CHAPTER VIII.—THE THERMIONIC VALVE

ELECTRONIC EMISSION

1. For over a hundred years it has been known that the air in the immediate vicinity of an incandescent conductor also becomes conductive. The effect was studied experimentally by Edison in 1883 and later by Fleming. The apparatus used consisted of an electric lamp, i.e. a glass bulb evacuated in accordance with the best technique of the period, containing a hairpin filament of carbon and a metal plate entirely separate from the filament. The plate could be maintained at any desired potential with reference to the filament, as illustrated in fig. 1. It was found that the space between the filament and the plate became conductive (allowing an electric current to flow) if the plate was maintained at a positive potential with respect to the filament, but was non-conductive if the plate potential was negative with respect to the filament. This unilateral conductivity was later shown to be due to the emission of particles of negative electricity—electrons—from the filament, and their passage to the plate in the presence of a positive potential on the latter.

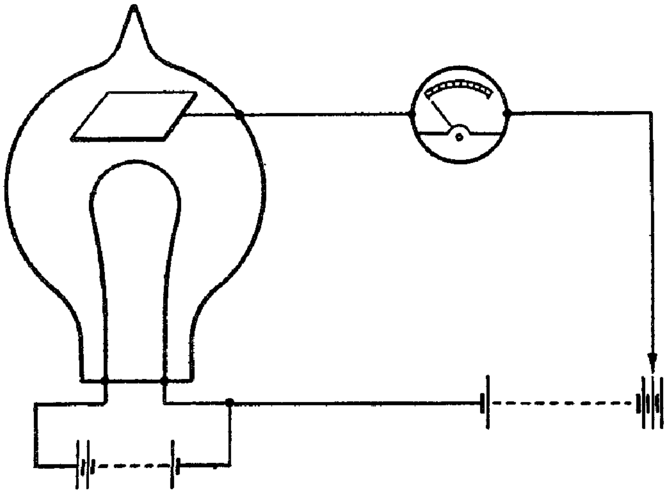


FIG. 1, CHAP. VIII.—The Edison effect.

The mechanism by which electrons are emitted by a hot body was explained by O. W. Richardson in 1901. He assumed that the electrons inside a conductor behave in the same manner as the gas molecules in an enclosed space, that is, they are in a state of continual agitation and random motion, the R.M.S. velocity depending upon the absolute temperature. On the absolute scale, zero temperature is that at which all the particles cease to possess kinetic energy and therefore have no velocity, and is equal to − 273° C. The absolute scale of temperature is often referred to as the Kelvin scale, thus 0° Centigrade = 273° K.

Although the electrons inside a hot body may possess considerable velocity, no electrons leave the boundary surface under normal conditions, because there is at the surface a force tending to hold the electrons within the substance. In order to escape from the atom an electron must do work, and this work must be at the expense of its own kinetic energy. In most instances the amount of work necessary to break the surface tension is greater than the kinetic energy possessed by the electron, so that the latter are bound to the substance. When electrons are detached from a body the phenomenon is known as electronic emission. Electronic emission can be caused in at least three ways:—

(i) By raising the temperature of the body—*thermionic emission.*

(ii) By bombardment of a body by electrons or ions—*secondary emission.*

(iii) By the absorption of electromagnetic radiation of extremely high frequency—*photo-electric emission.*

In this chapter it is proposed to consider thermionic emission and its application in the wireless valve. The name valve obviously rose from analogy with the mechanical non-return valve. The thermionic valve consists of an evacuated bulb in which an electrode designed to be a good emitter of electrons is placed as well as other electrodes which perform various functions.

Thermionic emission

2. As already stated, the mobile electrons in a conductor are continually moving from atom to atom, and if the conductor is heated the velocity of the electrons is increased and some electrons acquire sufficient kinetic energy to overcome the surface tension and leave the conductor. This phenomenon is closely analogous to the evaporation of molecules from the surface of a liquid, the number of molecules which evaporate increasing rapidly with increase of temperature. Thermionic emission can be considered as an evaporation of electrons, the energy given up by the electrons in escaping corresponding to the latent heat of vaporisation in a liquid.

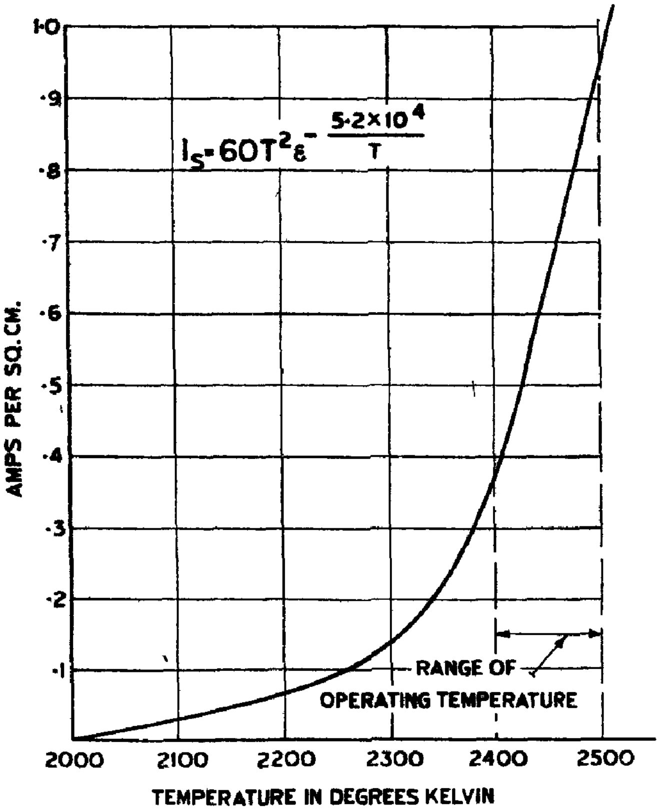


FIG. 2, CHAP. VIII.—Emission from tungsten cathode.

If there is no external electric field acting on the emitted electrons, they return immediately to the parent substance, which was left positively charged by their departure. The conductor is thus surrounded by a cloud of electrons, which are continually being ejected from its surface and re-attracted. In thermionic practice, any conductor specially designed to emit electrons is called a cathode. Its design will be considered later.

