TRANSISTORS
AND
CRYSTAL DIODES

WHAT THEY ARE
AND
HOW TO USE THEM

B. R. BETTRIDGE

(Osram Valve and Electronics Dept. of the General Electric Co., Ltd.)

A transistor receiver using two transistors in a reflex circuit. Its total current consumption is 6mA at 18V.

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INTRODUCTION

For many years the experimenter has been tantalized by reading about transistors without being able to obtain any for his own use. The situation has now changed and several types are generally available, with others likely to find their way into circulation shortly, so that the amateur may at last work with them himself.

In this book devices which still appear to be some way off have been dealt with briefly and the majority of circuits given are of immediate interest in that they are built around transistors and diodes that are actually on the market. In addition, the circuits are in nearly every case ones which have been made up and tested by the author so that there is a practical background to them.

Component values are given wherever possible and circuits requiring critical adjustments have been avoided; however, the values given should be regarded as typical rather than absolute and the reader is advised to experiment a little to obtain the highest performance. This applies more especially to circuits using transistors which tend to exhibit greater characteristic variations under working conditions than do thermionic valves.

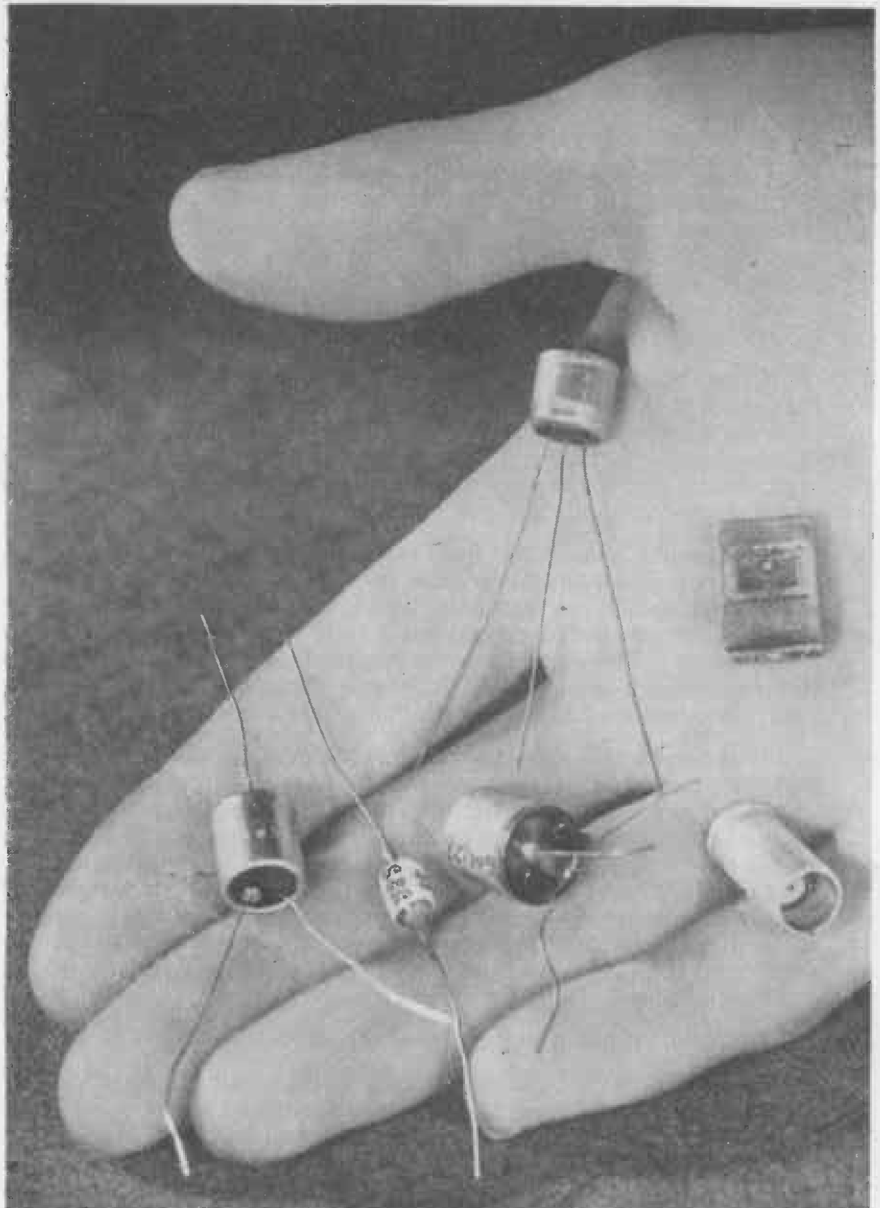
It is hoped that the explanation of how these devices work plus the practical circuits described will enable readers to carry on with developments of their own. Certainly the best way to get to know the transistor is to use it oneself and for this purpose the greater the number of circuits tried the better, even though some of them may be of doubtful advantage with transistors at their present stage of development. Nothing will be found to replace actual use of them in achieving the reorientation of viewpoint that is necessary when turning to transistors after years of experience with thermionic valves.

It should be noted that many of the circuits are patented.

The author would like to express his appreciation and thanks for the help received from colleagues in compiling and checking the material and for the permission granted by the General Electric Company Ltd. to undertake the writing of this book.

B. R. BETTRIDGE

LONDON, 1954.



(*By courtesy The General Electric Co. Ltd.*)

A SELECTION OF SEMI-CONDUCTOR DEVICES HELD TO ILLUSTRATE THEIR SMALL SIZE.

I

SEMI-CONDUCTORS

THE term semi-conductor has only recently come into common use in technical literature, but devices depending on the properties of semi-conductors have been known for many years, one particular example, the crystal detector, dating back to 1906.

Most detectors consisted of a catswhisker of springy wire in light contact with a piece of suitable crystalline material and substances in this category included silicon, galena and iron pyrites. Variants were the Perikon detector consisting of two crystals, zincite and bornite, in quite firm contact and carborundum-steel where a sharp point of carborundum was pressed on to a flat and fairly rigid blade of steel. This, incidentally, required a little bias to bring it to its most sensitive operating condition. Both these latter types were very stable mechanically. It is interesting to note that for many years the mode of operation was not in the least understood and that even now there are aspects of their behaviour which cannot be completely explained.

The crystal detector, almost always in the form of a brand of synthetic galena (lead sulphide) and a catswhisker, reached the peak of its popularity in the early days of broadcasting when it enabled simple and effective receivers for headphone operation to be made at a very reasonable cost. It might be noted here that natural crystals were not uniformly sensitive and some search had to be made to find the best point; synthetic materials were a great improvement in this respect, but even so, sensitivity would often fall off so that frequent searching for a new point had to be made.

Crystal detectors were eclipsed by thermionic valves which could do the job with more certainty and, what was far more important, could amplify and enable long-range reception and loud-speaker operation to be achieved. Their eclipse might have been complete had not a function been found in centimetric radar, namely, that of mixer, which crystals would fulfil far better than thermionic valves. After extensive trials silicon was found to be the most suitable material for these extremely high frequencies and is still so at the present time.

During the course of these investigations germanium was noted as having promising properties in other directions and when the war ended its possibilities were more fully explored and widespread use was found for it in television, radio and electronics. So in its up-to-date form the crystal detector once again came into its own although, being only a diode, its range of applications was necessarily limited.

Then came a discovery of immense significance. It was found that when two whiskers, separated by a few thousandths of an inch, were placed in contact with a piece of germanium, current flowing in one influenced current in the other and amplification could be achieved. The property which had enabled the valve to oust the crystal was now shared by the crystal. Furthermore, this important property was obtained without evacuated envelopes or heated emitters and there seemed no reason why the device, which is now known as the point-contact transistor, should not go on working indefinitely.

An intensified effort in semi-conductor research was the immediate result of this great extension of possible application, and other important developments and discoveries followed in both diode and transistor categories, probably the most important being the junction devices.

Before considering the various devices individually it is necessary to have some idea of the nature of semi-conductors and fortunately, although a full treatment of the subject would be lengthy and abstruse, a highly simplified explanation is quite sufficient to give a reasonable understanding of the general way in which semi-conductor devices work.

In solids which are good conductors, such as most of the common metals, conduction takes place because electrons in the outer orbits of the atom can move freely from one atom to the next on the application of an electric field. On the other hand insulators have no electrons free to move. Semi-conductors have only a limited number of current carriers available and their conductivity is perhaps a million times poorer than that of copper. The presence of these current carriers is best illustrated by the example of a typical semi-conductor.

Germanium when in the form of a perfect crystal has its atoms arranged in an orderly fashion often referred to as a lattice. It is as if the material were divided into a vast number of diamond shapes at the corners of which the atoms were placed. Each atom then has four nearest neighbours and each of the four electrons in the outer orbit of each atom shares an orbit with an electron from one of these neighbours. All the electrons have partners and are not free to move from their shared orbits. With certain reservations which will be dealt with later, it can be said that absolutely pure germanium in perfect crystalline form is an insulator because it has no available current carriers.

Now, suppose that atoms of arsenic, which have five electrons in their outer orbits, are introduced into the lattice of germanium atoms. They will fit into the general scheme to the extent that four of the electrons will pair with those of neighbours; the fifth, however, will have no partner and will be available for conduction. With only a limited amount of impurity to the order of one part in ten million, the current carriers will be relatively sparse and the material will have only a limited conductivity. Such a material is a semi-conductor and is called *n* type because the current is carried by the electrons which are, of course, negative. Other impurities with five outer electrons such as antimony will produce a similar effect.

The effect of impurities, *e.g.*, indium or gallium, with only three electrons in their outer orbits is different. In fitting into the lattice they can only satisfy the requirements of three out of their four nearest neighbours in pairing with their electrons and an unsatisfied electron remains. This electron is not available for conduction, but since it is without a partner its orbit represents a vacancy which readily accepts an electron and this is known as a positive hole. An electron moving from an orbit to fill a positive hole in another orbit leaves a similar vacancy in its initial orbit, so that the hole itself appears to move in the opposite direction to the electron. A helpful analogy is that of a vacancy in a row of cinema seats. If the person next to the gap moves into it he leaves a gap which his neighbour can fill in turn, and so on along the row, so that people moving in one direction cause the gap to move in the opposite direction. The movement of a bubble in a spirit-level offers another comparison.

Whatever way is used to help explain the conception, the fact remains that the vacancy behaves in practice like a mobile positive charge, and it is convenient to think of it in these terms without attempting to visualize its behaviour in detail. A material such as germanium with indium impurity is called a *p* type semi-conductor because the current is carried by positive holes.

Now that *n* and *p* type semi-conductors have been described we can proceed to deal with devices using them.

II

CRYSTAL DIODES AND HOW THEY WORK

ALTHOUGH discovered later the junction diode is better understood than the point-contact type and will be dealt with first. Fig. 1 shows a germanium junction diode diagrammatically. It consists of a piece of germanium one end of which is *p* type with its positive hole current carriers and the other *n* type with its current carriers of negative electrons. The transition from one type to the other is called the junction. The crystal lattice has to be continuous across this junction and it is not, therefore, possible to make a diode by placing in contact separate pieces of *p* and *n* type material. There are two common ways of producing such a junction.

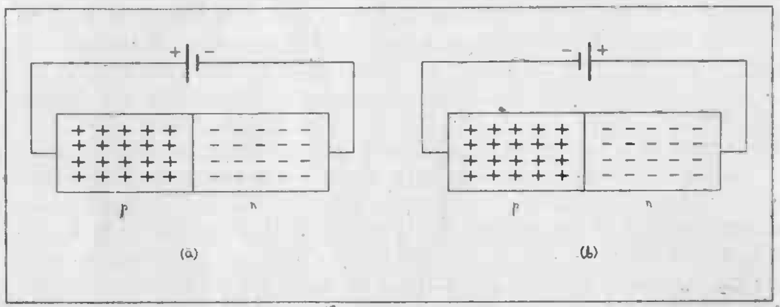


FIG. 1. JUNCTION TRANSISTOR CONNECTED AT (a) FOR EASY CURRENT FLOW AND (b) FOR SMALL REVERSE CURRENT

The first is represented in Fig. 2. A crystal of *n* type germanium is grown in the usual way by slow withdrawal under accurate temperature control from molten germanium containing a trace of arsenic. An impurity such as indium is now introduced which in pure germanium would produce *p* type material. In *n* type material it is able first to neutralize the effect of the arsenic and then confer *p* type properties, so that a crystal is formed with a continuous lattice having a transition within it from *n* to *p* type material. The second method is shown in Fig. 3. An indium bead is placed on a wafer of *n* type germanium and the assembly is heated. At a temperature of about 500° C, the indium dissolves some of the germanium to form an alloy. When this alloy cools some of the dissolved germanium is redeposited on the parent germanium. This redeposited germanium is saturated with indium and is, therefore, *p* type. Again, a transition from *p* to *n* is obtained within a continuous

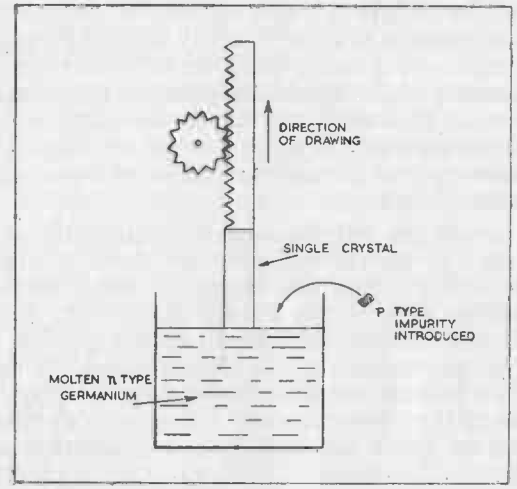
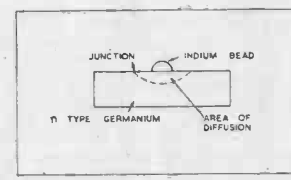


FIG. 2. MAKING A GROWN JUNCTION.

FIG. 3. MAKING AN ALLOY JUNCTION



crystal lattice. Avoiding confusing details, a clear explanation is possible of the rectifying action of such a junction. Referring to Fig. 1, we have on one side of the junction positive holes only as current carriers and on the other only negative electrons. If a voltage is applied across this junction so that the left-hand end (*p* type) is positive, current due to this potential can consist of either electrons moving from right to left or positive holes moving from left to right; and, since the right-hand side contains electrons and the left-hand side positive holes, current flows readily across the junction. Now, what happens when the applied potential is reversed so that the left-hand side is negative? The appropriate direction of current would occur either by electrons moving from left to right, and there are no electrons available in the left-hand side, or by positive holes moving from the right, where there are none, to the left. Obviously, then, no current can be made to flow in this direction, and the junction behaves as a non-return valve as far as electricity is concerned.

In practice, a small current does flow in the reverse direction, because *p* type material does in fact contain a small proportion of free electrons and *n* type a minor number of positive holes. The reason for the presence of these minority carriers as they are called need not be explained in detail, but it can be loosely stated that they originate in certain lattice bonds being broken by thermal agitation and, therefore, their number and the current carried by them will increase with temperature. It is this thermal breaking of bonds that prevents absolutely pure germanium from being a complete insulator at ordinary temperatures.

Fig. 4 shows the current-voltage characteristic of a typical junction diode. In the forward direction there is a rapid rise in current with applied voltage, and at currents within the rating of the device the voltage drop is only a fraction of a volt. In the reverse direction the current is low and tends to show saturation, *i.e.*, it does not increase proportionately to the applied voltage. This is because once all the current carriers have been brought into action there is nothing to carry any further current. However, at a sufficiently high voltage called the Zener voltage there is a complete breakdown of

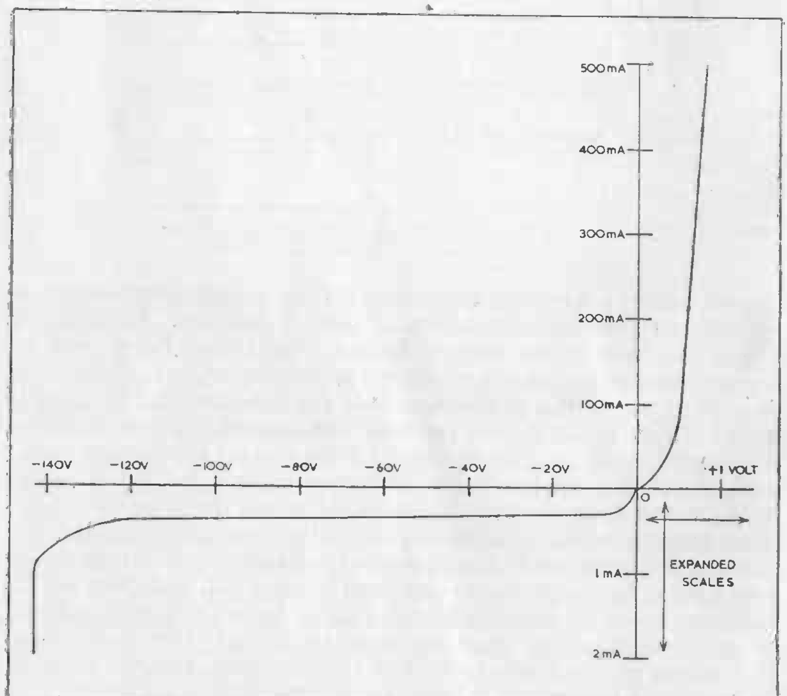


FIG. 4. CHARACTERISTIC CURVE OF A *p-n* JUNCTION DIODE.

back resistance and current increases very sharply. This effect was predicted by Zener many years before junction diodes existed to demonstrate the effect experimentally.

