer in the collector circuit.

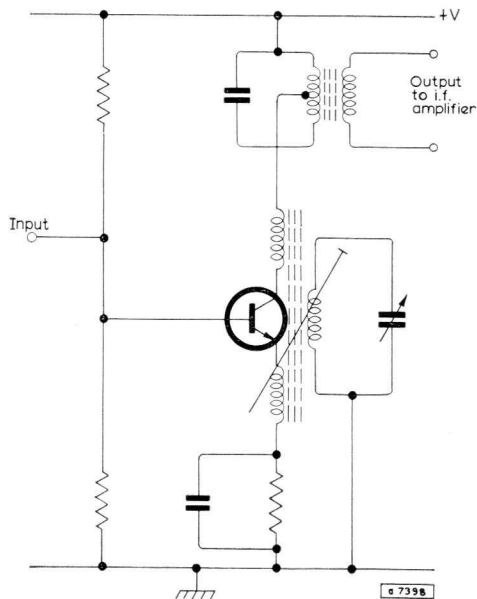


Fig. 10—Basic self-oscillating mixer circuit

A typical self-oscillating mixer for a.m. reception is shown in Fig. 11. The circuit is shown for one waveband only, the different wavebands being obtained by switching other coils into the aerial circuit and additional capacitors into the oscillator circuits. The aerial input is taken to the base of the transistor, and the oscillator feedback from the collector is taken through low-impedance coupling coils to the emitter.

To ensure that the oscillation starts easily, the transistor is biased initially for class A operation by the potential-divider bias circuit. As the oscillation increases in amplitude, rectification of the oscillating signal occurs at the base-emitter diode. This causes the loop gain after each cycle to decrease, stabilising the amplitude of the oscillation and causing the quiescent emitter current to rise slightly (from 250 to 300 $\mu$ A in the circuit shown in Fig. 11).

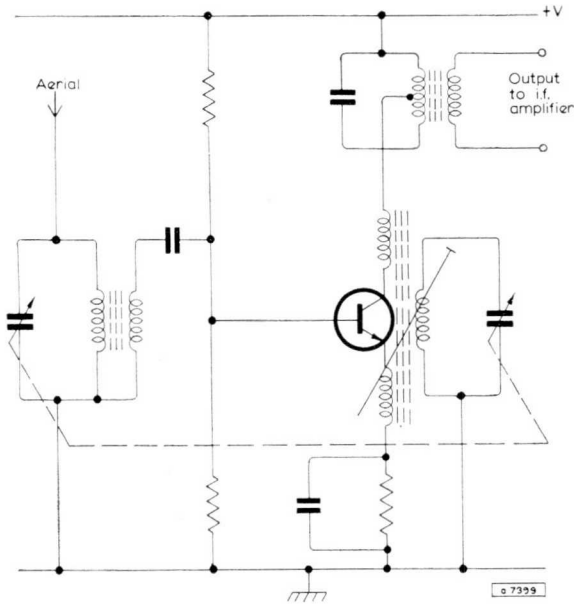


Fig. 11—Typical practical self-oscillating mixer circuit

Correct tracking of the aerial and oscillator tuned circuits to maintain the 470kHz difference in frequency can be obtained by a conventional padder circuit or by using a tuning capacitor with specially-shaped vanes for the oscillator circuit. The value of the tuning capacitance is not critical but must be sufficient to provide the required frequency coverage.

Stray capacitance can exist between the aerial and oscillator sections of the tuning capacitor and so form a path for unwanted feedback between the two sections. To prevent this feedback and the resulting possibility of spurious oscillations, a screen is usually placed between the two sections. Another source of feedback between the oscillator and aerial sections is

through the stray capacitance of the leads to the wave-change switch, and these leads should, therefore, be kept as short as possible.

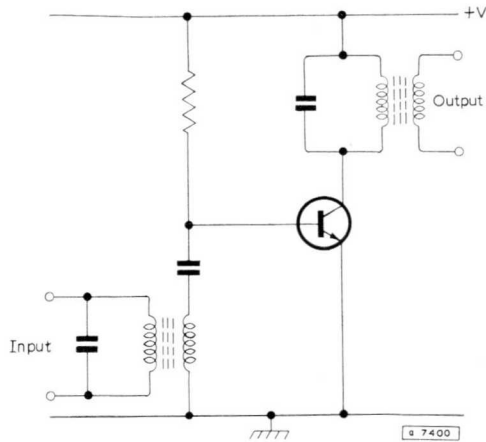


Fig. 12—Basic i.f. amplifier circuit

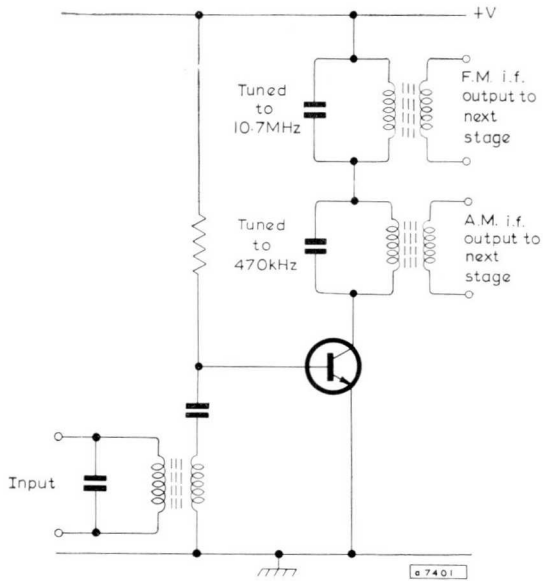


Fig. 13—Basic i.f. stage for an a.m./f.m. receiver

## I.F. AMPLIFIER

The basic circuit of an i.f. amplifier stage is shown in Fig. 12. The input and output transformers are tuned to the intermediate frequency, the selectivity and bandwidth being improved if both windings of the transformers are tuned. In an a.m./f.m. receiver it is necessary for two i.f. transformers to be provided between stages—one tuned to 470kHz and the other to 10.7MHz. A method of connecting these i.f. transformers is illustrated in Fig. 13. The remaining i.f. stages are similar to the first except that, in an a.m./f.m. receiver, the a.m. and f.m. outputs must be separated so that each can be fed to its own detector circuit.

## DETECTOR

The a.m. detector of a transistor receiver is usually a semiconductor diode feeding a potentiometer load. The potentiometer forms the volume control, which feeds the demodulated signal to the audio-frequency stages of the receiver. The potentiometer is usually shunted by a 10nF capacitor, as shown in Fig. 14, to filter out the i.f.

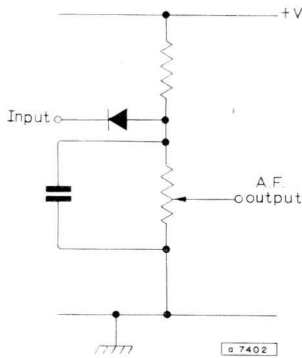


Fig. 14—Basic a.m. detector circuit

The detector stage for f.m. signals is usually of the type known as a ratio detector, the basic circuit of which is shown in Fig. 15.

The ratio detector depends for its operation on the fact that as the frequency of the signal varies, the phase relationships in a circuit tuned to the nominal frequency change. The transformer has three windings, the primary and secondary tuned to the intermediate frequency and the tertiary, close-coupled to the primary, injecting a voltage into the secondary