3. The work, in ergs, which an electron must do in order to escape from the surface of a given substance is called the electron evaporation constant and is denoted by *w*. It is often expressed as the electron affinity in equivalent volts. The electron affinity is related to the electron evaporation constant by the equation

$$\varphi = \frac{w}{e}$$

where φ is the equivalent voltage in E.S.U. and e the charge of one electron. To express φ in volts this must be multiplied by 300. The two properties required in a cathode material are firstly, low electron affinity, so that a comparatively small temperature rise above the normal will impart sufficient kinetic energy to the electrons to endow them with the ability to break through the cathode surface; and secondly, ability to withstand the necessary rise of temperature without volatilisation or evaporation of material molecules, for this would lead to short life of the cathode as well as irregular behaviour of the valve.

The law of thermionic emission can be shown to be

$$I_s = AT^2 \varepsilon^{-\frac{b}{T}}$$

where I_s is the emission current in amperes per square centimetre of emitting surface, ε is the base of naperian logarithms ($\equiv 2{\cdot}71828$), and T is the temperature in degrees Kelvin. A is a constant, which is theoretically the same for all pure metal conductors, but in view of the difficulty of obtaining absolutely pure surfaces in practice, the value of A for a number of materials has been determined experimentally by various research workers. The constant b is $1{\cdot}16 \times 10^4 \times \varphi$, φ being expressed in volts. Values of A, φ and b for different substances are given in the following Table.

	A	φ (volts)	b
Tungsten	60	4·53	$5{\cdot}2 \times 10^4$
Molydbenum	55	4·58	$5{\cdot}32 \times 10^4$
Tantalum	60	4·12	$4{\cdot}77 \times 10^4$
Nickel	1,380	5·03	$5{\cdot}84 \times 10^4$
Platinum	17,000	6·27	$7{\cdot}27 \times 10^4$
Thorium	60	3·35	$3{\cdot}88 \times 10^4$
Calcium	60	2·24	$2{\cdot}6 \times 10^4$
Magnesium		2·7	$3{\cdot}13 \times 10^4$
Mixture of Barium and Strontium Oxides ..	0·1 to 0·3	2·3	$2{\cdot}65 \times 10^4$
Barium	141	3·58	$4{\cdot}16 \times 10^4$
Barium oxide	—	1·12	$1{\cdot}3 \times 10^4$
Thoriated Tungsten	3	2·63	$3{\cdot}05 \times 10^4$

It is possible that the high values of A for platinum are due to impurities on the surface. It will be observed that for many substances A is about 60, which is one of the values which have been deduced theoretically as the universal constant mentioned above.

The metal tungsten has a melting point of 3540° K. and can be operated at a temperature of 2400° K to 2500° K without fear of volatilisation, giving a copious emission at this temperature as shown in fig. 2. In these respects it is better than any other pure metal.

The anode

4. The action of the second electrode may now be discussed. If this electrode is given a potential positive with respect to the cathode the emitted electrons will be attracted to it, afterwards passing round the external circuit back to the cathode. The plate is then said to function as an anode, and the electron current which is established in the evacuated space and external circuit is called the anode current. The anode may thus be considered to act as a collecting electrode. It is found experimentally that no such current is established if the potential of the plate is negative with respect to the emitting body.

The velocity acquired by an electron in its passage from cathode to anode depends upon the magnitude of the potential difference between the electrodes, or more accurately upon the potential gradient. The potential gradient is measured in volts per centimetre and is synonymous with the electric field strength. This velocity may be estimated by the application of fundamental principles, as follows.

The force F exerted by an electrostatic field upon a charged body is equal to the product of the charge q carried by the body and to the electric field strength Γ or

$$F = q\Gamma \times 10^7$$

where F is the force in dynes, q the charge in coulombs and Γ the electric field strength in volts per centimetre. This force acts in the direction of the field at the point occupied by the charge and causes an acceleration in this direction. Provided that the velocity of the body does not approach that of light the ordinary laws of mechanic may be applied to find the acceleration and since $F = ma$ (see Introduction)

$$a = \frac{\text{force in dynes}}{\text{mass of body in grams}}$$

a being then given in centimetres per second per second. The velocity of the moving body will increase or decrease during its passage through the field, according to the relative signs of field and charge. The kinetic energy acquired is equal to the product of the field strength Γ, the distance moved through, d, and the magnitude of the charge, q. If d is in centimetres and q in coulombs, the kinetic energy is W ergs, where

$$\begin{aligned} W &= dq\Gamma \times 10^7 \\ &= Vq \times 10^7 \end{aligned}$$

because $\Gamma d = V$, the P.D. between the points of arrival and departure of the charge. The latter is said to fall through this potential difference.

Suppose the charge to start from rest under an attractive force, attaining a final velocity of u centimetres per second. The kinetic energy gained during its motion is $\frac{1}{2} mu^2$ ergs, hence

$$Vq \times 10^7 = \tfrac{1}{2} mu^2$$

$$\text{and } u = \sqrt{\frac{2 \times 10^7\, Vq}{m}} \text{ cm. per second}$$

Example 1.—The charge on an electron is $1{\cdot}59 \times 10^{-19}$ coulomb and its mass 9×10^{-28} gram. Calculate the velocity gained by an electron in falling through a P.D. of 10 volts.

$$\begin{aligned} u &= \sqrt{\frac{2 \times 10^7 \times 10 \times 1{\cdot}59 \times 10^{-19}}{9 \times 10^{-28}}} \text{ cm. per second} \\ &= 1170 \text{ miles per second.} \end{aligned}$$

Owing to the high velocity attained by electrons when moving through space comparatively free from matter, it is convenient to express the velocity in terms of the voltage through which the electron has fallen. It is obvious that a body of greater mass, such as a hydrogen ion, will acquire a much lower velocity for the same P.D. In the above example, substitution of the mass of a hydrogen ion will give $\frac{1170}{\sqrt{1840}}$ or 27 miles per second.

5. The assembly so far considered, consisting of an evacuated space enclosed by a container called the envelope, a cathode or emitting electrode and an anode or collecting electrode, is called a two-electrode valve or diode. Its essential property is that of unilateral conductivity.

The original function of the diode was that of a detector of radio-frequency currents in a wireless receiving aerial, and is dealt with in Chapter X. It was later found that by the addition of other electrodes the valve could be rendered much more sensitive and endowed with amplifying properties. The valves so evolved are often designated by the total number of active electrodes they possess, e.g. a valve possessing three active electrodes is called a triode, four active electrodes a tetrode, and so on. Two or more independent electrode assemblies are sometimes enclosed in a single envelope, for example a diode-triode possesses a single cathode, an anode which in conjunction with the cathode constitutes a diode, and an additional anode and grid forming with the cathode a triode which functions quite independently of the diode assembly.