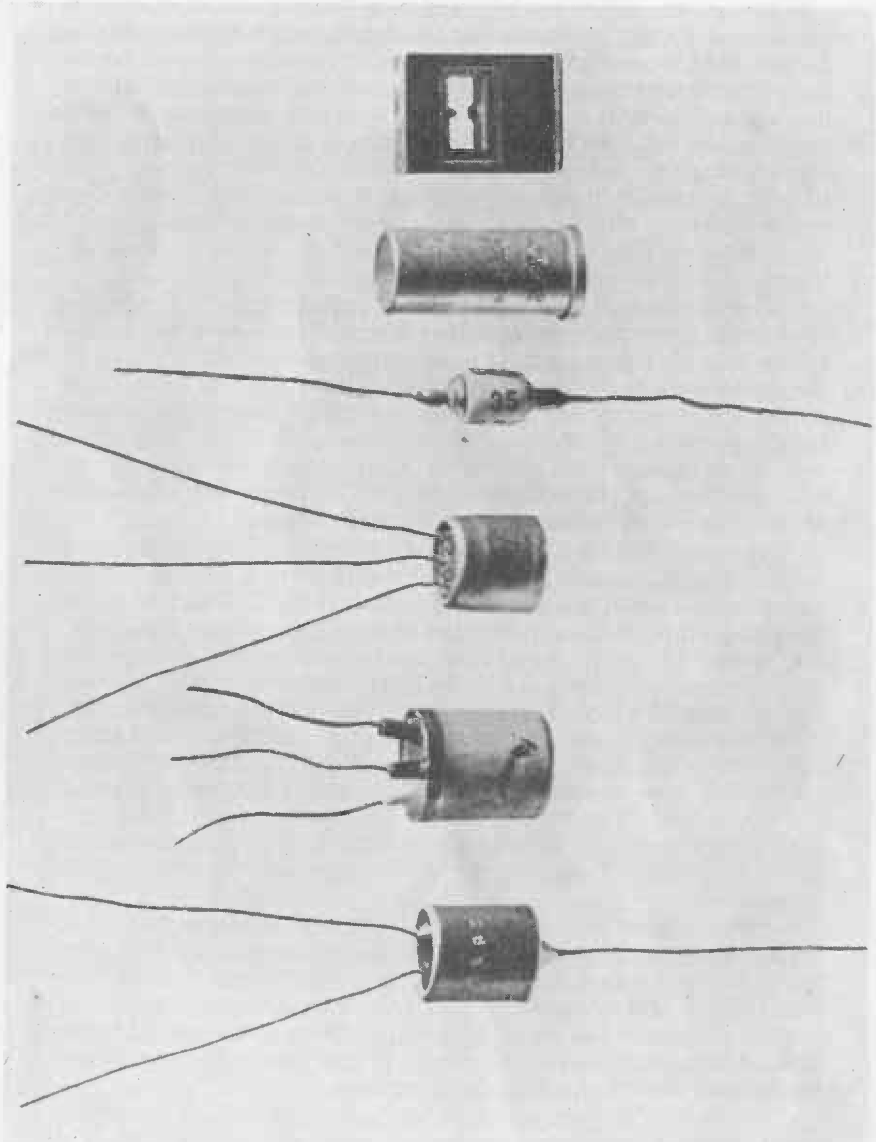
The point-contact diode has already been mentioned as consisting of a springy, pointed wire in contact with a semi-conductor crystal. The crystal may be of *p* or *n* type material, and, whilst silicon mixer diodes are made of *p* type silicon, germanium diodes use *n* type material. This results in opposite directions of easy current flow for the two types; in silicon diodes it is with the whisker negative, and in germanium with the whisker positive. The whisker is usually made of tungsten or a platinum alloy. The pressure is not critical, but needs to be heavy enough to give mechanical stability without being sufficient to distort the point or injure the surface of the crystal.

There is no completely satisfactory explanation of the working of a point-contact diode and that which is usually given is too complex for inclusion here. It is concerned with the surface state of the semi-conductor where the atoms behave differently from those in the solid material because they no longer have other atoms equally spaced from them in all directions. One very convenient way of thinking of their working is to imagine the presence of a *p–n* junction directly below the whisker. This has some foundation in fact, but is by no means a complete explanation.

The current-voltage characteristic of a typical germanium point contact diode is given in Fig. 5. The forward curve is good compared with that of a small thermionic diode such as the D77 or 6AL5, but the voltage drop is higher than that of most types of junction diode. The reverse current increases considerably with applied voltage and the resistance value obtained by dividing voltage by current is lower at –50V than at –10V. It is clear from this that it is useless to talk about the back resistance of a crystal without specifying the voltage at which it is measured. At a voltage known as the turnover voltage, the reverse current rises sharply and the curve exhibits a negative resistance kink. This feature has not been fully explained, but it is not of great practical significance because it is not permissible to use crystals under these conditions where the safe dissipation limit is exceeded.

Point-contact diodes are not intended for power rectifiers, but they have a surprisingly large current handling capacity for their size, the allowable forward current being up to 50mA, whilst the reverse voltage they will withstand varies from about 60 in the case of general purpose types up to as much as 200 in some special types. The self-capacitance of these diodes is less than 1pF, so they are particularly suitable for high frequency use.

By varying the amount and kind of impurity and modifying whisker material, germanium diodes can be made with somewhat different properties from those described above. The mixer crystal



A SELECTION OF TRANSISTORS AND CRYSTAL DIODES.

Reading from left to right: Point-contact transistor GET 1; Junction transistor—H.E. type point-contact transistor—Germanium diode GEX 35.

(By courtesy The General Electric Co. Ltd.)

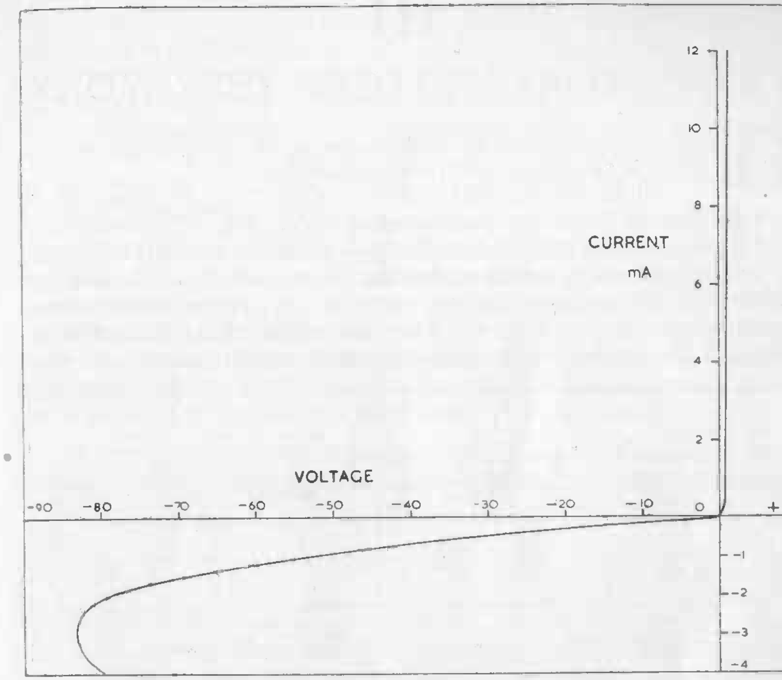


FIG. 5. CHARACTERISTIC CURVE OF A TYPICAL POINT-CONTACT GERMANIUM DIODE.

GEX66 for frequencies up to 1,000 mc/s is one example. In this, low forward resistance and increased efficiency at u.h.f. are gained at the expense of the back voltage it can handle (a point of no importance in a mixer). Type GEX64 has a still lower forward resistance at the expense of capacitance which may be as high as 30pF. Its use is mainly in modulators in multi-channel carrier telephone circuits, but it also has possibilities in logarithmic amplifiers and as a meter rectifier.

Silicon diodes are of importance in being the only efficient mixers for centimetric frequencies, but since this is a somewhat specialized field it will not be discussed here. The diodes will only handle a few volts in the reverse direction and are more liable to damage through overload than those made with germanium.

III

TRANSISTORS AND HOW THEY WORK

ONCE the operation of diodes has been grasped, it is not difficult to understand transistor action.

Junction varieties will be taken first as being more straightforward than the point-contact type. Fig. 6 shows *p–n–p* and *n–p–n* junction transistors. The *p–n–p* version consists of a zone of *n* type material a few thousandths of an inch thick flanked on either side by zones of *p* type material. A reverse arrangement results in the *n–p–n* version. They are made by an extension of either of the methods described in connection with junction diodes.

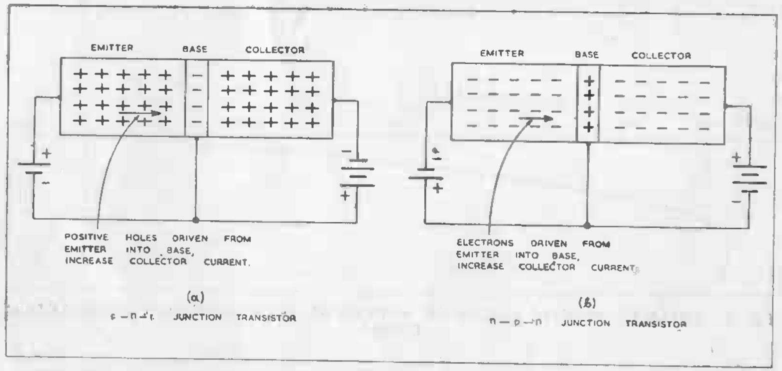


FIG. 6. (a) *p-n-p* JUNCTION TRANSISTOR. (b) *n-p-n* JUNCTION TRANSISTOR.

The two outer zones are called emitter and collector, whilst the inner zone is known as the base. Amplifying action is obtained because current between emitter and base influences current at higher power level between collector and base.

In the *p–n–p* transistor shown in Fig. 6 (a), the collector is made negative to base, and, ignoring the emitter for a moment, the circuit is that of a junction diode connected in its reverse direction with its current due to the minority carriers, *i.e.*, negative electrons from the *p* type collector zone and positive holes from the *n* type base region. Since the number of these is small the current will be low. By making the emitter positive to base this part of the circuit becomes a junction diode conducting in its forward direction by means of its majority carriers; *i.e.*, negative electrons from the base and positive holes from the emitter. It is these positive holes which cross the junction into the base region that interest us, for, if the base zone is thin enough, most of them come under the influence of

the negatively biased collector and increase the collector current. In a fairly typical transistor each 1mA change in the emitter current will vary the collector current by about 0·97mA and amplification occurs because of the different impedances in which these currents flow. The emitter current is in the direction of easy flow so that the impedance may be less than 50 ohms, whilst the collector current is in the direction of difficult flow so that the impedance may be of the order of a megohm or more.

Fig. 7 shows the family of curves of collector-current against collector-voltage of a *p-n-p* junction transistor; these resemble the anode current-anode voltage curves of a thermionic pentode. The important difference is that in the case of the transistor each curve is for a separate value of emitter *current* instead of grid voltage, emphasizing that the transistor is a current-operated device and must be thought of in these terms when applying it to circuits.

The *n–p–n* transistor operates in a similar fashion except that the additional current carriers which increase the collector current

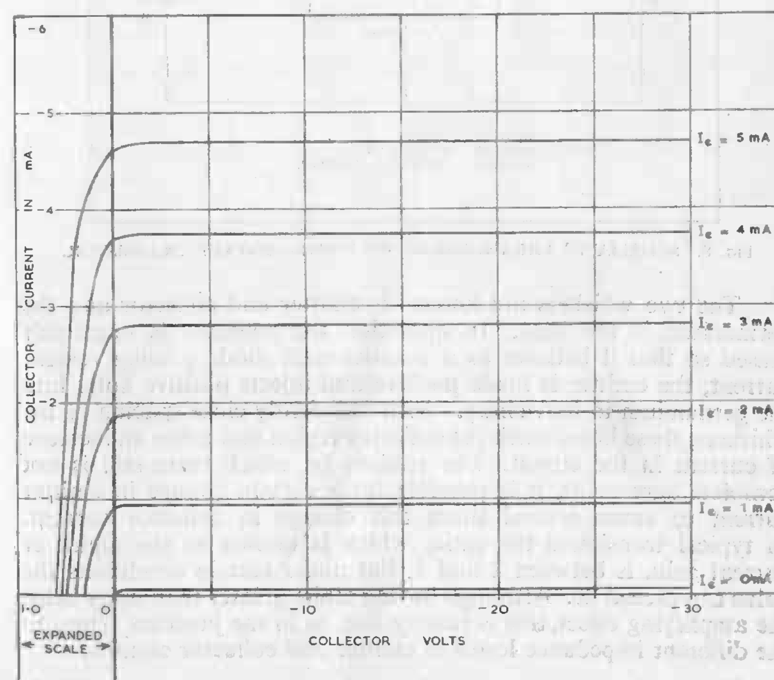


FIG. 7. COLLECTOR-CURRENT CURVES OF A TYPICAL *p-n-p* JUNCTION TRANSISTOR OF $\alpha = \cdot 95$ APPROX.

consist of electrons flowing from the *n* type emitter into the *p* type base. Polarities are naturally reversed and the collector is made positive to base whilst the emitter is negatively biased; otherwise the characteristics are of the same form.

The point-contact transistor is shown schematically in Fig. 8, and it consists of a diode with a second whisker touching the surface of the germanium a few thousandths of an inch from the first; *n* type germanium is commonly used for the crystal although transistors employing *p* type material have been demonstrated.

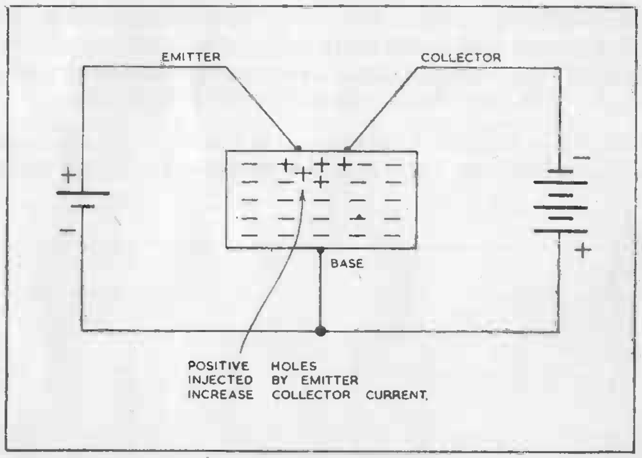


FIG. 8. SCHEMATIC ARRANGEMENT OF POINT-CONTACT TRANSISTOR.

The two whiskers are known as emitter and collector and the germanium is the base. In operation the collector is negatively biased so that it behaves as a point-contact diode passing reverse current, the emitter is made positive and injects positive holes into the germanium in its vicinity. With sufficiently close spacing of the whiskers, these holes reach the collector region and cause an increase of current in the circuit. For reasons on which there still is not complete agreement, it is possible for a certain change in emitter current to cause several times this change in collector current. In typical transistors the ratio, which is known as the alpha or current gain, is between 2 and 3, but under certain conditions the value can exceed 20. Although having alpha greater than unity helps the amplifying effect, this is mainly due, as in the junction types, to the different impedance levels in emitter and collector circuits.

Fig. 9 shows the curves of a point-contact transistor. Their general shape is again similar to that of a thermionic pentode.

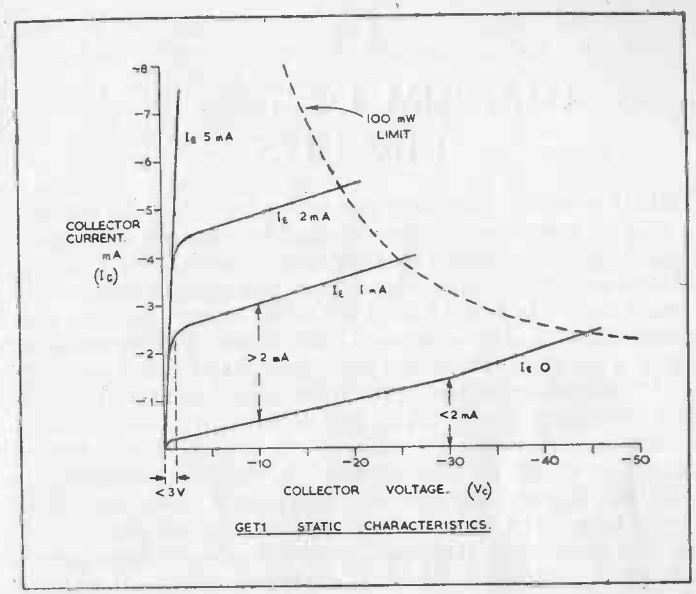


FIG. 9. COLLECTOR-CURRENT CURVES OF POINT-CONTACT TRANSISTOR.

The significance of the characteristics of both junction and point-contact transistors will be dealt with in greater detail when describing their circuit applications.

IV

GERMANIUM DIODES IN TV CIRCUITS

THERE are few television sets nowadays that do not employ one or more germanium diodes, because of the particular advantages conferred by their use.

The almost universally adopted use is as vision detector where the circuit shown in Fig. 10 does not differ materially from that for a thermionic valve. Its use saves a valve holder, but more important than this is the elimination of a most prevalent form of interference due to i.f. harmonic feedback, for there is no heater wiring to carry it into the earlier stages of the set and other wiring can be made very short and non-radiating by placing the crystal diode within the screening can of the i.f. transformer. Its rectifying efficiency tends to be a little higher than that of a thermionic diode and its life is extremely long. The 330-ohm resistance *R* is to safeguard the diode in case of a momentary flashover inside the valve between screen and control grids. Minute particles of carbonized dust can cause such effects with destruction of the crystal, so the incorporation of the

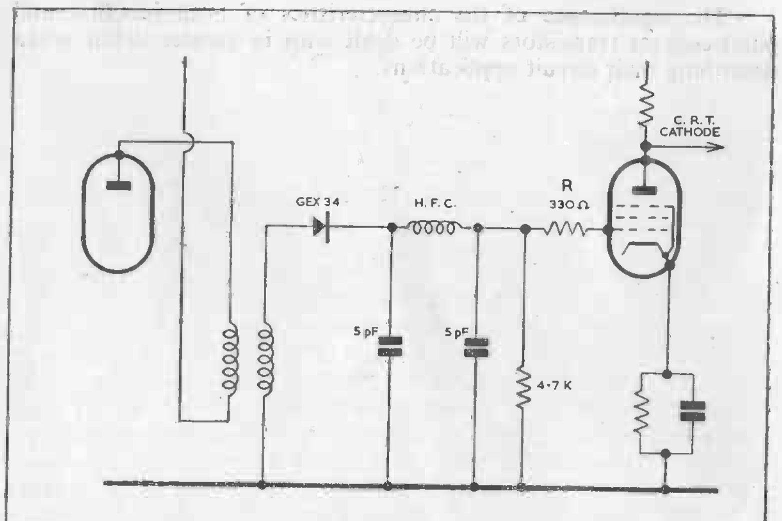


FIG. 10. VISION DETECTOR.

resistance is well worth while. Vision i.f. transformers are normally tuned by stray circuit capacitance including that of the detector diode itself; the low capacitance of a germanium diode sometimes makes it necessary to use a few more turns on the secondary than would be the case with a thermionic diode to ensure tuning to the correct frequency. Although the above has been written in terms of the super-het., crystals can, of course, be used with equal success in t.r.f. vision strips.