The following paragraphs, dealing briefly with the design of the cathode and the general construction of valves, are applicable to all types in common use. The cathode is invariably heated by electrical means although this is merely a matter of practical convenience. Two methods of achieving the desired end are in common use, the resulting designs being known as " directly heated " and " indirectly heated " cathodes respectively.

The directly heated cathode

6. This consists of a filament of wire, which is heated by passing through it a current of electricity obtained from dry cells, accumulators, or in certain instances from the supply mains. This filament current plays no part whatever in the action of the valve, other than providing the necessary heating. The material of the filament is generally either pure tungsten, thoriated tungsten or oxide coated wire.

Pure tungsten has an operating temperature 2400° K to 2500° K. It is drawn into filaments of from ·05 mm. diameter for use in small receiving valves, to 1·3 mm. in large transmitting valves, the corresponding heating currents being from ·5 to 75 amperes. Pure tungsten filaments are not used in service receiving valves.

Thoriated tungsten.—Thorium was originally added to tungsten lamp filaments in order to render them less brittle, and it was discovered that these filaments gave a copious emission of electrons at a lower temperature than pure tungsten. The actual substance added is thoria (thorium oxide), which forms a " solid solution " in the tungsten. When the filament is heated, the oxide is reduced, and molecules of pure thorium are deposited on the surface of the filament, forming a kind of tube which is rich in electrons of a low affinity. Hence such filaments give ample emission when heated to a temperature of from 1800° K to 1900° K. This thin layer of thorium is easily destroyed by excessive temperature or by bombardment by positive ions formed from gas molecules in the envelope. The filament then fails to emit at its normal temperature.

If a thoriated-tungsten filament loses its emission, it may be " reactivated " by applying two and a half times the normal filament voltage for 20 seconds with no anode potential. This will decompose some thoria and so provide a supply of thorium molecules. If a filament voltage of about 20 per cent. above normal and an anode voltage not exceeding 20 volts is now applied for a short period the thorium molecules will be distilled out to the surface of the filament. The thinnest thoriated tungsten filament is designed to emit with a filament current of ·06 amp.

Some service transmitting valves are made with thoriated tungsten filaments although they function as " bright emitters." The admixture of thoria in this case is to reduce the brittleness of the filament rather than to increase the emission. Others such as the V.T.25 valve, have thoriated tungsten filaments designed to run at a dull red heat. These valves are given a hydrocarbon treatment, being run in an atmosphere of volatilised naphthalene or some similar compound during a certain stage in the manufacture. This converts some of the surface tungsten into tungsten carbide, and the filament will then stand up to considerable positive ion bombardment without disintegration of the emitting surface, but the process tends to make the filament more brittle than the ordinary thoriated tungsten filament and this should be borne in mind when handling these valves.

Oxide coated filaments.—The oxides of barium, strontium and calcium will emit copious supplies of electrons at a dull red heat, about 1200° K. These substances cannot be drawn into wire but can be deposited upon a core of some metal, for example, platinum with 10 per cent. iridium or 5 per cent. nickel, commercial nickel, or an alloy of nickel, cobalt, iron and titanium called Konel metal. The coating material frequently used is a mixture of equal weights of barium carbonate and strontium carbonate, ground to a fine powder and thoroughly mixed, being then formed into a thin paste or paint by the addition of water or amyl acetate. The coating is applied by drawing the wire through a series of baths containing the oxide, a drying process occurring between each bath. The latter process consists of baking for a few seconds at a temperature of about 700° C. in an atmosphere of carbon dioxide. The correct thickness of coating is maintained by weighing samples of the coated materials, and when sufficiently coated the surface is given a protective coating of paraffin wax or of collodion. This type of emitter requires activation after being fitted in the valve, in order to reduce the carbonates to oxides, as described in the section on valve manufacture.

The indirectly heated cathode

7. If alternating current is used to heat a directly heated cathode, the variations of voltage between its ends produce fluctuations of the anode current at the supply frequency, producing a hum in the telephone receivers or loud speaker. This effect is overcome in the indirectly heated type by making the cathode and heating device electrically independent, the cathode being heated by radiation and conduction of heat from the "heater." The cathode is an oxide-coated metal tube or thimble, while the heater takes the form of a spiral or hairpin filament (fig. 3), which is connected to the A.C. supply. The filament is kept in position in the thimble, and insulated from it, by a packing of porcelain, magnesia or silica. The heater is not regarded as one of the active electrodes of a valve, thus an indirectly heated diode has two active electrodes, viz. anode and cathode, and also a heater for the latter, four external connections being therefore necessary.

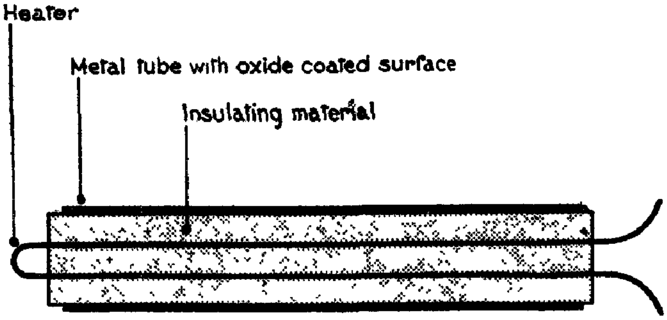


FIG. 3, CHAP. VIII.—Indirectly heated cathode.

Anode dissipation

8. When electrons emitted by the cathode impinge upon the anode, their kinetic energy is almost entirely converted into heat, causing an increase in the temperature of the anode. Suppose that n electrons of charge e coulombs reach the anode every second, having fallen through a P.D. of V volts. The rate of conversion of kinetic energy into other forms is neV joules per second. For example, if $n = 10^{18}$ and $V = 1600$ volts, since $e = 1{\cdot}59 \times 10^{-19}$ coulomb, the energy converted per second is

$$P = 10^{18} \times 1{\cdot}59 \times 10^{-19} \times 1600$$
$$= 254 \text{ watts}$$

In practice the anode current is measured in milliamperes, e.g. 159 milliamperes in the above example. The power expended in the form of heat is then equal to the product of the anode current I_a and the anode-filament P.D. V_a or

$$P = \frac{I_a V_a}{1000}$$

The rating of a power valve is the amount of power which the valve can safely dissipate in the form of heat. The power supplied to the valve will generally—always in practical working circuits—be greater than this, because some of the electrical energy supplied to the valve will be transformed into some other form of useful energy and not into heat.

9. The anode, and any additional electrodes which the valve may possess, must be constructed from a material which will withstand the heat generated in manufacture and use, and

will not retain gas molecules in adsorption. As the heat evolved can only be lost by radiation to the walls of the envelope, the anode must possess good radiating properties and must also be

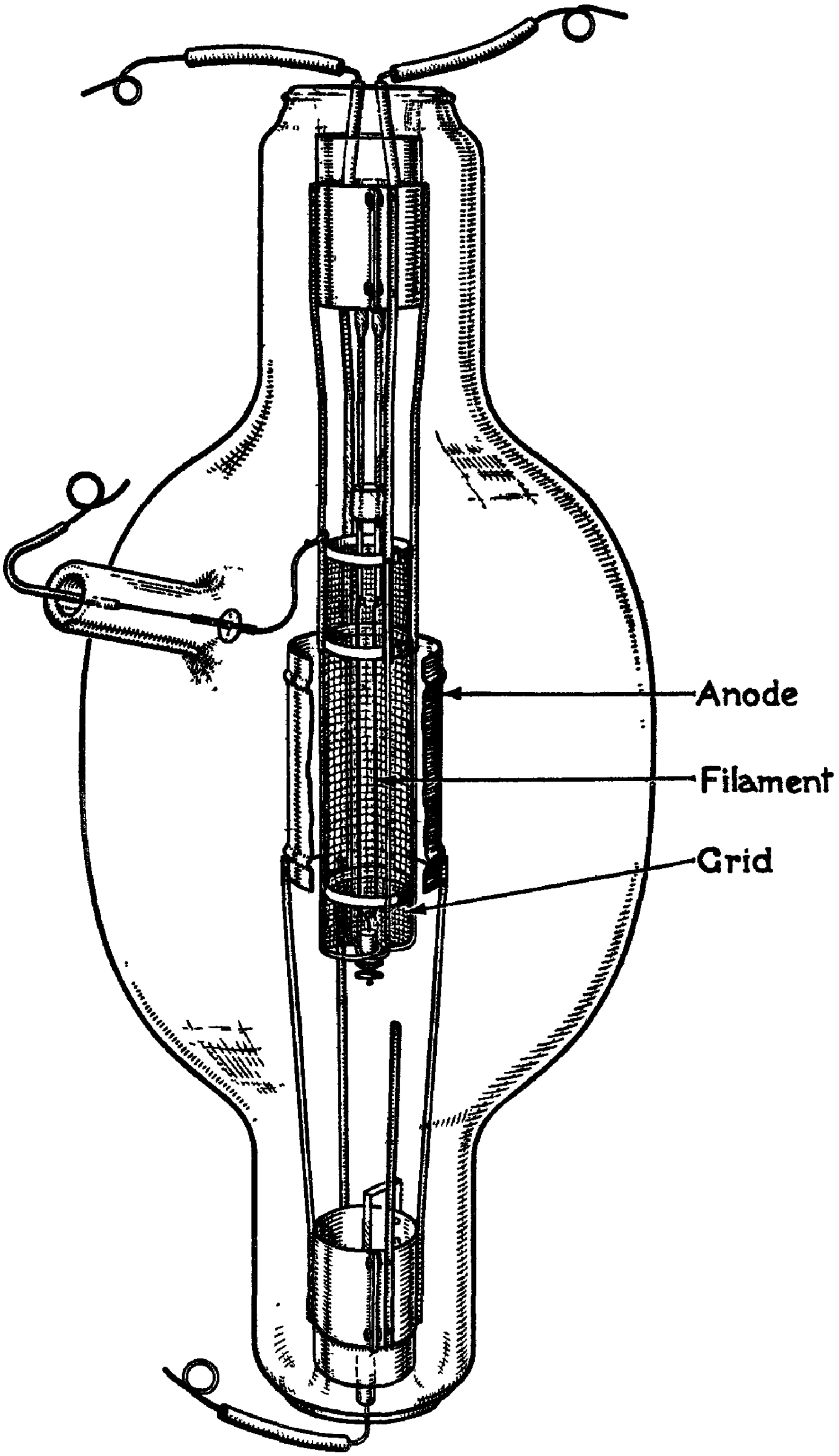


FIG. 4, CHAP. VIII.—Typical transmitting valve.

capable of taking and maintaining the desired shape and size. It is essential that no appreciable amount of gas is liberated by the anode when operating at its normal temperature, for if this is the case, gas molecules will become ionised by collision with electrons, and the result is an increase of anode current, with further rise of anode temperature and increased liberation of gas molecules. The effect is therefore cumulative and may lead to the establishment of an arc discharge between anode and cathode. The nature of the gas is of importance in valves having filaments of thoriated tungsten. The electronic emission is due to a very thin layer of thorium on the surface of the filament, and a very small amount of oxygen is sufficient to oxidise this layer which then loses its emission property to a considerable extent.

For receiving valves and low power transmitting valves, nickel is largely used for the construction of anodes and other electrodes. For higher powers, the metal molybdenum is largely employed. If heated to about 1400° C. during the evacuation process, the adsorbed gas is largely given off, and the anode may be operated at a working temperature as high as 1000° C. without further liberation of gas. The mechanical properties of molybdenum are not ideal, and it is difficult to obtain in large thin sheets such as are used to form nickel anodes. In certain types of valve the anode is formed of molybdenum strip about 2 millimetres wide, which is woven into a basket-work structure, and is more easily degassed during evacuation than a solid electrode. It also warps to a much smaller extent when heated, and tends to give constancy of inter-electrode capacitance which is of considerable importance in operation.

During the last few years, graphitic carbon has come into use to some extent. The advantages claimed are (i) its high mechanical rigidity and (ii) good heat-radiating properties. Against this must be set a greater tendency to gas adsorption, although it is claimed that this difficulty can be overcome by suitable treatment during manufacture.

10. The envelope is usually of glass, at any rate up to a rating of 1000 watts (e.g. V.T.9B). A glass valve typical of the largest size made is shown in fig. 4. Larger envelopes are made of silica (fused quartz). This material has a negligible coefficient of expansion with temperature, and does not soften unless heated to about 1400° C. This leads to a smaller valve for a given power, since the envelope may be brought nearer to the heated anode without ill effects.

The silica valve can be cut open with a carborundum wheel for replacement of a burnt-out filament, after which it is re-assembled and evacuated. Defective silica valves are thus of definite value, and should be treated as carefully as new ones.