The same factors which favour its use in a vision detector also apply when the germanium diode functions as a sound detector. Fig. 11 illustrates crystal diodes for sound detection and noise

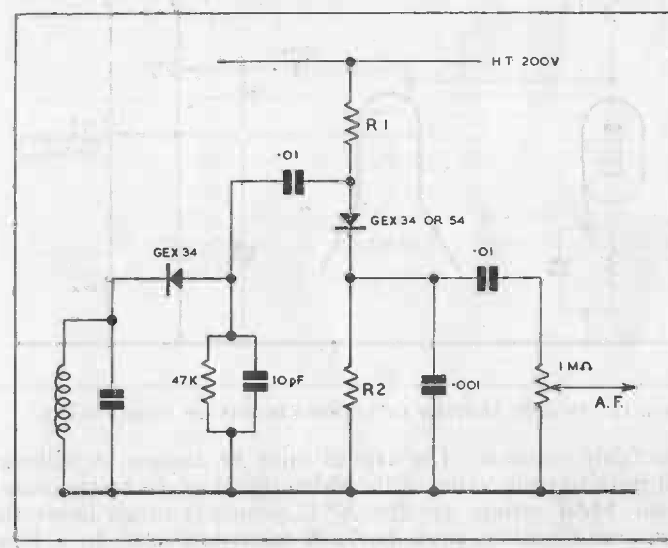


FIG. 11. TV SOUND DETECTION AND LIMITING.

limiting. The circuit is particularly suitable for feeding high-quality amplifiers because it removes a common form of hum introduction, a point of less importance perhaps with less ambitious systems of limited frequency response. The values of R_1 and R_2 should be kept as high as possible to keep the residual value of the suppressed noise impulses as low as possible. Their value is determined by the size of the signal to be handled.

Thus, to take a practical example, suppose the a.f. amplifier requires 1V for full output, then, to allow a little margin in the setting of the volume control, the limiter should be designed to handle about 2V peak. Values of R_1 and R_2 would then be 10 megohms each. The crystal in the limiter should have a reasonably high back resistance and should be able to withstand high back voltage because noise peaks can reach a surprisingly high figure. A crystal with a high level functional test such as type GEX34 is recommended for this purpose and has been used commercially on a large scale.

For vision spot limiting crystal diodes are extremely effective because of the steep slope of their forward characteristic. Fig. 12 shows one in use in the anode circuit of the video amplifier. A word of caution is necessary about this arrangement, since conditions of

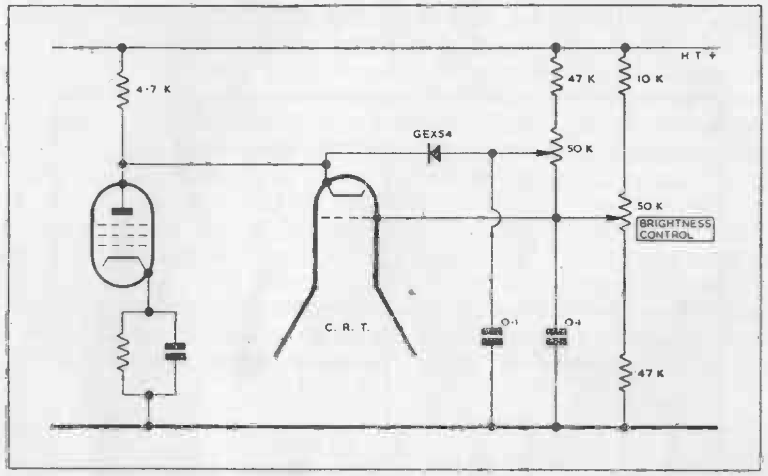


Fig. 12. TV SPOT LIMITER IN ANODE CIRCUIT OF VIDEO VALVE.

use are fairly onerous. The crystal must be chosen to withstand the full peak to peak value of the video signal *at the temperature of operation.* Most ratings are for 20° C, which is much lower than temperatures found in some parts of television sets. In a home-constructed set it is often possible to mount the crystal in a well-ventilated position near the base of the c.r.t. well away from the main sources of heat in the remainder of the set.

Where the voltage swing is very high as in a 17″ set with perhaps 16kV e.h.t. or where it is not possible to find a cool working position for the diode the grid limiter arrangement is advisable. This is shown in Fig. 13. High back resistance or working voltage is not important here, but good forward conductance is essential so that the GEX35 is suitable for this purpose.

Practical circuits will be confined to those given above, but for the experimenter there are a number of additional possibilities including use in the discriminator circuit for flywheel sync. and the mixer stage in Bands III and IV receivers.

In many areas, adaptors for commercial television will not need the gain of the triode-pentode type of frequency changer, and in this

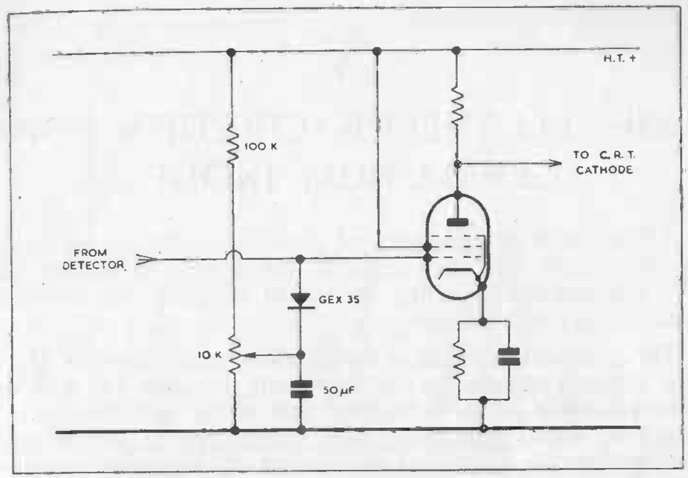


Fig. 13. TV SPOT LIMITER IN GRID CIRCUIT OF VIDEO VALVE.

case a crystal mixer is a good thing to use. A suitable basic circuit is given in Fig. 14. The danger of oscillator radiation may be reduced by an h.f. stage in front of the mixer.

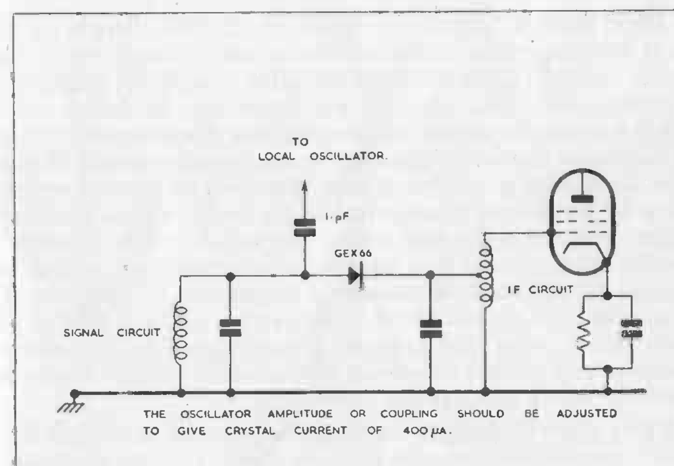


Fig. 14. 200 Mc/s MIXER.

V

MISCELLANEOUS CIRCUITS FOR GERMANIUM DIODES

ALTHOUGH the majority of germanium diodes are used in television sets, they are still widely used in various radio applications including the oldest of them all: the simple crystal receiver with headphones.

The germanium diode is the modern counterpart of the old crystal detector and can be used in exactly the same way with great advantage owing to its consistent and stable performance. The strength of signal obtainable with simple crystal sets is mainly determined by the aerial and no amount of circuit refinement will obtain a strong signal when an indifferent aerial is used in an area where the field strength is low. It is only within a few miles of a powerful station that comfortable reception can be obtained on a small indoor aerial. The standard of acceptable loudness has increased greatly since the early days when any signal at all was regarded as marvellous, people in the meantime having become used to loud and clear reception from valve sets.

Unless there is difficulty in separating stations, there is no point in using anything more elaborate than a simple single circuit tuner shown in Fig. 15. Coils intended for valve circuits are not ideal for this arrangement, since there is no centre tap available and the coupling winding for the aerial does not give efficient power transfer when the tuned winding is damped by the crystal current. It is easy to wind a coil with a number of taps taken out so that the optimum match may be found experimentally for both crystal and aerial. An alternative method which avoids the use of taps is to use a coil of low inductance tuned by a large value of capacitance so that both aerial and crystal may be connected to the end of the coil. This arrangement is in general better in receivers with fixed tuning, since variable capacitors of high value are inconveniently bulky; however, the sections of a ganged condenser connected in parallel can be used successfully where space is not important.

Where there is difficulty in separating stations a double circuit becomes essential and the main problem then is to strike a reasonable compromise between selectivity and loss of strength. Fig. 16 shows an arrangement which retains signal strength by making the aerial part of the first tuned circuit by series tuning and which gives good selectivity by top capacitance coupling to a low L/C ratio circuit

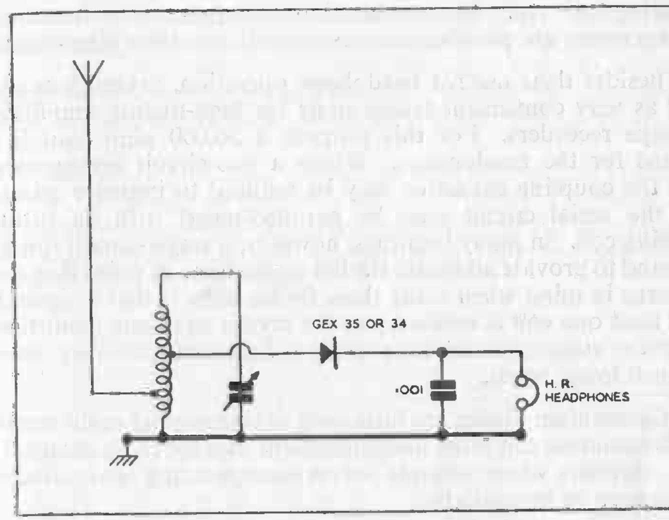


Fig. 15. SIMPLE CRYSTAL RECEIVER.

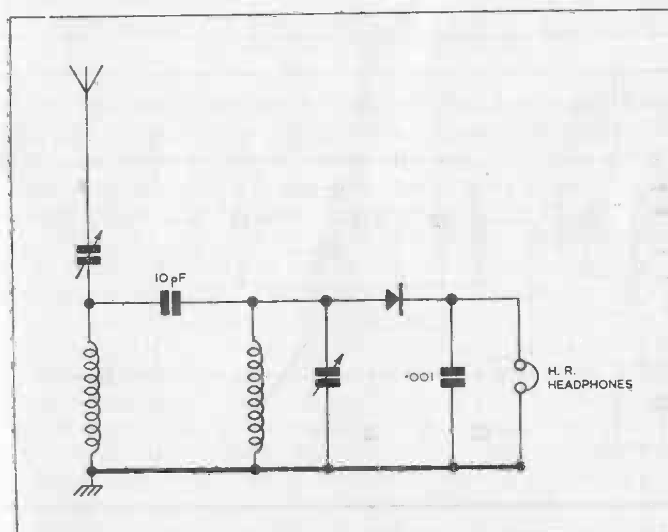


Fig. 16. TWO-CIRCUIT CRYSTAL RECEIVER.

requiring no tap. Many variations of these two fundamental arrangements are possible and results will not differ significantly.

Besides their use for headphone operation, crystal sets can be used as very convenient feeder units for high-quality amplifiers or for tape recorders. For this purpose a 50,000 ohm load is substituted for the headphones. Where a two-circuit arrangement is used the coupling capacitor may be reduced to improve selectivity and the aerial circuit may be paralled-tuned with an orthodox coupling coil. In many localities, however, a single-circuit tuner will be found to provide adequate station separation. A point that should be borne in mind when using these feeder units is that a signal level of at least one volt is necessary at the crystal to ensure distortionless detection, although acceptable results for most purposes are obtained at much lower levels.

Germanium diodes are little used in commercial radio receivers, but the amateur can often find convenient uses for them as signal and a.v.c. rectifiers when multiple valves incorporating spare diodes do not happen to be available.

A probable use of the near future is in ratio detector circuits for F.M. reception where they will give advantages owing to the possibility of locating them in the i.f. screening can.

The circuit is the conventional one used with thermionic diodes and is shown in Fig. 17. For optimum a.m. interference rejection it is necessary to use a transformer with the windings designed for

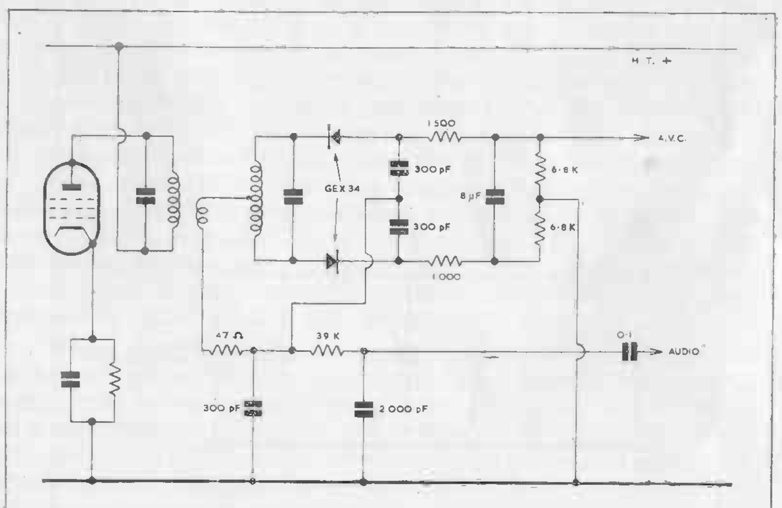


FIG. 17. RATIO DETECTOR USING CRYSTAL DIODES.

crystal use, but in a region of high signal strength the direct replacement of valves by crystals gives satisfactory performance.

There are numerous miscellaneous uses to which the experimenter may put these convenient diodes. A few typical ones are given below, but many others will suggest themselves during the course of work.

The use of automatic bias in an amplifier reduces the available h.t. by the amount of the bias and this in the case of triodes can be a significant amount. This loss can be avoided by the use of a separate bias supply which can well use germanium diodes, and a suitable circuit is given in Fig. 17 (a).

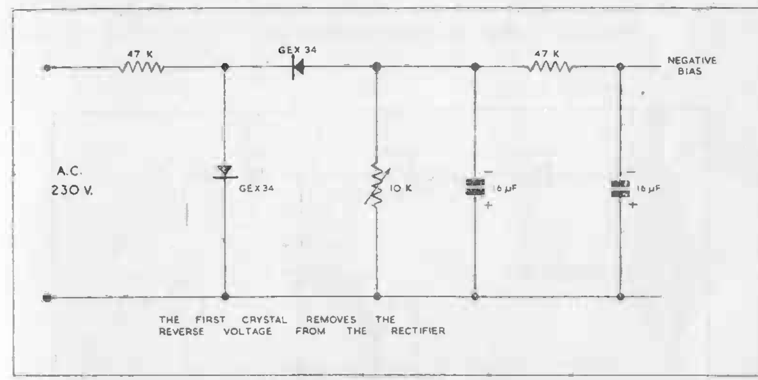


FIG. 17(a). VARIABLE BIAS SUPPLY. THE FIRST CRYSTAL REMOVES THE REVERSE VOLTAGE FROM THE RECTIFIER.

An extremely simple yet effective signal tracer may be made up from just a crystal and a pair of headphones in series. The only precaution which must be observed when using this simple device is always to connect it across two points with a complete d.c. path between them. For instance, when testing for a signal at the anode of a valve, the free end of the crystal should be connected to the anode and the free end of the 'phones to the other end of the anode coil and *not* to earth. The crystal may suffer damage by failure to observe this precaution, and in any case the device will only function when such a d.c. return path is provided for the rectified diode current. Obviously no d.c. potential should exist between the points across which this simple tracer is connected or the crystal will be biased to a non-rectifying portion of its characteristic. A more elaborate signal tracer may be made without the above restrictions on conditions of use and its circuit is given in Fig. 18.

Where an a.c. meter is required and only a d.c. one is to hand the matter is easily remedied by use of a germanium diode or, for better efficiency, two or even four in a bridge circuit. An advantage

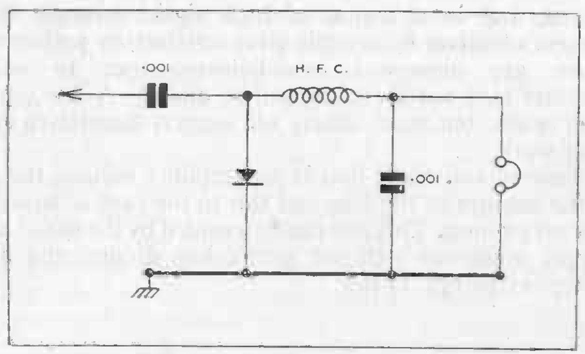


FIG. 18. SIGNAL TRACER.

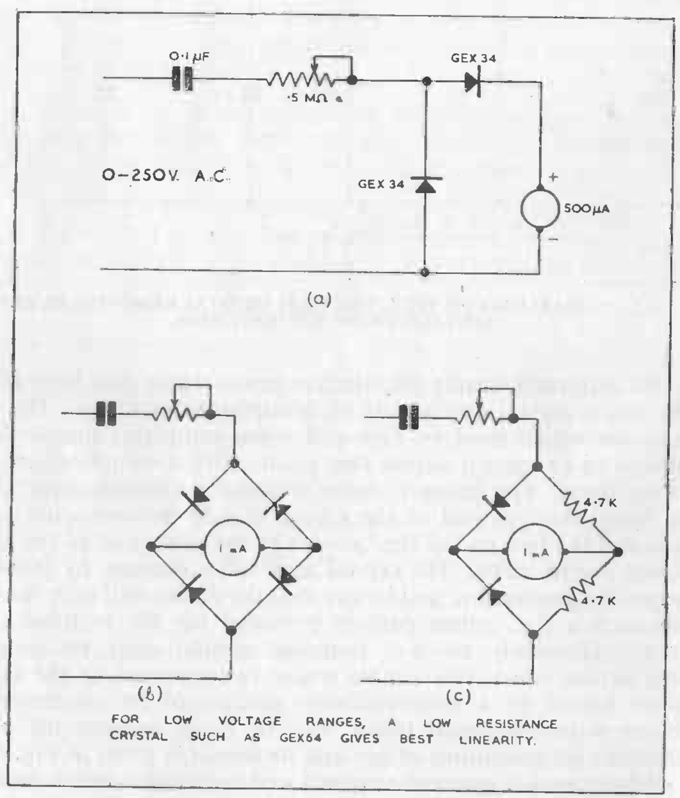


FIG. 18(a). SOME A.C. METER CIRCUITS. FOR LOW VOLTAGE RANGES A LOW RESISTANCE CRYSTAL (SUCH AS GEX 64) GIVES BEST LINEARITY.

gained is that the meter, having been calibrated on 50 cycles, can be used without correction factor at very much higher frequencies into the radio frequency range. Some suggested meter circuits are given in Fig. 18 (a).

General classes of use in electronic gear are clipping and gating. Their particular advantage for such use is that the absence of heater removes problems associated with heater cathode insulation. The finite reverse resistance of these diodes must be taken into account and the circuit constants adjusted to minimize its effects. The aim, of course, should be to refrain from making associated impedances higher than is absolutely necessary.

It is worth noting that the bias supply mentioned above for amplifier use is a useful source of h.t. for small transistor equipments, both the polarity and the current capacity being suitable.

VI

TRANSISTOR CIRCUITRY

ALTHOUGH transistors fulfil similar functions to thermionic valves they perform them in a somewhat different way and, therefore, the circuit techniques of the two devices diverge to a considerable extent. As already stated, whereas a valve is essentially a voltage-operated device a transistor is essentially current-operated. This basic difference has led to the concept of circuit duality, where valve circuits can be transformed for transistor use by suitable substitutions. This, however, tends to be a mathematician's rather than an experimenter's province and will not be dealt with here. The best practical approach at present seems to be in terms of valve circuits adapted rather than transformed for transistor use and most amplifier circuits now in use do not look unfamiliar apart from some of the components having unusual values. The point-contact transistor with its special feature of alpha greater than unity produces one or two novelties, but, even so, analogous valve circuitry can be found by considering dynatrons and transitrons.

Fig. 19 shows a family of point-contact transistor collector current curves with three operating points and load lines. Output voltage and power in the collector circuit are derived by the same

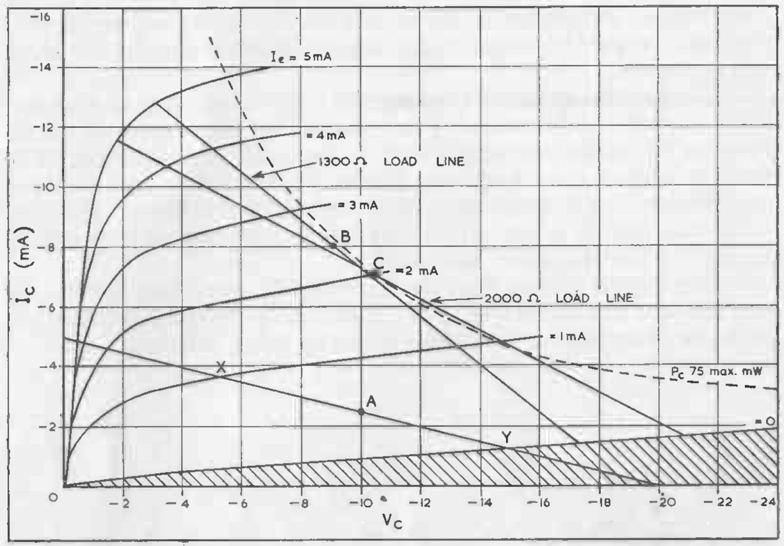


FIG. 19. CURVES OF POINT-CONTACT TRANSISTOR TYPE GET2 WITH LOAD LINES. SHADED PORTION CANNOT BE USED.

methods as with valve curves but, of course, the input signal is in terms of emitter-current swing instead of grid voltage swing. An important point of difference between valve and transistor curves is that only positive emitter-current has any appreciable effect on collector-current and the region beyond the $I_e = 0$ curve is one in which the transistor cannot operate. To emphasize this point this area has been shaded. This might be said in a loose way to correspond to the positive grid region of a valve in certain types of circuit where it is unusable, but there is no complete comparison of a really helpful nature. The distance between the curve for $I_e = 0$ and $I_e = 1$mA is the change of collector-current for a one milliamp increase in emitter-current and, therefore, represents the current gain or alpha of the device. For this particular transistor the value is about 3·5 and decreases somewhat for further increases in emitter-current.

Point *A* on the figure is a suitable point for small-signal amplification. The collector voltage is –10 derived from an h.t. of –20 through 4,000 ohms and the current is 2·5mA. Emitter bias is 0·5mA. *X Y* is a 4,000-ohm load line. Under these conditions a swing of emitter current down to 0mA and up to 1·0mA will produce a voltage swing across the collector load of 10 volts peak to peak. Since the emitter impedance is low (200 ohms approx.), the voltage required to produce the above change of current is only about 0·2V, so that there is a voltage gain of 50 in this stage.

Thinking in terms of voltage gain is, however, apt to be misleading because of the different impedance levels and it is much more realistic to deal in terms of power gain. Thus, in the above case the input is 0·025mW, whilst the output is 3·0mW, so that a power gain of 120 times or about 21·0db is achieved.

For an output stage a point is chosen to give maximum power. Two points are chosen. *C* for a slightly higher value of h.t. supply voltage than *B*. The output power is similar in each case, 20mW approximately, but the optimum load is lower for the lower voltage higher current condition.

Fig. 20 shows the circuit of an output stage and illustrates the preferred method of obtaining the bias current needed to bring the transistor on to the correct part of its characteristic. So long as *R* is high compared with the input resistance of the transistor, *e.g.*, not less than 1,000 ohms, the bias current will be mainly determined by the value of *R* and the voltage of the supply and not appreciably affected by the transistor itself.

Automatic bias can be obtained by a resistance in the base circuit in an analagous manner to cathode bias in a valve, but the arrangement has to be used with caution because it emphasizes the effects of variations in applied voltage and in transistor characteristics. In the case of valves, of course, auto-bias helps to smooth out such effects.

The low input resistance of a transistor may be disconcerting at first because to match into it from a previous stage demands a step-down transformer which would appear to be throwing away gain. However, there is another way of looking at the matter; the transistor is a current-operated device and a transformer with a

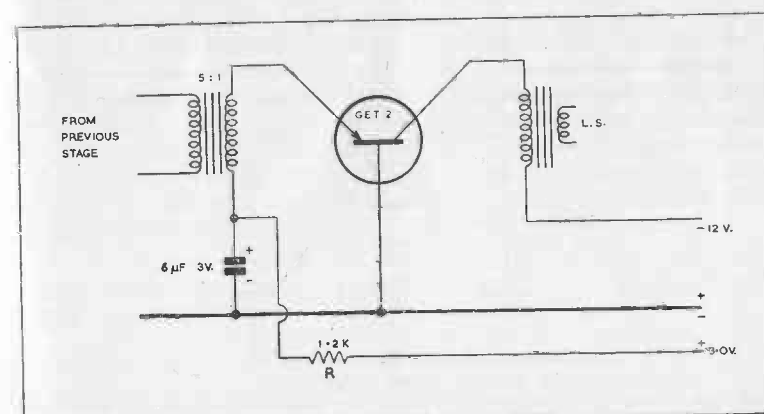


FIG. 20. POINT-CONTACT TRANSISTOR OUTPUT STAGE.

step-down turns ratio actually steps *up* the current so that there is no loss by this circuit arrangement. Detailed methods of matching at both r.f. and a.f. will be discussed later in connection with practical circuits.

The above remarks presuppose the earthed base circuit arrangement, *i.e.*, where the signal is fed in between the emitter and base and taken out between collector and base. Other arrangements are possible; base input with emitter earthed or base input with collector earthed; but their use in point-contact transistor circuits is not frequent because positive feedback occurs in the input circuit which is common to both collector-base and emitter-base current paths. This raises problems of stability but an analysis of such circuits does not fall within the scope of this book and no practical amplifiers of this sort will be discussed.

For oscillators this feedback offers interesting possibilities and the way in which it operates may readily be seen by considering Fig. 21 (a). Suppose that initially a supply is connected to the collector but that the emitter is left free. A current of, say, 1mA flows in the collector-base circuit and causes a voltage drop across R making point A positive to point B. If the emitter is then connected

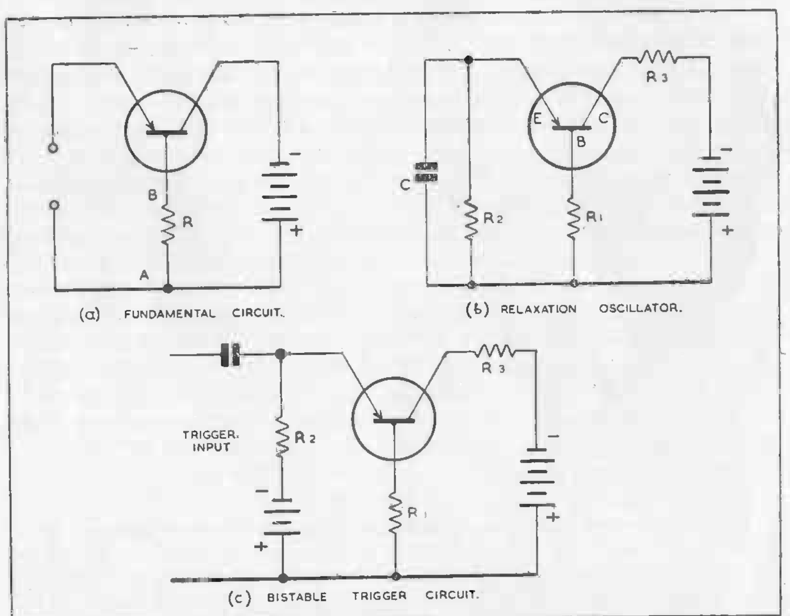
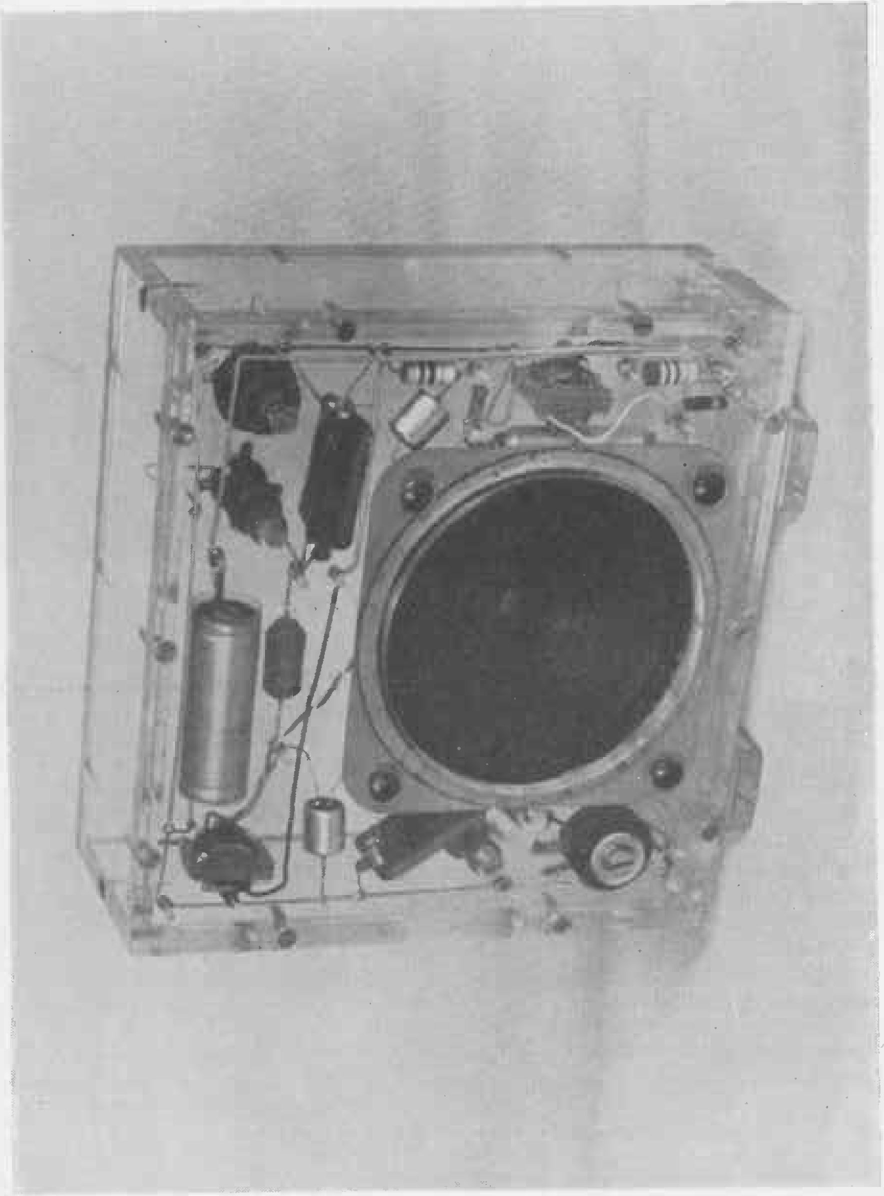


FIG. 21. NEGATIVE RESISTANCE CIRCUITS USING POINT-CONTACT TRANSISTORS.

to point A current will flow in this low-resistance path rather than in R, and positive emitter current will result amounting to perhaps 0·9mA. If the transistor has a current gain of two then this emitter current will increase the collector current by 1·8mA which in turn will add further to the emitter current again increasing collector current and so on until the transistor is driven to a point of saturation where it no longer exhibits current gain, and feedback therefore ceases. In practice such a circuit would destroy the transistor by excessive current, but by inserting sufficient resistance in the emitter circuit this can be prevented because the amount of current diverted to the emitter may be limited and the operating point will remain at a safe value of collector and emitter current. Such a resistance is shown in Fig. 21 (b), but the shunting of it by C produces an interesting state of affairs. The capacitor acts as a short circuit to R_2 as far as rapid changes are concerned and a sequence of events such as those described above can drive the transistor into the high current mode as though R_2 were absent. During this process C will become charged to the potential between the emitter and earth line, which is approximately equal to the drop across R_1. Once the saturated state has been reached feedback ceases and the transistor immediately relaxes to its low-current state. Feedback cannot start again until the negative charge on C has leaked away through R_2 sufficiently to allow positive emitter-current again when the cycle recommences and repeats itself as long as supplies are connected. This gives an approximate sawtooth voltage at point E and positive and negative pulses at C and B. The purpose of R_3 is to limit the pulse current to a safe value. Without the capacitor the circuit can be arranged as in Fig. 21 (c) with a negative bias on the emitter so that it may be triggered from the low to high current condition or *vice versa* by the injection of positive or negative pulses respectively and remain stable in either state in the absence of further pulses. Circuits of this description are of value in computers.

If, in a base feedback arrangement, the resistance is replaced by a parallel-tuned circuit, maximum feedback occurs at the resonant frequency and sine wave oscillations may be generated. Oscillator circuits of other descriptions will be discussed in a later chapter and the only further point to be mentioned in this connection is that there is a certain amount of built-in base resistance in every transistor owing to the resistance of the germanium itself and this can in certain cases cause instability.



TRANSISTOR RECEIVER.
This receiver uses two transistors in a reflex circuit. Its total current consumption is 6mA at 18V.
(By courtesy The General Electric Co. Ltd.)

VII

PRACTICAL RADIO CIRCUITS FOR POINT-CONTACT TRANSISTORS

IT seems that the widest commercial use for point-contact transistors will probably be in computers of various descriptions, but from the experimenter's viewpoint the most interesting applications are undoubtedly in radio.

When making up the circuits which follow experimenters are strongly urged to insert a 0–2mA meter in the emitter supply and a 0–10mA meter in the collector supply. Their use will help to avoid overload conditions and will also ensure a quicker appreciation of the mode of operation.