The " cooled anode " valve—cooled anode transmitting or C.A.T. and cooled anode modulating or C.A.M.—has for its anode a copper tube which forms part of the envelope and may be cooled by water or air circulation. The success of this valve is entirely due to the development of a method of making a gas-tight seal between glass and copper.

Evacuation

11. The evacuation process aims at the elimination of all occluded gas, as well as that filling the envelope itself. All the internal parts must be chemically clean after assembly, when the valve is ready for pumping. This process is carried out individually for large valves, but small receiving valves are pumped by semi-automatic " mass-production " processes. With this qualification, the general features of the evacuation process are the same for all valves. The pumping outfit consists of a series of pumps, the general arrangement being shown in Fig. 5. The first, or rough pump, consists of an air pump of ordinary piston type, and is capable of reducing the pressure to about ·01 mm. of mercury. This rough pump is followed by a rotary pump, which in turn reduces the pressure to some ·0001 mm. The rotary pump in turn is followed by a " mercury vapour " pump, the action of which is as follows. In a metal flask is a pool of mercury, which is vaporised by a bunsen flame. The molecules of mercury vapour rush up the flask, and on passing the mouth of a tube to which the valve is connected create a partial vacuum, and thus gas molecules are drawn from the valve into the flask. The mercury vapour condenses on the cold upper part of the flask, and trickles back to the pool to undergo further vaporisation. A liquid air trap is inserted between the valve and the mercury pump in order to " freeze out " any few molecules of mercury vapour which might find their way back towards the valve.

The final pressure in the valve may be less than ·0000001 mm. of mercury. During the pumping process, the valve is raised to as high a temperature as possible consistent with the envelope remaining rigid, in order to remove occluded gas from the envelope. In the later stages of evacuation, the metal parts inside the valve are heated to about 400° C. either by " electronic bombardment " or by eddy currents induced by means of radio frequency current in a small coil surrounding the valve, with the same object.

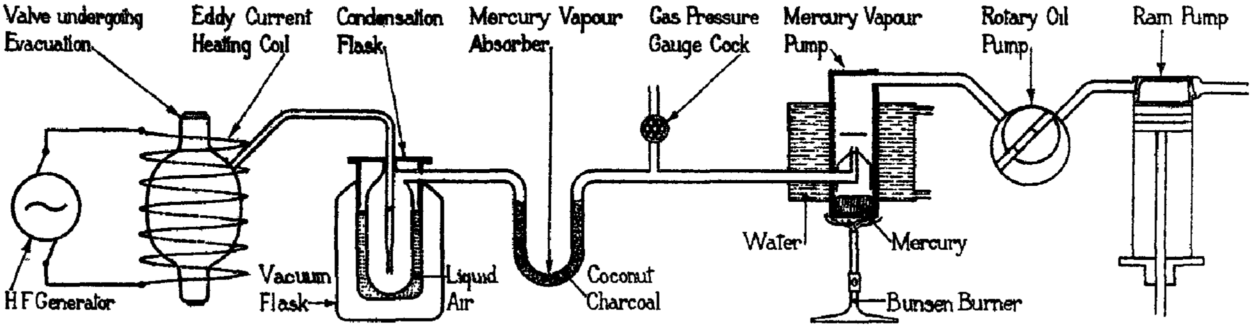


FIG. 5, CHAP. VIII.—Evacuation of transmitting valve.

Activation.—If the valve is fitted with an oxide-coated emitter, the latter must now be activated. A heating power of about double the normal, i.e. that at which the heater will be run in actual service, is applied to the cathode for several minutes, then somewhat reduced and maintained until evolution of gas from the cathode becomes negligible. The pumping process is kept up during this period and when the gas pressure has been reduced to about 10^{-5} mm. of mercury, the activation is usually complete.

Gettering.—The gas which is most detrimental to the proper functioning of the valve is oxygen, and the residual traces of this gas are eliminated by causing it to combine with a small quantity of magnesium, calcium, or barium which is placed inside the bulb. When the temperature of the bulb and electrodes is raised to a certain degree by the eddy current treatment described above, the metal combines with the residual oxygen and the resulting compound is deposited upon the inside of the bulb, causing the silvery or bronzed appearance characteristic of a "dull-emitter" valve. This process is applied to both thoriated-tungsten and oxide-coated filaments but not to transmitting valves, owing to the high temperature at which they operate which would cause re-volatilisation of the deposit and consequent lowering of the vacuum.

Metallising.—A deposit of soft metal is frequently sputtered over the outside of the envelope of receiving valves to assist or complete the screening of circuits by confining oscillatory electric or magnetic fields proper to the valve to its interior and by excluding unwanted fields from the vicinity of the electrode system. The metallising is usually connected to one filament pin, i.e. that one which is at or near earth potential, or in some instances to a separate pin.

Hard, gas-filled and soft valves

12. In the foregoing outline of valve manufacture, it has been assumed that the finished valves are exhausted to the highest degree of vacuum attainable. This may be said of all valves in general use for transmission and reception in which the presence of gas is undesirable, and they are known as " hard " valves. In some valves gas molecules are introduced deliberately, after the exhaustion has been carried out and these are known as " gas-filled " valves. Examples are the " mercury vapour diode " and the " thyratron." When a gas-filled valve is made, it is first thoroughly exhausted, and a definite quantity of the desired gas afterwards introduced.

A hard valve may become " soft " in use, i.e. the degree of vacuum lower than normal owing to some imperfection in manufacture or irregular usage in its subsequent life. The signs of this are " hot spots " on the filament and possibly a " blue glow " in the valve when its anode potential is raised to nearly its working value. This blue glow is due to ionisation of the gas molecules by the impact of the travelling electrons. A valve which shows such signs of softness should be replaced as soon as possible, otherwise it may cause a wireless failure at a critical moment. The blue glow due to ionisation forms an aurora round the cathode, which may extend and fill the space between cathode and anode ; a slight bluish fluorescence may exist in localised places on the anode of an indirectly heated valve, but this is not harmful.

13. When the diode is connected as shown in fig. 1, electrons flow through the exhausted space from filament to anode. The anode current (I_a) thus established is, in general, less than that calculated from the emission equation (para. 3 and fig. 2). Although the emission given by this formula actually occurs, not all the emitted electrons reach the anode, a large number returning to the cathode in spite of the attraction of the anode. The cause of their return is the " space charge," which consists of the cloud of emitted electrons occupying the interelectrode space. This is in effect an electric field of negative sign, and therefore tends to repel the electrons which are leaving the cathode, causing them to return to it. The anode current of the valve is thus influenced both by the positive potential of the plate and the negative potential of the space charge. In fig. 6 an attempt is made to show the distribution of the electric field between the cathode and anode when the cathode is emitting freely and the anode is maintained at a positive potential with respect to it. In some instances the presence of gas causes a positive space charge, because the emitted electrons colliding with gas molecules, dislodge electrons from the latter. These electrons then join the stream flowing to the anode, while the positive ions (gas molecules) are attracted to the filament, impinging on it with considerable velocity, and causing the " hot spots " mentioned above. It will be seen that a soft valve will, with similar operating potentials, give a larger anode current than a hard valve of identical design.