The first circuit to be described is the simple detector. It has already been explained that only positive emitter-current has any influence on the collector-current so that only the positive half cycles of a signal in an unbiased emitter-circuit produce a current change in the collector circuit and rectification occurs in a way somewhat analogous to the thermionic anode bend detector. Fig. 22 shows the circuit of a single transitor receiver operating headphones. The emitter is matched to the tuned circuit by means

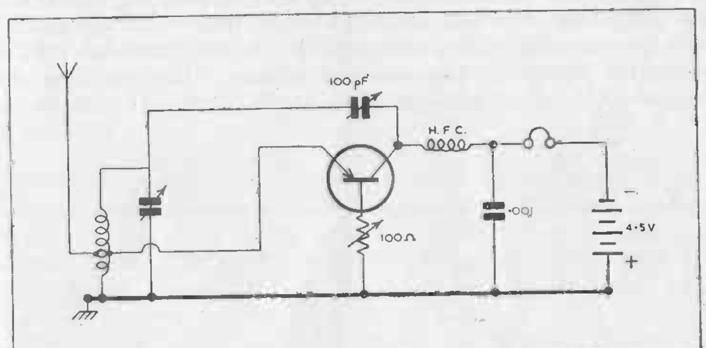


FIG. 22. SIMPLE TRANSISTOR RECEIVER.

of a tap on the coil. The position of this tap is not so critical as might be expected and a good starting point is to have it 25 per cent. from the earthy end. Adequate power for the operation of headphones is obtained with an h.t. supply of 4·5 volts and it should be noted that in this and all following point-contact transistor circuits *the polarity of the h.t. supply is opposite to that used in thermionic valve circuits.* A momentary lapse of memory on this point can destroy the transistor, so it is very important to bear it in mind. However, it should be realized that the damage can only occur if the current is allowed to reach an excessive value so that limiting resistance in the circuit can make it quite safe. In this particular case the telephone receivers should provide ample protection, since the short-circuit current of a pair of high resistance 'phones and a 4·5 volt supply is little over 1·0mA. The capacitor between the collector and the top of the tuned circuit is to provide reaction and increase the sensitivity of the arrangement. This simple arrangement is possible due to the absence of phase reversal between emitter and collector. The small resistance in the base lead provides a little bias current to the emitter and its value is best determined by experiment. It is needed because the impedance of the emitter with no bias current at all is so high that very little signal-current will flow in it until a certain level has been reached and this will result in low sensitivity for small signals. A little bias brings the transistor to a suitable operating point for maximum sensitivity; of course, more than the correct amount would give linear amplifying conditions and detection would not then occur. All transistors have inherent resistance in the base due to the resistance of the germanium itself and, in some cases, the bias due to this will be quite sufficient without the addition of any external resistance.

This detector may be followed by an amplifier stage of the sort already described when explaining characteristics, and the resulting receiver, whose circuit is shown in Fig. 23, may then be used for loudspeaker reception of a strong station. The h.t. has been increased to 12 volts and decoupling has been added to the detector

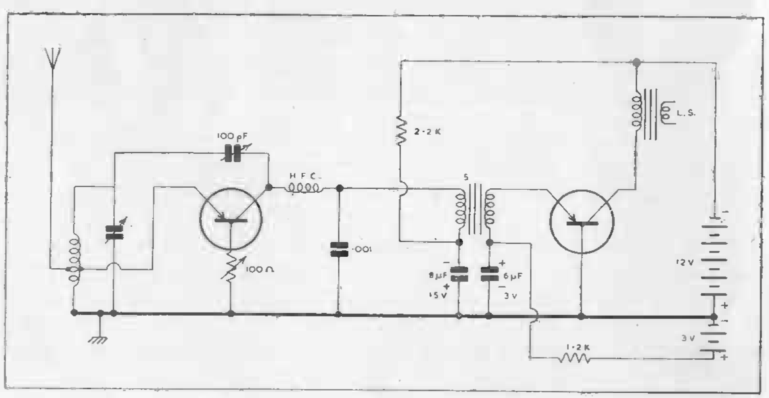


FIG. 23. LOCAL STATION RECEIVER.

collector circuit. The step-down coupling transformer must not be an ordinary inter-valve type connected in reverse because the resistance of the windings will be too high; the secondary winding in particular should have low resistance and a value of 50 ohms is reasonable. To ensure that the transistor is being worked at high enough dissipation to give sufficient output and yet is not being overrun it is essential to use a meter in the collector supply. When working out the collector dissipation the actual voltage at the collector should be taken. If an output transformer of primary resistance 500 ohms is being used, then with a collector-current of 8mA there will be 4 volts dropped across it which is a significant proportion of the total h.t. and would mean that with a 12V h.t. line the collector dissipation would be 64mW instead of 96mW. Since transformers with even higher resistance than the example are not unknown this is a point that should be watched. Variation of the bias resistor will enable the collector-current to be set at any desired figure. The optimum load for matching purposes will depend upon the actual operating point that has been chosen but a close approximation can be arrived at by dividing the operating voltage by the collector-current when the result will be given in thousands of ohms. For example, 12V 6mA will require a load of 2000 ohms approx. A power output of about 20 milliwatts may seem too small to be of any use but it is surprising how acceptable a volume is produced especially if occasional overloading on peaks is tolerated. One practical point should be mentioned in this connection; unless it is desired to make the smallest possible receiver (and, of course, this is one aim that is greatly helped by the use of transistors) it is advisable to use the biggest loudspeaker available to achieve greatest sensitivity. It is a mistaken notion that a big loudspeaker requires more drive.

Increased power can, of course, be obtained by use of a push-pull output stage. Maximum efficiency suggests the use of class B operation but distortion of rather an unpleasant sort is difficult to avoid and class AB operation is recommended for a start. An output stage is shown in Fig. 24, and it will be seen that series resistance has been inserted in each emitter lead; this is a good practical precaution against oscillation to which all push-pull circuits are liable and at the same time it ensures more linear amplification by masking variations in emitter impedance and providing a measure of negative feedback. Gain is reduced somewhat but the circuit is intended for cases where the chief consideration is maximum power output. It is not possible fully to load such a stage without an intermediate stage between it and the detector.

An interesting output stage that is capable of about 400 milliwatts from a pair of transistors makes use of the duality concept mentioned previously. It will not be described in detail

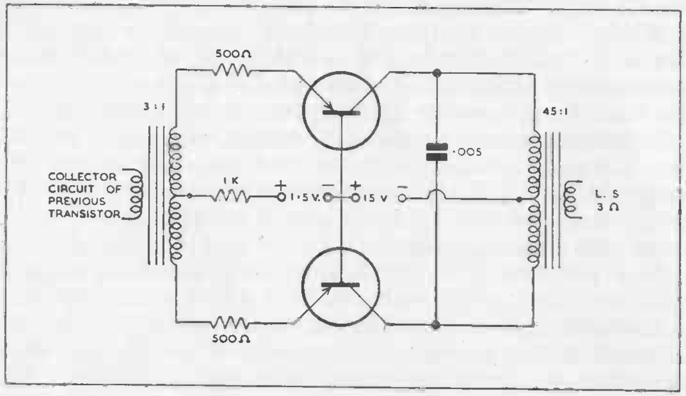


FIG. 24. PUSH-PULL OUTPUT STAGE.

here since its use would be of advantage only under exceptional conditions.

The transistors in their " quiescent " state are biased so that their collector-currents are high and their voltage low. Application of a signal results in a decrease in current and an increase in voltage. The current is derived from a constant-current source consisting of a voltage supply in series with a high impedance composed of both resistance and inductance. In aircraft where a high current 24V supply is available the use of such a circuit would enable a good output to be obtained without vibrators or other means of providing a higher voltage supply.

Provision of gain at radio frequencies is not difficult with transistors and the circuit in Fig. 25 shows an h.f. stage feeding into

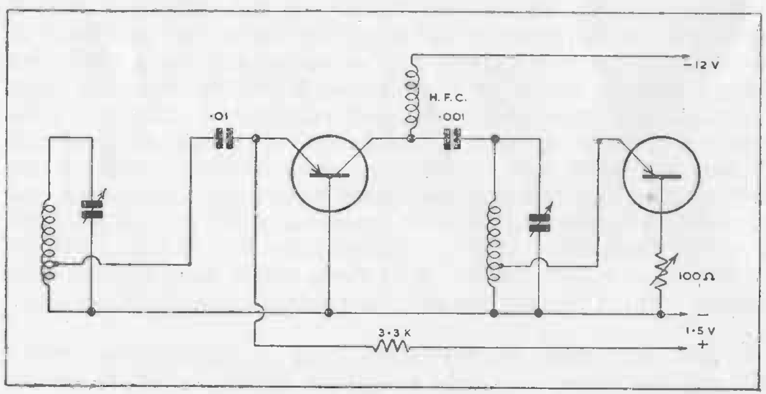


FIG. 25. POINT-CONTACT TRANSISTOR H.F. STAGE.

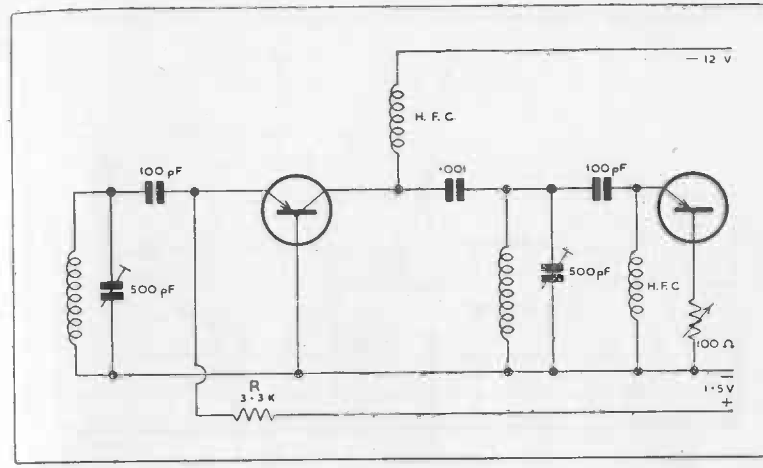


FIG. 26. H.F. STAGE WITH ALTERNATIVE FORM OF MATCHING.

a detector. Matching has been performed by tapping down on the tuned circuits and bias for the h.f. stage is obtained in substantially the same way as in the output stage already described. Fig. 26 shows an alternative method of arranging h.f. and detector stages. In this case the matching depends on the relative values of the capacitors directly across the tuning coils and those in series with the emitters. These latter capacitors also constitute part of the tuning capacitance being connected across the coils through the comparatively low resistance of the emitter-base path of the transistor. This type of matching is most convenient in receivers fixed tuned to a number of stations selected by switching. It is somewhat easier for the experimenter to determine the optimum matching condition by varying capacitance values than by altering the position of tappings especially when pie-wound coils are employed. Bias to the h.f. stage is supplied through *R* which, being high compared to the input impedance of the transistor, has no appreciable effect on gain. In the detector stage, too, a d.c. path is required for the emitter-current and this is provided by the r.f. choke. A resistance cannot be used here without sacrificing gain because a path must be provided in this part of the circuit with low impedance at audio frequency to prevent what is in effect negative feedback.

Where utmost gain with the minimum number of transistors is required it is worth considering reflex arrangements. There is no particular difficulty about these provided that the possibilities of instability are clearly understood and guarded against. A practical two-transistor circuit is given in Fig. 27 where the output stage also provides r.f. amplification. Variants of this using the other type of

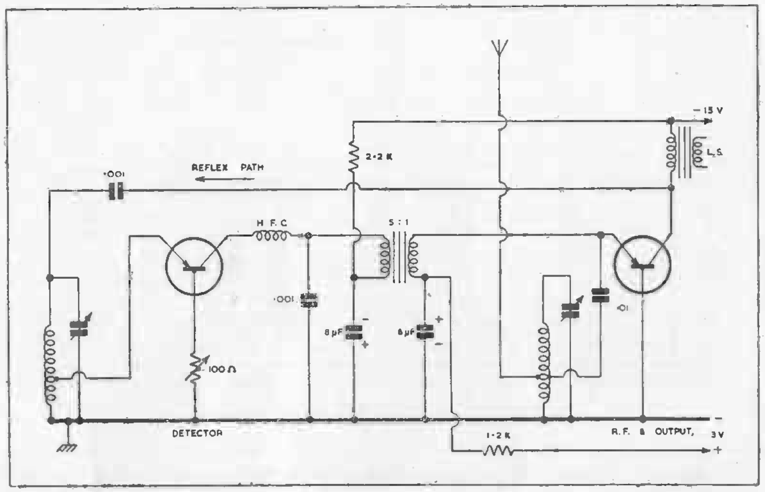


FIG. 27. REFLEX RECEIVER.

h.f. matching described above are, of course, possible.

Where higher gain than that given by the above simple sets is required, *e.g.*, for small frame aerial use, it is desirable to think in terms of a super-het. since with more than one h.f. stage stability is not easily ensured. An interesting frequency changer circuit is given in Fig. 28 where it will be seen that the three electrodes of the transistor are each connected to a tuned circuit. The signal tuning coil is matched by the usual tapping, oscillation being obtained by inserting a parallel-tuned circuit in the base lead and the i.f. is developed in the tuned circuit in the collector lead. The resistance to the emitter controls the strength of oscillation and its value should be varied to achieve the highest conversion gain; in some cases returning it to $1\frac{1}{2}$V positive instead of earth will give improved signal strength. In no circumstances should this resistance be reduced to zero since it would then allow excessive currents to flow. It is necessary, to avoid undue damping of the i.f. circuit, to use a low L/C ratio here or tap the collector down on the coil. It is also desirable in the interests of stability to use a low L/C ratio for the oscillator tuned circuit. I.F. stages to follow this frequency changer can take the same form as the h.f. stage already described.

Gain control has not been shown in any of the above circuits, but sufficient is obtainable in most cases by using variable resistance or capacitance in series with the aerial. As an alternative the signal may be fed to the emitter of the h.f. transistor *via* a potentiometer of value 1,000 ohms or so. More elaborate methods than these are

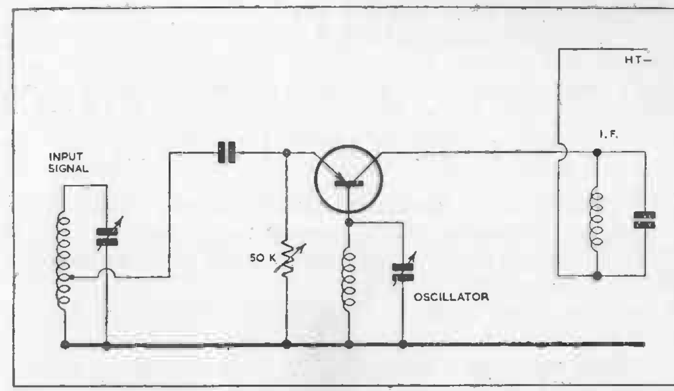


FIG. 28. FREQUENCY CHANGER USING POINT-CONTACT TRANSISTORS.

not needed in sets of limited sensitivity and where higher gain sets are designed ganged controls of the potentiometer type are recommended. Practical a.v.c. circuits still await development and provide a rewarding line of enquiry to the experimenter.

VIII

MISCELLANEOUS POINT-CONTACT TRANSISTOR CIRCUITS

THE circuits to be described in this chapter depend on the negative resistance effect already mentioned in Chapter 6 which renders possible a greater variety of oscillators than is the case with thermionic triodes.

Four sine wave oscillators are given in Fig. 29. In (a) the feedback is provided by the high impedance at resonance of the parallel-tuned circuit in the base. This feedback can be reduced to any desired extent by resistance in series with the emitter and limiting the feedback in this way ensures good waveform and stability. A low L/C ratio gives best frequency stability in this circuit which is perhaps the best for most purposes. A 4·5V supply is sufficient for an oscillator which can be used to operate a bridge or provide a source of l.f. or h.f. for amplifier or receiver testing. If modulated r.f. is required, it is only necessary to put the r.f. and l.f. tuned

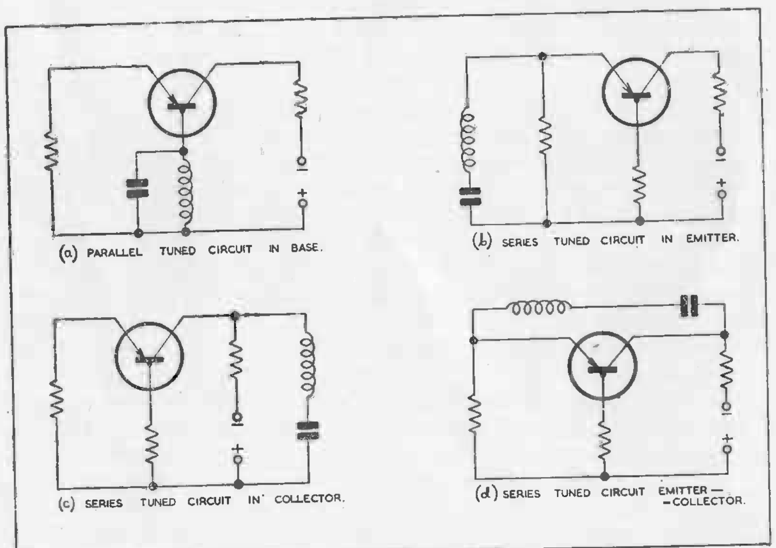


FIG. 29. FOUR POSSIBLE SINE WAVE CIRCUITS.

circuits in series with one another in the base. The output is best extracted by windings coupled to the oscillatory circuits.

In the other circuit arrangements shown the feedback is provided by the resistance in the base and the frequency at which it is effective is determined by the series-tuned circuits which, of course, have a minimum impedance at resonance. Best stability and waveform are obtained when a high L/C ratio is used and when the base resistance is not larger than is necessary to maintain the oscillation.

Although a crystal controlled oscillator is possible without any L/C circuit the most satisfactory arrangement which avoids the possibility of spurious modes is shown in Fig. 30. Such a circuit

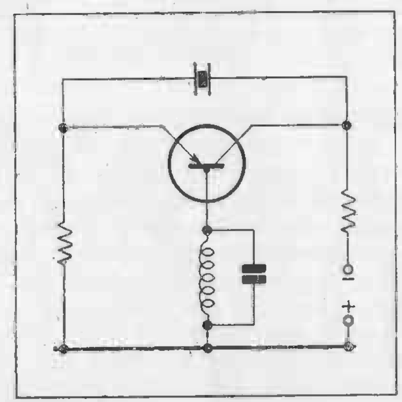


FIG. 30. CRYSTAL CONTROLLED TRANSISTOR OSCILLATOR.

may be made the basis of a low-powered transmitter and ranges of 100 miles and more have been achieved using such arrangements. For telephony, modulation may be carried out in the collector circuit similarly to the anode modulation of a thermionic valve oscillator.

The relaxation type of oscillator has already been described in Chapter 6 and it is attractive owing to its simplicity and modest power requirements. An electronic version of the bagpipes has been demonstrated using this type of oscillator for the tone source and this suggests that other similar uses might be worth investigation.