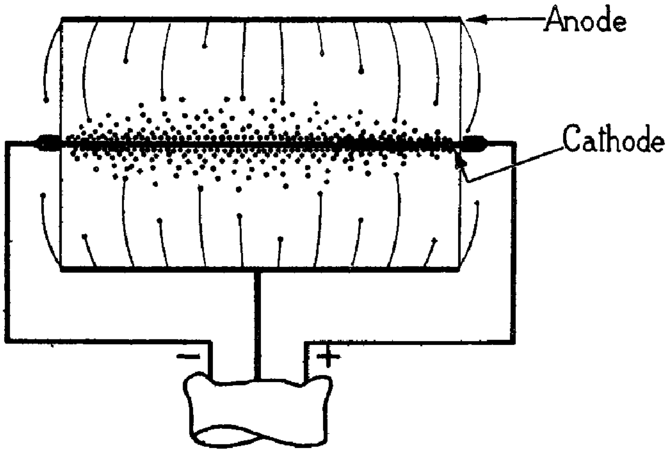


FIG. 6, CHAP. VIII.—Space charge in diode.

Characteristic curve of diode

14. If the cathode of a two-electrode valve is maintained at its normal temperature, i.e. that which will provide ample emission, and the P.D. between anode and cathode is varied in steps, the relation between " anode-cathode P.D." and " anode current " can be exhibited in graphical form as shown in fig. 7. This graph resembles the B/H curve shown in fig. 16, Chap. II, and its shape can be explained in similar terms. Thus for low values of anode voltage, the resulting attraction of the emitted electrons is nearly overcome by the repulsive effect of the space charge, and the anode current is correspondingly small. When the anode voltage has been raised to such a value that the space charge is entirely annulled, an increase of anode voltage leads to a proportional increase in anode current. When the anode voltage is raised above a certain value, however, the anode current no longer increases proportionally, because nearly all

the emitted electrons are already reaching the anode, and an increase of anode voltage cannot increase the number of electrons emitted. The current is then said to have reached " saturation value " or " full emission." Oxide-coated filaments do not give a well marked saturation value, nor, to a less extent, do thoriated tungsten filaments.

The relation between anode current (I_a) and anode voltage (V_a) in the curve of fig. 7, is given by the equation

$$I_a = A{V_a}^{\frac{3}{2}}$$

where A is a constant depending upon the design of the electrode system. This law is only true provided that the emission is sufficient to avoid saturation, i.e. when the anode current is limited by the space charge. As an example of the practical use of this formula, consider the design of a pure tungsten filament for a large diode with cylindrical anode. For pure tungsten the constant A is

$$\frac{2{\cdot}92\,l}{\beta^2\,d \times 10^2}$$

where l is the length (centimetres) of the filament.

d the diameter (centimetres) of the anode.

β a function of the ratio $\frac{\text{anode radius}}{\text{cathode radius}} = R$ which is approximately unity for all values of R greater than 10.

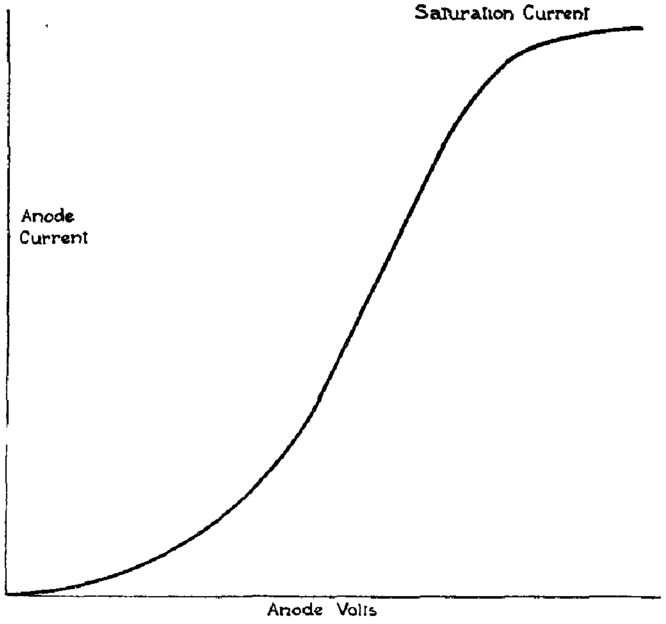


FIG. 7, CHAP. VIII.—Characteristic curve of diode.

Example 2.—A tungsten filament is required to give an anode current of 500 milliamperes at 400 volts, the anode diameter being 2 cm. and the filament diameter 1 mm. Find the length of filament necessary.

Since $R > 10$, $\beta^2 \doteqdot 1$.

$$I_a = \frac{2{\cdot}92 \times 400^{\frac{3}{2}} \times l}{2 \times 100}$$

$$l = \frac{2 \times 100 \times 500}{2{\cdot}92 \times 8000}$$

$$= 4{\cdot}3 \text{ cm.}$$

In the service the diode is used.

(i) As a power rectifier, for supplying high voltage of steady value from alternating supply mains. Both the " hard " diode and the " mercury vapour " diode are used for this purpose.

(ii) As a " limiting " device in certain Transmitter-Receivers.

Both these functions will be described in the appropriate chapters.

THE TRIODE

Introduction of the grid

15. It has been observed that if the cathode of a valve is maintained at a temperature giving ample emission, and the anode is maintained at some potential positive to the cathode, the electron current is limited by the negative space charge, while if owing to the presence of gas molecules a positive space charge is formed, the anode current is increased. This at once suggests that a control of the anode current could be obtained by means of a space charge of variable amount and sign. The equivalent of this can be achieved by inserting a third electrode, whose potential is variable, between cathode and anode. This electrode must be perforated in order that the electron flow is not entirely obstructed and in practice is in the form of a grid or wire spiral. The component parts of a directly heated three-electrode valve or triode are shown in fig. 8, while fig. 9 shows two standard holders used for these valves and is self-explanatory.

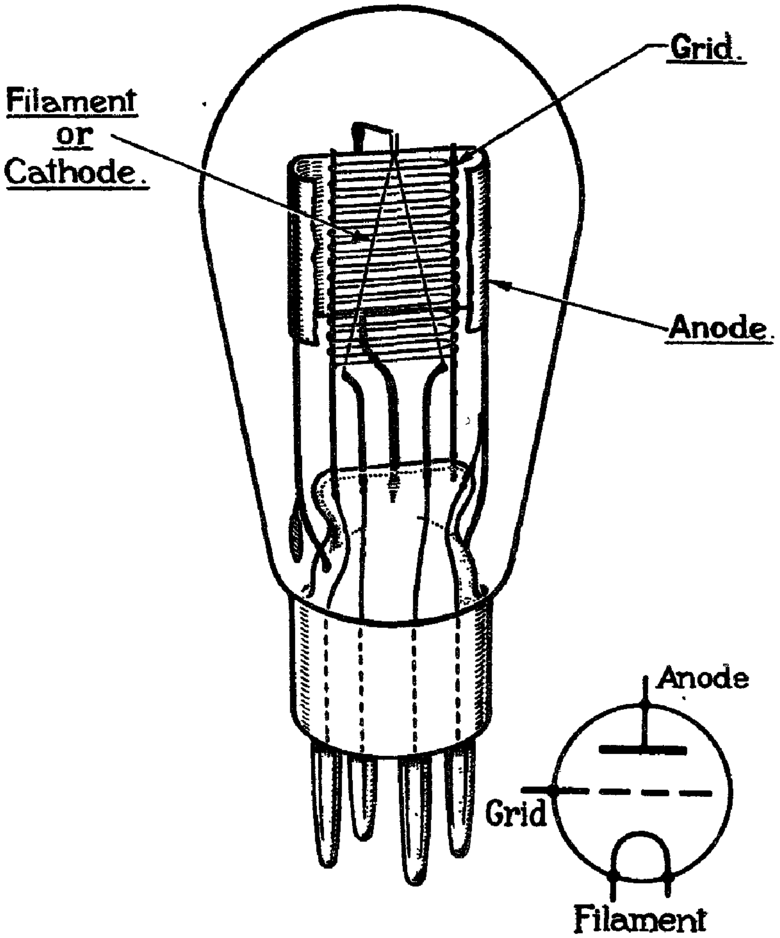
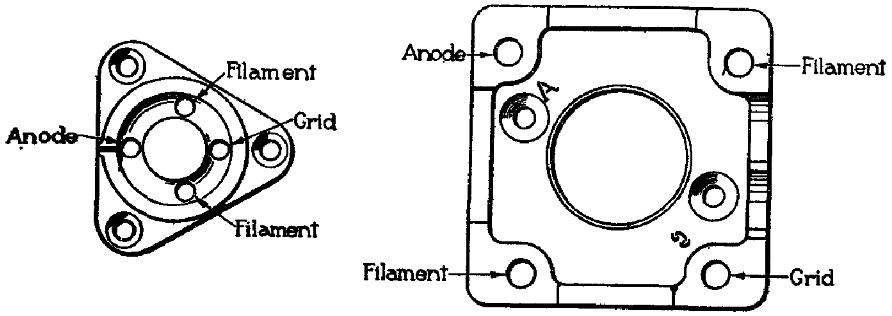


FIG. 8, CHAP. VIII.—Construction of triode.

Different specifications are necessary for triodes which perform various functions, but these fall into five main classes :—

(i) Receiving triodes for general amplification.
(ii) Receiving triodes specially selected as detectors.
(iii) Receiving triodes for power amplification.
(iv) Transmitting triodes for low power (e.g. aircraft) transmitters.
(v) Transmitting triodes for high power (e.g. ground station) transmitters.

The following general theory is the same for all these unless specifically stated to the contrary.



Standard holder for receiving and small transmitting valves

Low capacity holder for medium power transmitting valves

FIG. 9, CHAP. VIII.—Valve holders.

Characteristic curves of the triode

16. A graph which exhibits the relationship between the current flowing to any electrode, and the P.D. between any one electrode and the cathode, is called a static characteristic curve. It is necessary to specify that any electrode whose potential variation is not the subject of investigation shall be maintained at some constant potential, during the process of obtaining the points for plotting one curve.

Fig. 7 is actually the " anode current—anode voltage characteristic " of a diode. A triode has four such characteristics, viz :—

(i) The Anode Current—Anode Volts Curve ($I_a - V_a$) (the grid voltage being maintained constant).

(ii) The Anode Current—Grid Volts Curve ($I_a - V_g$) (the anode voltage being maintained constant).

(iii) The Grid Current—Grid Volts Curve ($I_g - V_g$) (the anode voltage being maintained constant).

(iv) The Grid Current—Anode Volts Curve ($I_g - V_a$) (the grid voltage being maintained constant).

It must be noted, however, that there is an indefinite number of possible curves in each " family " denoted by (i), (ii), (iii), (iv) above, each curve corresponding to one particular value of the potential of the electrode whose voltage is fixed. The latter is called a " constant parameter " for each curve of a family. Characteristic curves are used to explain the action of the valve under given conditions, and to determine suitable operating conditions for any desired purpose.

17. The characteristic curves of a given valve are obtained by plotting the current and voltage relations, which are observed by means of the circuit shown in fig. 10, in which it will be seen that it is possible to apply variable voltages between grid and cathode and between anode and cathode, as well as to vary the emission of the latter by variation of the current through the

filament. By an established convention, all P.Ds. are specified with reference to the cathode, or to the negative end of the filament when a directly heated cathode is used. It is important to connect the milliammeter I_a and the microammeter I_g in the positions shown, so that they measure only the actual current flowing at the anode and grid respectively.

The change-over switch (S) is fitted in order that the grid potential may be made either positive or negative to the filament. It is not usual to provide a similar switch for the anode potential, but it should be verified by reversing the necessary connections, that if the anode is given any potential negative to the filament, no anode current will flow.