A typical trigger circuit is shown in Fig. 31. The particular function it is performing is to operate a relay requiring a current of about 10mA from a photocell giving an output current of a few tens of microamps. Having been triggered the transistor remains in the high-current condition until the supply is interrupted. Modifications of this fundamental circuit are possible to suit individual require-

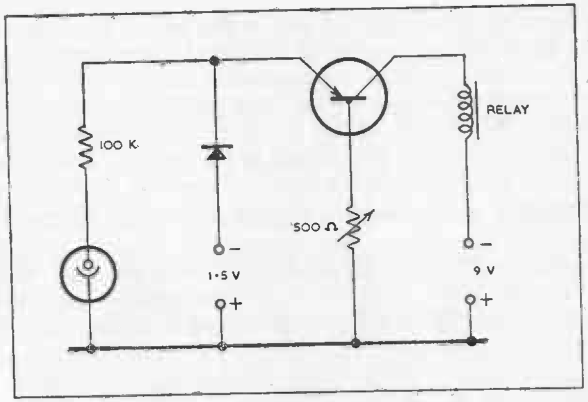


FIG. 31. TRIGGER CIRCUIT.

ments. The crystal diode is used as a non-linear resistance to prevent any large proportion of the emitter current from passing through the photocell. The operation of the circuit is straightforward; initially there is sufficient negative bias to prevent the flow of emitter current which would otherwise result from the presence of base resistance. A small current from the photocell increases the current in the collector-base path so that the voltage drop across the base resistance is sufficient to overcome the bias so that feedback and triggering to the high current condition occurs. Once the diode has started to conduct its resistance falls to a low value so that the majority of the emitter-current takes this path rather than through the photocell.

It would seem that these oscillator and trigger circuits might well be adapted for model control where size and current consumption are of so great importance and the basic circuits given above should be sufficient indication to enable the enthusiast to explore the possibilities.

IX

JUNCTION TRANSISTOR CHARACTERISTICS

THE collector current-collector voltage curves for a typical *p–n–p* junction in its earthed base connection have been given in Fig. 7 and comparison with those of the point-contact type already shown in Fig. 19 shows them to be generally similar. Such differences as exist are in points of detail. For instance, the curve for zero emitter current indicates a value of 10 to 20 microamps instead of 1 to 2 milliamps. Then, the knee of the current curves actually crosses the zero voltage axis instead of approaching within a volt or two of it. These two factors lead to current economy when the transistor is used near or at cut-off, high efficiency when used for power output and ability to operate at extremely low h.t. voltage. The spacing between the collector-current curves for one milliamp. steps of emitter-current is uniform, indicating excellent linearity, and the current gain which this spacing represents is a little less than unity instead of being between 2 and 4 as for the point-contact type. This might suggest lower stage gain, but because of the very low input resistance—less than 50 ohms—and the high output resistance of about 0·5 Megohm, a gain of 30db can be achieved as compared with 20 db for the point-contact type. With the earthed-base connection there is no phase reversal between input and output. The low value of alpha has important consequences as far as circuits are concerned, and the earthed-emitter and earthed-collector configurations which were difficult with point-contact types because of instability, are fundamentally stable and commonly used.

Because it is a popular method of use, separate curves are usually published for earthed-emitter conditions and a typical set of characteristics is shown in Fig. 32. The collector-current curves are drawn for various fixed values of base-current instead of emitter current since for this arrangement the base can be regarded as the control electrode. As the collector-current, in its return to the base, has to share the path through the input circuit with the emitter current which flows in the opposite direction, the net current to the base will be the difference between emitter and collector currents. Reference to the previous curves will show that the value of this difference is small; *e.g.*, when at collector-voltage 10·0 the emitter current is 1mA, the collector-current is 0·95mA so that the base current is 50 microamps, whilst at emitter-current 2·0mA the collector-current of 1·9mA gives the base-current a value of 100 microamps. It is apparent, then, that a change in base-current

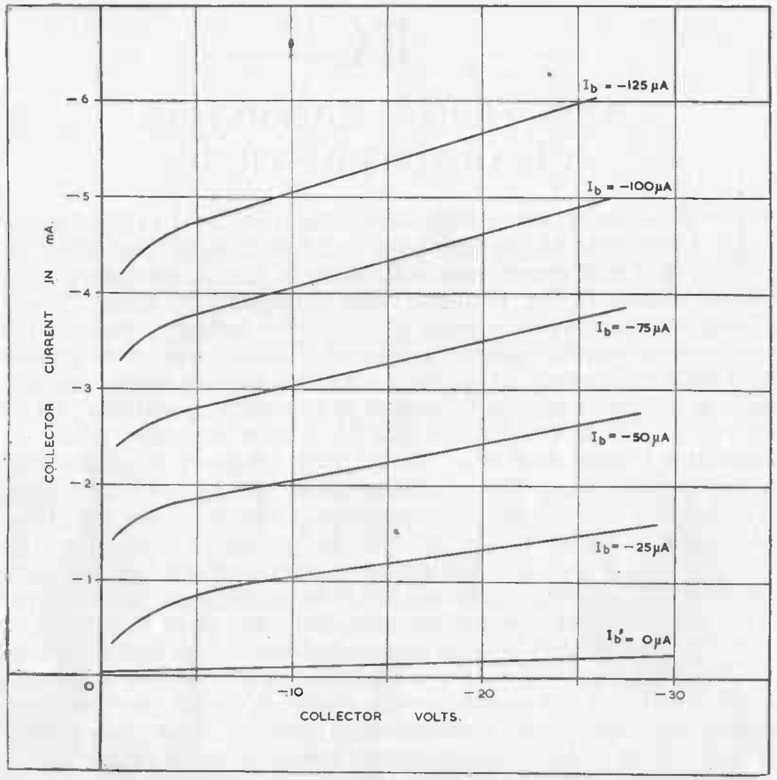


FIG. 32. COLLECTOR-CURRENT CURVES OF A TYPICAL *p-n-p* JUNCTION TRANSISTOR IN EARTHED-EMITTER CONNECTION.

of 50 microamps results in a change in collector-current of nearly 1·0 millamp, so that with the earthed emitter base input circuit there is a current gain of about 20. The symbol β is sometimes used for this parameter. In fact the value is equal to $\frac{\alpha}{1-\alpha}$ so that the nearer α is to unity the greater is its magnitude, and when alpha is, for example, 0·98 the current gain rises to 50 approx. The curves in Fig. 32 are for such a transistor.

The overall effects of this mode of operation are increased gain, higher input resistance and lower output resistance, and there is phase reversal between input and output. Linearity suffers to some extent, but the arrangement is more convenient than the earthed-base one when stages are to be used in cascade because of the less disparity in output and input resistance values. Typical values are 1000 ohms for input resistance and 50,000 ohms for output resistance.

Power gains of 40 db can be achieved with optimum matching, but where stages are cascaded with R/C coupling the stage gain is reduced to about 30 db.

The earthed-collector connection is used less frequently than either of the other arrangements because the stage gain drops to about 14 db. The input impedance is high and the output impedance is low, so that it is useful for impedance matching like a cathode-follower valve which it resembles in some respects including a lack of phase reversal between input and output. The actual impedance values depend largely upon load impedances; in a typical case of an earthed-collector transistor operating into an output load of 600 ohms the input impedance might be about 30,000 ohms. As an approximation the ratio of the input to output impedance is equal to $\frac{1}{1-\alpha}$.

Although the above remarks refer primarily to the *p–n–p* type of transistor they are equally applicable to the *n–p–n* type provided that the necessary change in polarity of supply current is taken into account.

A specific point of difference in operation between the two types is the better h.f. performance of the *n–p–n* type. This is because the current carriers responsible for the transistor action are electrons instead of positive holes and their greater mobility reduces transit time.

X

JUNCTION TRANSISTOR CIRCUITS

BECAUSE the *p–n–p* type is the more commonly available it will be used for most of the circuit illustrations in this chapter, but the data is also valid for the *n–p–n* type provided that the polarity of the supplies is reversed.

In l.f. amplifiers, where junction types are at present mainly used, the high ratio between the values of input and output impedance causes matching difficulties in the earthed-base connection and so it is rarely used. On the other hand in tuned amplifiers the difficulty is easily overcome by driving the emitter from a series-tuned circuit whose impedance is, of course, very low at its resonant frequency. Fig. 33 shows part of an i.f. amplifier using this arrangement. Transistors now available begin to fall off in performance above about 10 kc/s but, even so, at 500 kc/s a stage gain of about 10 may be expected with this circuit. The collector is tapped in at about one-third of the coil for optimum matching, which may seem odd in view of the high values which have been quoted for collector impedance, but at frequencies near the upper limit of operation figures taken statically no longer apply. Separate supplies are used for collector and emitter bias. "Automatic" bias from a resistance in the base is not ruled out by instability as in the case of the point-contact transistor, but the curves show that over the majority of the usable characteristic the emitter-current is greater than the collector-current so that such a circuit places a severe limit on the range of operating conditions. Feeding extra current into the base resistance from the h.t. overcomes the limitation, but the arrangement is no less extravagant than the use of a separate supply.

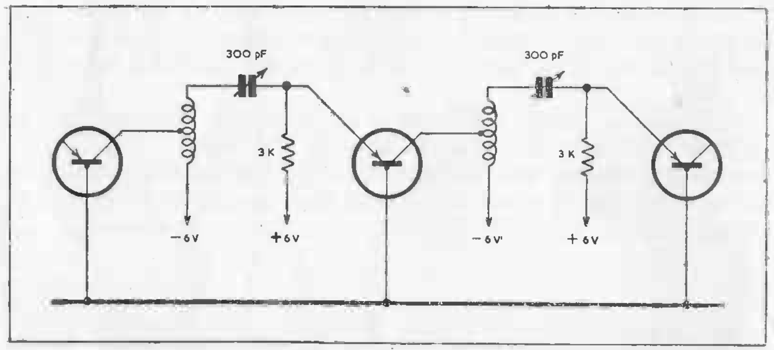


FIG. 33. SERIES-TUNED I.F. STAGE WITH JUNCTION TRANSISTORS.

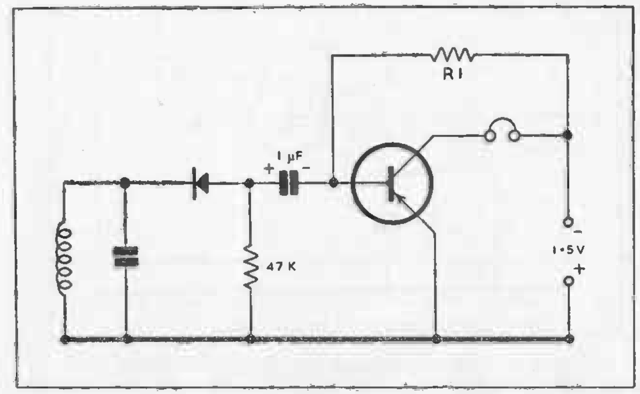


FIG. 34. L.F. JUNCTION AMPLIFIER FOLLOWING CRYSTAL RECEIVER.

Fig. 34 shows a typical earthed-emitter l.f. amplifier which is intended to follow a crystal set and give increased power. For headphone working the sole power supply is a single 1·5V cell, which provides both collector and emitter currents. The resistance R_1 allows the emitter-current to be higher than the collector-current so that a satisfactory operating point can be chosen. Another way of looking at the function of this resistance is to regard it as supplying the negative base current shown in the earthed emitter curves in Fig. 32. If this resistance is omitted and the base is left floating then the operating point must be that where collector and emitter currents are equal. It is possible to work at this point, but the condition is unlikely to be the most favourable, and it is best to use a resistance of a value determined by trial to suit a particular transistor and the signal to be handled. A typical starting value would be 100,000 ohms. As an alternative, the bias current may be supplied by the crystal detector itself, in which case the coupling capacitor may also be omitted. This arrangement is most satisfactory when the initial signal is not very weak.

The gain given by the above arrangement is of a useful order, but is not the maximum that can be achieved because there is a mismatch between the output of the crystal set and the input of the amplifier. A coupling transformer of step-down ratio 5: 1 is used to give correct matching in Fig. 35. The bias circuit previously described can no longer be used because the transformer secondary provides a low resistance path between base and emitter. The battery is, therefore, placed in the emitter lead and a resistance is connected in series with the transformer secondary to control the amount of current flowing in the emitter circuit. This is by-passed

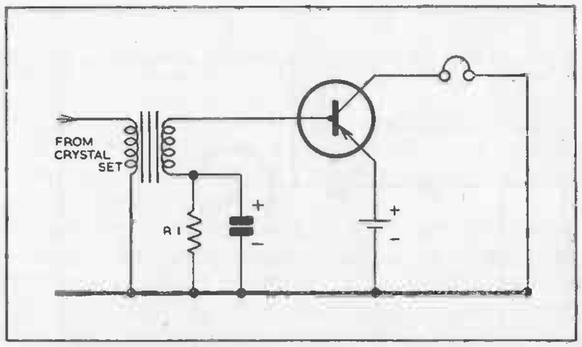


FIG. 35. TRANSFORMER COUPLED AMPLIFIER.

to provide a low impedance path for the l.f. signal. Omission of the resistance would, of course, result in the equal collector and emitter-current condition mentioned above.

Although it is not likely to be desirable in this particular application, to illustrate the point for cases where it might be of use the circuit is shown in Fig. 36 with the battery moved to enable operation in the region where collector-current is greater than emitter-current.

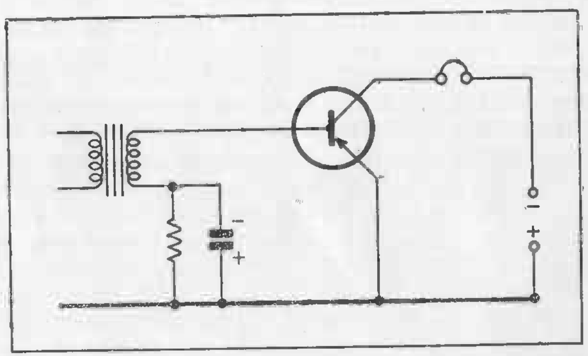


FIG. 36. BIAS ARRANGEMENT TO GIVE Ic GREATER THAN Ie.

An interesting alternative circuit for a crystal set amplifier is shown in Fig. 37, where the earthed-collector connection is employed with its high input resistance to match direct to the crystal set and on the output side to low-resistance headphones. The provision of bias presents no novelty and the circuit will be seen to be the same as that for the earthed-emitter connection except that the load is placed in the collector-emitter path between emitter and earth instead

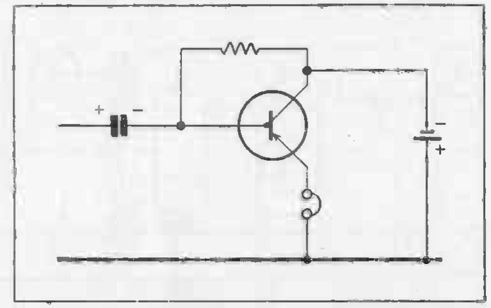


FIG. 37. EARTHED-COLLECTOR AMPLIFIER.

of between collector and earth. This, of course, results in negative feedback which reduces the voltage gain to unity as in the case of a cathode-follower circuit (which it resembles) but gives an impedance transformation and current gain. The power gain given by this arrangement is enough to be useful, but is appreciably below that of the circuits previously described.

A detailed consideration of hearing aid circuits is of too specialist an interest for inclusion here, but the circuits have a more general application and are worth examination. A basic three-stage amplifier is shown in Fig. 38 employing the earthed-emitter

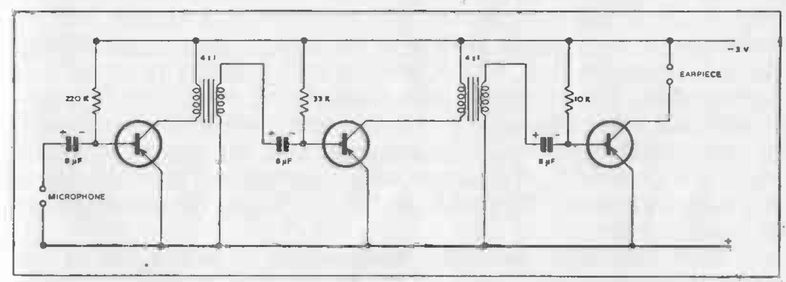


FIG. 38. FUNDAMENTAL CIRCUIT OF HEARING AID AMPLIFIER.

connection in each stage. Bias is provided by yet another minor variant of the fundamental arrangements already described and is graduated in each stage to suit the signal level. It is usual to use a moving coil type of microphone to match into the relatively low impedance of the earthed-emitter transistor, but a crystal microphone may be employed with a matching transformer or another possibility is the use of an earthed-collector stage for this purpose. The circuit of an American hearing aid is shown in Fig. 39, and it is interesting for the rather unusual circuit configuration which at first sight looks as if it includes two earthed-collector stages. In fact

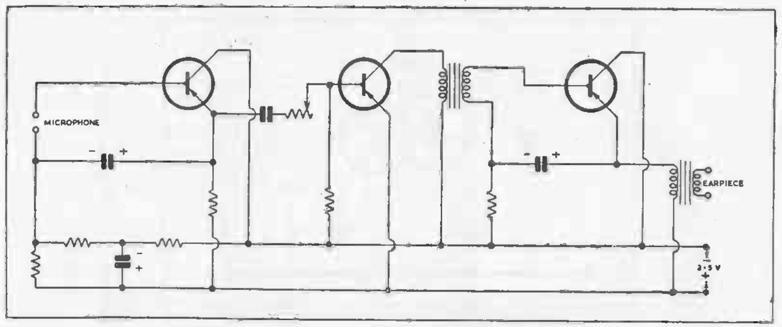


FIG. 39. CIRCUIT OF COMMERCIAL HEARING AID.

all three stages are of the earthed-emitter type because in each case the signal is fed in between base and emitter, not base and collector. A careful examination of such circuits as this will help the rapid recognition of the essential features of other unfamiliar configurations which may otherwise prove puzzling.

The collector-current of germanium junction transistors is strongly dependent on temperature and with simple bias circuits it is difficult to avoid changes of operating point and consequent variations in gain with temperature changes. Solutions of this problem inevitably result in higher power consumption, but not to such a degree as to be prohibitive. Resistance in the emitter lead is one effective measure; this operates in a similar way to resistance in the cathode lead of a thermionic valve in stabilizing the d.c. condition and, like it, should be by-passed to avoid a.c. degeneration. The subject is complicated and need not be over-emphasized where operation under domestic conditions is concerned. Its main importance is in the industrial and Services applications where the possibility of unfavourable temperatures must be taken into account and where, apart from this limitation, the transistor has so much to offer.

When used as an oscillator the junction transistor has to use feedback circuits of a similar type to those in thermionic valve practice. A typical circuit is shown in Fig. 40, and a feature of it which is not shared by any other electronic oscillator is its ability to operate from supplies of fractional voltage. Such an oscillator will work from the power derived from a small coin and a crocodile clip separated by a piece of blotting paper moistened in the mouth or from the output of a small photocell illuminated by a pocket torch.

No treatment of transistor circuits would be complete without some reference to what has been called complementary symmetry. Circuits making use of this principle have only been demonstrated experimentally up to the present time because there are some practical difficulties in their employment which have yet to be cleared.

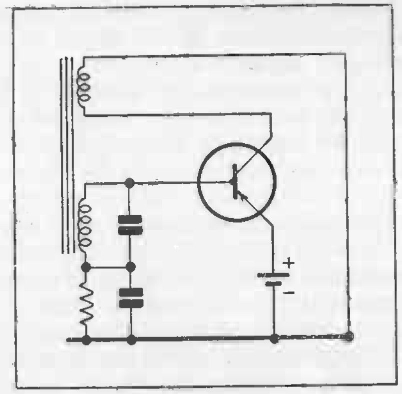


FIG. 40. JUNCTION TRANSISTOR L.F. OSCILLATOR.

However, they are of the very greatest interest in the way they are able to dispense with many of the usual coupling components. Complementary symmetry circuits depend on the fact that *p–n–p* and *n–p–n* transistors can be made having identical characteristics but operating with reversed polarity. One of the difficulties of direct coupling in valve circuits is that the anode of one valve at a positive potential has to be connected to the grid of the next, which is at negative potential, and if an alternative type of valve existed whose anode ran at negative and grid at positive potential, direct coupling

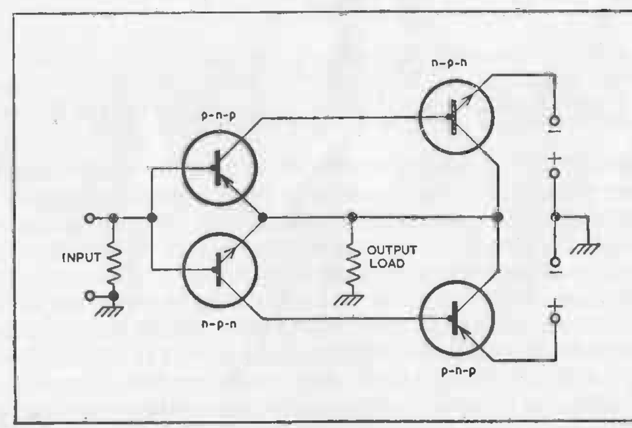


FIG. 41. A PUSH-PULL AMPLIFIER USING COMPLEMENTARY SYMMETRY.

would be greatly simplified. In the case of transistors such an alternative type exists and makes possible such a circuit as that in Fig. 41. This shows direct inter-stage coupling between the *p–n–p* and *n–p–n* transistors in the upper part of the circuit and between the *n–p–n* and *p–n–p* transistors in the lower part. In addition, it shows how push-pull operation may be achieved without the usual phase-splitting arrangements by using complementary types in the two halves of the amplifier. A complete explanation of the working of this amplifier would be too lengthy for this handbook, but the subject was dealt with more fully in the September, 1953, issue of *Electronics*.

F.M. transmitters and receivers and even a television set have been demonstrated using transistors in all functions normally carried out by thermionic valves, but many of the types used were still in the development stage so that circuit data would be of little value. These achievements must for the moment be regarded as peeps into the possible future and a striking indication of the extent to which the transistor can eventually replace the thermionic valve.

XI

TESTING OF DIODES AND TRANSISTORS

GENERALLY speaking the amateur needs a rough check of serviceability rather than a complete measurement of all characteristics of a diode or transistor. This is just as well because there is rather more than would appear at first sight even in the testing of an apparently simple diode.

In the case of the diode, the obvious points to check are the forward and reverse resistance. There is no particular difficulty in doing this, but it is easy to be thoroughly misled by the results if they are obtained on the resistance scale of a multi-range test meter. An example will make this clear. A typical crystal may pass 4mA at +1V which corresponds to a resistance value of 250 ohms, but at 0·5V the current passed will be less than 1mA corresponding to a resistance value of more than 500 ohms. That is to say that the crystal has varied its resistance by a ratio of more than two to one over this small range of applied volts. A similar state of affairs obtains when

measuring reverse resistance though the variations tend to be more complex, for, whilst forward resistance falls with increasing voltage, back resistance has a maximum (usually at somewhere between 3 and 10 volts) and falls away at both higher and lower values. Clearly then it is useless to compare measured values of resistance with published ones unless it is certain that the conditions of measurement are identical.

However, bearing in mind this limitation, use of a multi-range meter can give some useful indications of a comparative nature by testing a suspect crystal against one known to be good and, of course, it can give an absolute indication of short circuits and open circuits.

A practical method of test for crystals other than mixer types, which gives conditions sufficiently near to those used by makers and yet is very simple, is shown in Fig. 42 (a) and (b). When measuring

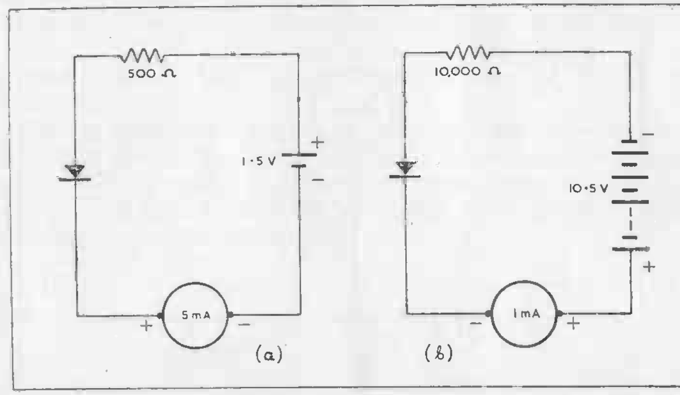


FIG. 42(a). CIRCUIT TO CHECK FORWARD RESISTANCE OF A GERMANIUM DIODE.
(b). CIRCUIT TO CHECK REVERSE RESISTANCE OF A GERMANIUM DIODE.

the forward resistance the 500-ohm limiter prevents the current rising above 3·0mA even with a short circuit. An average diode will read about 2·0mA whilst one which passes 1mA at + 1V will give a reading of 1mA. Any reading below this would indicate high forward resistance. For reverse measurements in the region of 10V a 10·5V battery and a 10,000-ohm limiter should be used with a 1mA meter. A reading of 0·1mA will indicate a resistance of 100,000 ohms, so most crystals of the GEX34 class will read less than this value of current. Some low-impedance video-detector types may read up to half-scale. Tests in the region of 50 volts should be taken with a 50V battery and a 50,000-ohm limiter. A crystal with a back resistance of 200,000 ohms will give a reading of about 0·2mA and one of 0·1mA will indicate nearly 0·5 Megohm. Particularly with the lower-resistance crystals, the applied potential will be less than 50V because of the drop in the limiting resistor, but

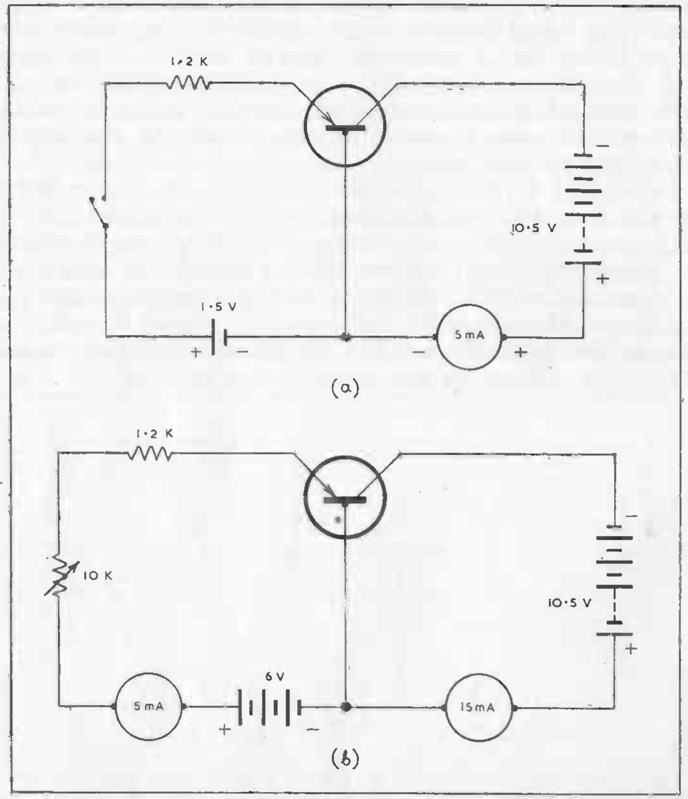


FIG. 43(a). CIRCUIT FOR ROUGH CHECK OF JUNCTION OR POINT-CONTACT TRANSISTORS.

(b). CIRCUIT FOR TAKING CHARACTERISTIC MEASUREMENTS OF POINT-CONTACT OR JUNCTION TRANSISTORS.

a fair idea can be obtained of the condition of the device by this simple check. More accurate measurements may be taken where there is a real reason for requiring them by setting up an arrangement with an extra meter to measure the voltage across the diode and a variable resistance to adjust it to the correct value. It must be remembered in this case to make allowance for the voltmeter current.

Unfortunately, these static figures are only half the story in many cases. They give a good idea of the performance of the diode at d.c. and low frequencies but they do not show what will happen at r.f. For this reason functional tests are carried out by most makers at the frequency and voltage for which their use is intended; *e.g.*, video detectors are usually tested at 35 or 45 mc/s. These tests are not easy to duplicate, but a diode which had once passed them

would pass again unless it had been overloaded to such an extent that its static figures would be out of limits.

Transistors are more complex, and no amateur can hope to set up the gear for thoroughly comprehensive tests. However, here again a simple set-up will give a good idea of their state. Fig. 43 (a) shows the circuit which is satisfactory for point-contact or junction transistors with the reservation that some hearing aid types of junction transistors must not have as much as 10·5 volts applied to them, and in this case the voltage should be reduced to 4·5.

With the switch open the current will not normally exceed 1·0mA for a point-contact type, and it will be less than 20μA in most junction types. When the switch is closed the current will rise if transistor action is taking place. For point-contact types the rise will be at least 2·0mA and may even exceed 4·0mA. In junction types the rise will be a little less than 1·5mA. For more refined measurements the circuit should be modified to that in Fig. 43 (b) where the emitter current may be set to any desired value and measured exactly. Such an arrangement may be used to draw a family of curves.

Having established that the transistor is functioning under these static conditions, its further performance is best checked in a simple amplifier circuit using if possible a signal generator or service oscillator, but if not available, the signal from a local broadcast station makes a good substitute.

XII

THE TRANSISTOR AND ITS EQUIVALENT NETWORK

ALTHOUGH the radio engineer tends more and more to use equivalent networks when working on valve-circuit problems, it is well known that it is possible to do a great deal of effective design work with no knowledge of this convention. This is partly because there exists a great fund of valve-circuit knowledge which can be drawn upon and partly because in so many cases the valve circuit is simple in that there is no interaction between input and output. Furthermore, for most purposes, the input impedance may be regarded as infinite.

When designing around transistors a different state of affairs exists; there is as yet no accumulated circuit knowledge and complications arise from the inevitable presence of interaction between input and output together with a value of input impedance which is always low enough to have to be taken into consideration. There are, in addition, special complexities in the case of the point-contact transistor due to its current gain being greater than one.

In view of all this, a knowledge of the equivalent network and how to use it is virtually essential to anyone who wishes to go farther than to merely copy circuits already worked out by someone else.

The equivalent network of the transistor used as an earthed-base amplifier of small signals at frequencies well below cut-off is shown in Fig. 44.

The actual terminals of the transistor are shown by the points E, C and B. Since this is not an actual circuit but an arrangement to represent the behaviour of the transistor as a small signal a.c. amplifier, no details are shown of the d.c. supplies to the electrodes, which are, of course, necessary to bring the device into a suitable working state.

It is assumed that the d.c. bias arrangement is so chosen that it does not upset the a.c. operation of the amplifier. For instance, the emitter current bias is usually drawn through a resistance whose value is very much higher than the input resistance of the transistor amplifier.

The emitter resistance r_e represents the a.c. slope resistance of the emitter looked at as a diode biased in the direction of the forward current, whilst r_c represents the a.c. slope resistance of the collector as a diode biased in the reverse direction. The resistance of the actual material of which the base is composed is represented by r_b. Any additional resistance deliberately inserted in the base lead is also included in the value given to this symbol.

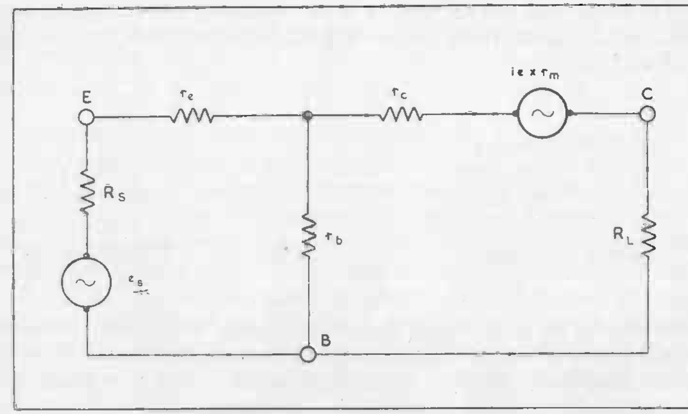


FIG 44. EARTHED BASE EQUIVALENT A.C. NETWORK.

Besides these straightforward quantities something is required to indicate the amplifying action of the transistor which is due to the transfer of current from the low-resistance emitter to base path to the high-resistance collector to base path. This transferred current requires a voltage to drive it through the collector circuit and this is supplied by the voltage generator marked $r_m i_e$ which thus represents the amplifying action of the transistor.

The voltage developed in the collector circuit for a certain value of emitter-current i_e will depend on the magnitude of r_m so this quantity is a measure of the efficiency of transfer. In a point-contact type, due to a " secondary emission " type of effect, the transfer is greater than unity and this is indicated by r_m being greater than r_c (the voltage given by the product of r_m and i_e will cause a current greater than i_c to flow in r_e).

To complete the network the external circuit elements are given consisting of e_s a voltage generator representing the input signal, R_s representing the resistance of the signal source (in a practical case this might be the output resistance of the previous stage after transformation by the coupling arrangement) and R_L representing the resistance of the output load.

Now, to compute the relationships between currents and voltages in such a network is a matter of straightforward algebra, but here we are only interested in some of the final results. The input resistance of the transistor is given by the expression:—

$$r_e + r_b - \frac{r_b\,(r_b + r_m)}{R_L + r_c + r_b}$$

The output resistance is given by:—

$$r_c + r_b - \frac{r_b\,(r_b + r_m)}{R_s + r_e + r_b}$$

To work out actual values it is necessary to assign values to r_e, etc., and typical ones for both point-contact and junction types are given below:—

Point-Contact		*Junction*	
$r_e =$	250 ohms	$r_e =$	50 ohms
$r_b =$	90 ohms	$r_b =$	100 ohms
$r_c =$	20,000 ohms	$r_c =$	1 Megohm
$r_m =$	45,000 ohms	$r_m =$	970,000 ohms

It should be mentioned that these values will vary appreciably according to the bias conditions, but the ones given can well be used as a starting point to give an indication of impedance levels to be expected under various conditions. Incidentally, there are certain simplifications of the formulæ which can sometimes be adopted without significant effect on the final answer. They vary in different circumstances, and this is best made clear by examples.

Take the case of a point-contact transistor with an external collector load of 10,000 ohms and compute its input resistance using the values given in the table. The value will be—

$$250 + 90 - \frac{90(90 + 45{,}000)}{10{,}000 + 20{,}000 + 90} = 205{\cdot}2 \text{ ohms. We can}$$

simplify here by ignoring the r_b in the bracket and the one in the denominator of the fraction, since in each case they are small compared to the quantities to which they are being added. The formula then becomes $r_e + r_b - \frac{r_b \times r_m}{R_L + r_c}$ and we get the result of 205 ohms, which does not differ for all practical purposes from the answer obtained by using the full expression.

If we now take the case of computing the input resistance under conditions where resistance has been inserted in the base lead, we can no longer use this particular simplification if the value of the resistance is high, say, 20,000 ohms. On the other hand, r_e in the first part of the expression is relatively small enough to be ignored without much effect on the answer. In fact, not taking it into account changes the answer from – 5,750 ohms to – 6,000 ohms.

It will be noted that high base resistance results in negative input resistance which accounts for the triggering action in such a circuit and its ability to produce oscillations. When a series-tuned circuit is placed in the emitter lead the negative resistance produced in the input circuit cancels out the positive resistance in the inductor and capacitor and allows oscillations to be sustained.

It will be seen that the input resistance becomes negative when

$\frac{r_b(r_b + r_m)}{R_L + r_c + r_b}$, the fractional part of the expression, is greater than $r_e + r_b$.

Now, in the case of the junction transistor, r_m is always less than r_c so that this term can never be greater than $r_e + r_b$ whatever the value of r_b so that the junction type is inherently stable.

It is instructive to plot the value of input resistance over a range of values of r_b and to do for a number of values of collector load. This has been done in Fig. 45. A careful examination of such curves reveals much useful information about the behaviour of point-contact transistors and, in particular, indicates criteria for stability. Obviously, for instance, a high collector load ensures stability over a wide range of conditions, and if made high enough it completely prevents instability.

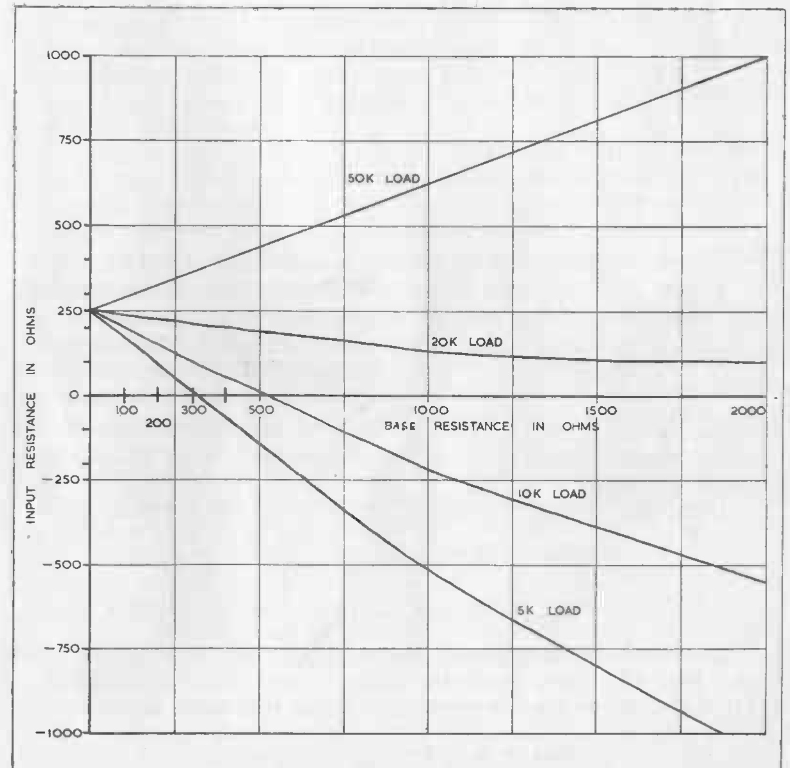


FIG. 45. CURVE SHOWING VARIATION OF INPUT RESISTANCE WITH BASE RESISTANCE.

It is equally interesting to plot values of output resistance against base resistance for various values of source resistance. This will be left as an exercise for the reader, for it is only by actual use of these formulæ that a thorough understanding of them can be built up.

It has already been pointed out that the earthed-base configuration is only one of three possible circuit arrangements and its use is not frequent in the case of junction transistors. To cater for this state of affairs it is necessary, therefore, to rearrange the equivalent network and compute new expressions for the earthed-emitter and earthed-collector circuits.

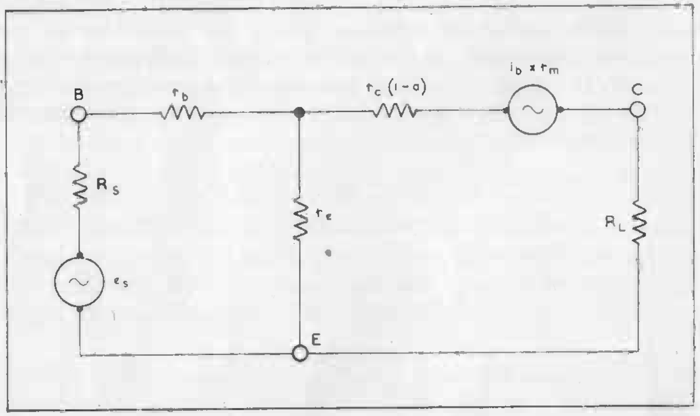


FIG. 46. EARTHED-EMITTER EQUIVALENT A.C. NETWORK.

Fig. 46 shows the earthed-emitter network. Besides the changing over of emitter and base connections and regarding the input as base current i_b it shows the value of the resistance in the collector circuit as $r_c(1 - a)$ where $a = \frac{r_m}{r_c}$. This reduced value of resistance allows increased current to be driven round the collector circuit by the voltage generator and represents the positive feedback resulting from this configuration.

Input and output resistances are given by the formulæ:—

$$R_{in} = r_b + r_e + \frac{r_e\,(r_m - r_e)}{r_c - r_m + r_e + R_L}$$

$$R_{out} = r_c - r_m + r_e + \frac{r_e\,(r_m - r_e)}{R_s + r_b + r_e}$$

A further rearrangement results in the earthed-collector network, Fig. 47. Here again the collector resistance is modified $r_c\,(1 - a)$. Formulæ for input and output resistance are:—

$$R_{in} = r_b + r_c - \frac{r_c\,(r_c - r_m)}{r_c - r_m + r_e + R_L}$$

$$R_{out} = r_e + r_c - r_m - \frac{r_c\,(r_c - r_m)}{R_s + r_b + r_c}$$

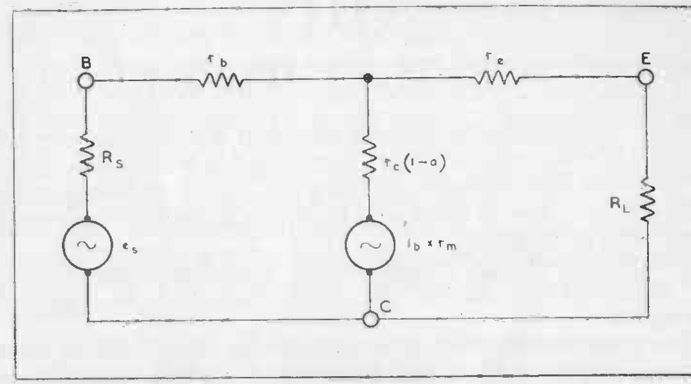


FIG. 47. EARTHED-COLLECTOR EQUIVALENT A.C. NETWORK.

Although most frequently used for junction types, these earthed-emitter and earthed-collector expressions are equally applicable to point-contact types. In many cases, particularly with junction types, simplifications may be introduced to save labour without significant effect on the answer.

This is only intended to be an elementary introduction to the use of equivalent networks and makes no pretence of being a complete treatment. It is hoped, however, that this simple approach will be found to give enough information to enable the reader to work out some of his own problems as they arise and to stimulate interest in this way of dealing with circuit behaviour.

It is suggested that the use of this more mathematical approach to circuits should not be allowed to replace practical work but merely be used to direct this work and, by explaining results obtained, give a lead to further experimental work. It should be remembered in particular not to ascribe to mathematical results a validity that they do not possess. The correctness of results depends on the reliability of the initial figures and the reader is again reminded that the values assigned to r_e, etc., are only approximate and, furthermore, can vary a great deal with circumstances. To take all these variations into account in the formulæ might be possible and then results could be taken as completely valid, but it would, to say the least of it, make them difficult to use. It is for this reason that stress is laid on experimental work in conjunction with calculation as being the most likely method of obtaining optimum results in a minimum time.

XIII

WHAT DOES THE FUTURE HOLD ?

SINCE semi-conductor devices represent a comparatively new field of endeavour, fresh developments are announced at short intervals and, although they may not reach a production stage for some time, a few of them will be briefly described to show the general trend of progress.

Generally speaking, present devices have limitations in three main directions: in power; in frequency; and in operating temperature.

The power limitation can be removed by using junction rather than point-contact devices, and transistors have been demonstrated with dissipations of several watts. Some falling-off of performance even at the higher audio frequencies might be expected from these owing to their higher capacitance, but the use of feedback circuits could probably get over this in practical circuits. One with a dissipation of 25 watts has been developed for control circuits where frequencies involved are usually below 1,000 cycles.

The frequency limitation due mainly to transit time and collector capacitance can be tackled in a number of ways. One is to use point-contact transistors with whisker spacings below one-thousandth of an inch. By this somewhat difficult technique specimens have been produced which have oscillated above 100 mc/s. Another method is to use a junction transistor with an additional base contact which can be biased to restrict the paths taken by the current carriers. A further recently announced method is the surface barrier technique which enables a transistor of somewhat similar make-up to the junction type to be made with minute spacings and minute electrodes thus overcoming transit time troubles and high capacitance. The power-handling capabilities are reduced to a few milliwatts, but in the early stages of a receiver where they would normally be used this is no disadvantage. The claims made for this interesting device include reliable oscillation at 70 m/cs and stage gains in tuned amplifiers at 30 m/cs or in video amplifiers with 3-m/c band-width of 15db or more. The special significance of this development lies in the electrochemical etching and plating processes which have been devised to obtain and control within close limits the small dimensions necessary for high-frequency working.

The latest developments of all at the time of writing are the *p–n–i–p* and *n–p–i–n* junction types. These have what is called a depletion layer of intrinsic type semi-conductor between the base and collector zones. Intrinsic semi-conductor is material with no *n* or *p* type impurity to produce current carriers so that the current

is carried solely by hole-electron pairs produced by certain lattice bonds being broken by thermal agitation.

The effect of this layer is to decrease the capacitance per unit area of collector to base junction, to increase the breakdown voltage and also increase the mobility of current carriers in this region. The overall result is to raise the frequency at which cut-off occurs without severe limitations on power handling. Experimental transistors using this principle have operated up to 95 m/cs and it is stated that the theoretical upper limit is as high as 3,000 m/cs. It would not seem unreasonable to hope for other equally promising developments to occur in view of the immense amount of effort being expended all over the world.

The temperature limitation is inherent in the use of germanium as a semi-conductor material and the solution must, therefore, be sought in the use of other materials. Silicon in a purer state than that needed for centimetric mixers is one that is being tried. There are, however, problems to be solved before large-scale production of the right grade of material is possible. In the meantime, certain compounds of group three elements such as indium or aluminium with group five elements such as arsenic or antimony are being investigated, and it may well be that one of these compounds rather than the element silicon will eventually be the preferred material.

The use of germanium will, however, continue for a considerable time because the problem of its production to any degree of purity likely to be required has already been solved, and in many applications its temperature performance is perfectly adequate. Once these developments have reached the production stage the scope of transistors will be enormously widened so that few of the territories previously the sole preserve of the thermionic valve will be free from invasion. When one adds to this the territory which is the special province of transistors because of their special properties it will be realized what an enormous potential use there is for these devices and why such great sums of money are being spent in their further development.

Sensational prophecies have been made of the rapid and complete elimination of thermionic valves by transistors. The failure of these to come true is a reflection on the prophets rather than the devices themselves, because they have not adopted a reasonable time-scale. Those who know the difficulties inseparable from the establishment of new techniques are not disappointed by the progress that has been made. Formidable problems have been tackled and solved, making the future bright indeed. In the meantime there are many circuit problems to be tackled in connection with the devices available at present, and it is hoped that this book will encourage the experimenter to try things for himself and experience the pleasure of sharing, instead of passively watching, the early stages of a fascinating new branch of electronics.

APPENDIX

ABBREVIATED DATA ON A FEW TYPICAL TRANSISTORS AND DIODES

(Manufacturers' literature should be consulted for full characteristics and operating data.)

POINT-CONTACT TRANSISTORS

Maker	Type No.	Maximum Collector Dissipation (mW)	Max. Peak Collector Voltage (V)	Current Gain	Remarks
Brimar, S.T.C.	TP1, 3X100N	150	—50	2.0 min.	Switching.
	TP2, 3X101N	150	—50	2.0 min. 5.0 max.	Amplifying.
G.E.C.	EW51	100	—20	3.0	Pulse Amplifier.
	GET 1	100	—50	2.5	
	GET2	75	—30	3.8	
Mullard	OC50	100	—30	2.0	
	OC51	100	—40	2.0	
U.S.A.	2N32	50	—40	2.2	
	2N33	30	—8.5	—	Tested for 50 Mc/s. operation.

JUNCTION TRANSISTORS

Maker	Type No.	Maximum Collector Dissipation (mW)	Max. Peak Collector Voltage (V)	Current Gain	Remarks
B.T.H.	JT1A	6	—9	—	
	JT2A	50	—50	—	
	JT3A	50	—25	—	
Brimar, S.T.C.	TJ1, 3X300N	200	—20	10.0 min†	
	TJ2, 3X301N	200	—20	30.0 min.†	
	TJ3, 3X302N	200	—20	50.0 min. †	
G.E.C.	EW53/1	70	—20	15.0 min.†	
	EW53/2	70	—20	30.0 min†	
	EW58/1	70	—10	15.0 min.†	
	EW58/2	70	—10	30.0 min. †	
	EW59	70	—40	30.0†	300mW per pair Class 'B
Hivac	XFT1	6	—4.5	40.0†	
Mullard	OC70	6	—10	0.97* 50†	Low-noise a.f. amplifier.
	OC71	6	—10	0.98* 50†	High-gain a.f. amplifier.
	OC72	50	—12	—	200mW per pair Class 'B'
Pye	V10/15	100	—10	15.0 min.†	
	V10/30	100	—10	30.0 min.†	
	V10/50	100	—10	50.0 min.†	
U.S.A.	2N34	50	—25	0.98	
	2N35	50	+25	0.98	*n-p-n*-type
	2N43	150	—45	0.98	
	2N44	150	—45	0.955	
	2N45	150	—45	0.92	
	2N63	33	—22	$\beta = 22$	
	2N64	33	—22	$\beta = 45$	
	2N65	33	—22	$\beta = 90$	
	CK721	33	—22	$\beta = 45$	
	CK722	33	—22	$\beta = 12$	
	CK723	33	—22	$\beta = 22$	
	CK725	33	—22	$\beta = 90$	
	CK727	30	—6	$\beta = 35$	Low noise
	CK760	—	—6	40.0†	18db at 2 Mc/s
	CK761	—	—6	45.0†	20db at 2 M/cs
	CK762	—	—6	65.0†	22db at 2 Mc/s

* *Grounded base.* † *Grounded emitter.*

JUNCTION TYPE GERMANIUM DIODES

Maker	Type No.	Peak Forward Current (amps)	Rectified Current in Resistive Load (mA)	Continuous Reverse Voltage	P.I.V.
B.T.H.	GJ3—D	0.33	100	65	200
	GJ4—D	0.5	150	30	100
	GJ5—D	0.25	75	100	300
G.E.C.	EW54	—	10 amps.	50	—
S.T.C.	R50A	0.35	100	120	140
	R50B	0.25	30	120	140
U.S.A.	IN91	0.47	150	30	100
	IN92	0.31	100	65	200
	IN93	0.25	75	100	300
	IN94	1.57	500	30	100
	IN150	1.57	500	65	200
	IN152	1.57	500	100	300
	IN153	1.57	500	185	380

POINT-CONTACT GERMANIUM DIODES

Maker	Type No.	Minimum forward current at +1V (mA)	Maximum inverse current at —10V (mA)	Maximum inverse current at —50V (mA)	Minimum turnover voltage	Peak working reverse voltage	Remarks
B.T.H.	CG1–e	4·0	—	1·0	80	—	
	CG3–e	1·0	—	—	—	—	
	CG4–e	3·0	—	0·1	100	—	
	CG6–e	2·0	0·05	—	85	—	
	CG10–e	2·0	0·05	0·25	120	—	
	CG12–e	3·0	0·4	—	30	—	
Brimar	GD3	3·0	0·02	—	25	—	
	GD5	2·0	0·2	0·1 (at—30V)	85	—	
G.E.C.	GEX34	1·0	0·1	2·0	60	—	High-level detector.
	GEX35	—	—	—	30	—	Functional test at 35 Mc/s.
	GEX45/1	4·0	—	1·0	75	—	
	GEX54	3·0	0·01	0·1	100	80	
	GEX54/3	3·0	—	0·655 (at—100V)	120	100	
	GEX54/4	3·0	—	0·8 (at—150V)	170	150	
	GEX54/5	1·5	—	0·6 (at—200V)	225	200	
	GEX55/1	1·0	—	0·2	75	—	
	GEX56	1·0	0·002	—	—	—	
	GEX64	—	—	—	—	—	Low-resistance telephone modulator.
	GEX66	—	—	—	—	—	Mixer for range 100-1000 Mc/s.
Inter-Services	CV442	3·0	1·0	—	30	—	
	CV425	4·0	—	1·0	80	—	
	CV448	3·0	—	0·1	100	—	
	CV2290	—	—	—	—	—	V.H.F. mixer GEX66
	CV2310	—	—	—	—	—	GEX64
Mullard	OA70	—	—	—	—	—	Video signal detector for frequencies up to 100 Mc/s. Functional test at 60 Mc/s.
	OA71	3·0	0·02	0·12 (at—60V)	120	—	
	OA73	8·0	0·1	1·2 (at—30V)	40	—	
S.T.C.	2X102G	2·0	—	0·14 (at—70V)	85	—	
	2X103G	4·0	0·2 (at—20V)	—	30	—	
	2X104G	1·0	0·2 (at—20V)	—	30	—	
	2X105G	3·0	—	0·1	100	—	
	2X106G	4·0	—	1·0	70	—	

(continued overleaf)

POINT-CONTACT GERMANIUM DIODES (*continued*)

Maker	Type No.	Minimum forward current at +1V (mA)	Maximum inverse current at −10V (mA)	Maximum inverse current at −50V (mA)	Minimum turnover voltage	Peak working reverse voltage	Remarks
Westing-house	WG4A	2·0	1·0	—	—	20	
	WG4B	10·0	1·0	—	—	20	
	WG5A	1·0	0·1	—	—	40	
	WG5B	5·0	0·1	1·0	—	60	
	WG6A	1·0	0·03	0·6	—	60	
	WG7B	5·0	0·01	—	—	40	
	WG7C	5·0	0·01	0·2	—	100	
	WG7D	3·0	0·01	0·1	—	100	
U.S.A.	1N34	5·0	0·05	0·8	75	—	
	1N38	3·0	—	—	120	100	
	1N39	1·5	—	0·8 (at −200V)	225	200	
	1N48	4·0	—	0·83	85	—	
	1N51	2·5	—	1·6	50	—	
	1N52	4·0	—	0·15	85	—	
	1N54	5·0	0·01	—	75	—	
	1N55	3·0	—	0·8 (at −150V)	170	150	
	1N56	15·0	—	0·3 (at −30V)	50	—	
	1N58	4·0	—	0·8 (at −100V)	120	100	
	1N60	—	—	—	30	—	Functional test at 40 Mc/s.
	1N63	4·0	—	0·05	125	—	
	1N64	—	—	—	20	—	Functional test at 44 Mc/s.
	1N65	2·5	—	0·2	85	—	
	1N69	5·0	0·05	0·85	75	—	
	1N70	3·0	0·25	0·3	125	—	
	1N81	3·0	0·01	—	50	—	

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