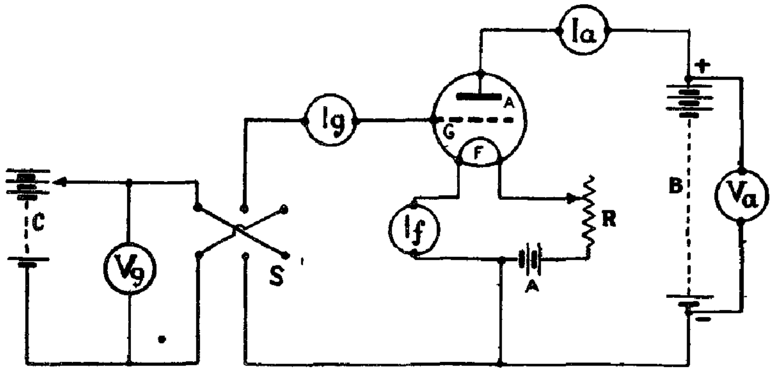


FIG. 10, CHAP. VIII.—Circuit used to obtain triode characteristics.

The various power supply devices used with all valve circuits may conveniently be defined with reference to this figure. The battery (A), supplying the heating current for the cathode, is called the L.T. (low tension) battery. The battery (B) applying a P.D. between anode and cathode, is called the H.T. (high tension) battery, and the battery (C) the grid bias battery. In American literature they are designated the A, B and C batteries respectively.

"Constants" of the triode

18. From the curves obtained by the use of the valve characteristic circuit it is possible and usual to derive numerical data which serve as a basis for the design of appropriate circuits for use with any particular valve, and to compare the merits of different valves for any special purpose. These data are usually called the constants of the valve, but it must be clearly understood that they are not constant over a wide operating range. These constants are :—

(i) The anode A.C. resistance, symbol r_a, which is the ratio of a small change of anode voltage to the corresponding change of anode current as determined from the static I_a — V_a characteristic, the grid voltage and electron emission remaining constant. The anode A.C. conductance, symbol g_a is the reciprocal of this : $g_a = \frac{1}{r_a}$.

(ii) The mutual A.C. conductance, symbol g_m which is the ratio of a small change of anode current to the corresponding change of grid voltage as determined from the static I_a — V_g characteristic, the grid voltage and electron emission remaining constant.

(iii) The amplification factor, symbol μ ,which is the numerical ratio of the slope of the I_a — V_g curve to the slope of the I_a — V_a curve, the slope in each case being taken at the point representing the particular adjustment under consideration.

$$\text{Algebraically, } \mu = \frac{g_m}{g_a} = g_m\, r_a$$

The I_a — V_a characteristics. Derivation of r_a and g_a

19. A family of I_a — V_a characteristics for a typical receiving valve having an oxide-coated filament is given in fig. 11, curves being drawn for various values of V_g, viz :— zero, + 2 volts, —2 volts and —4 volts respectively. It will be observed that the curves are approximately straight and parallel over a wide range, the lower limit being in the neighbourhood of two

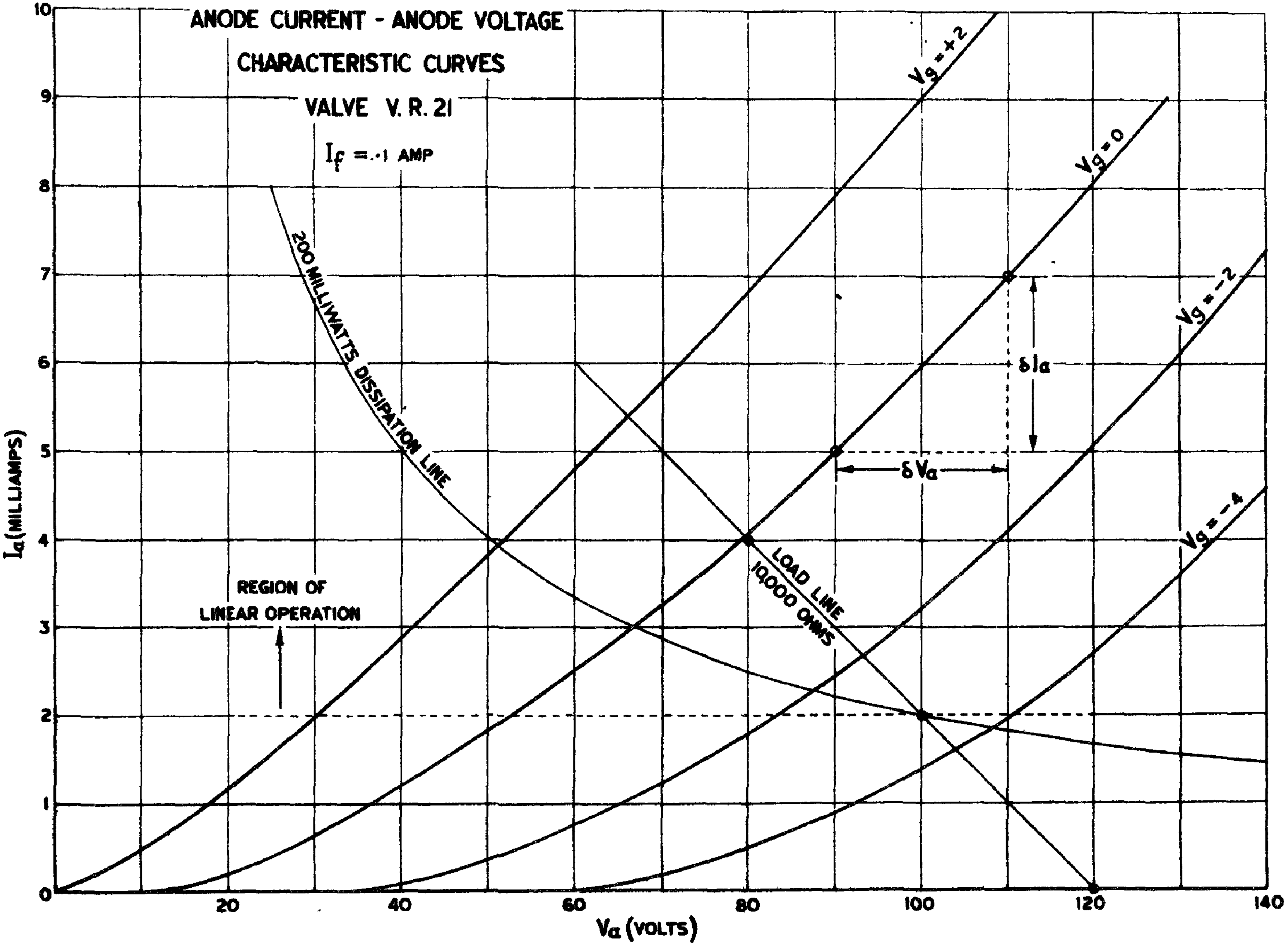


FIG. 11
CHAP VIII

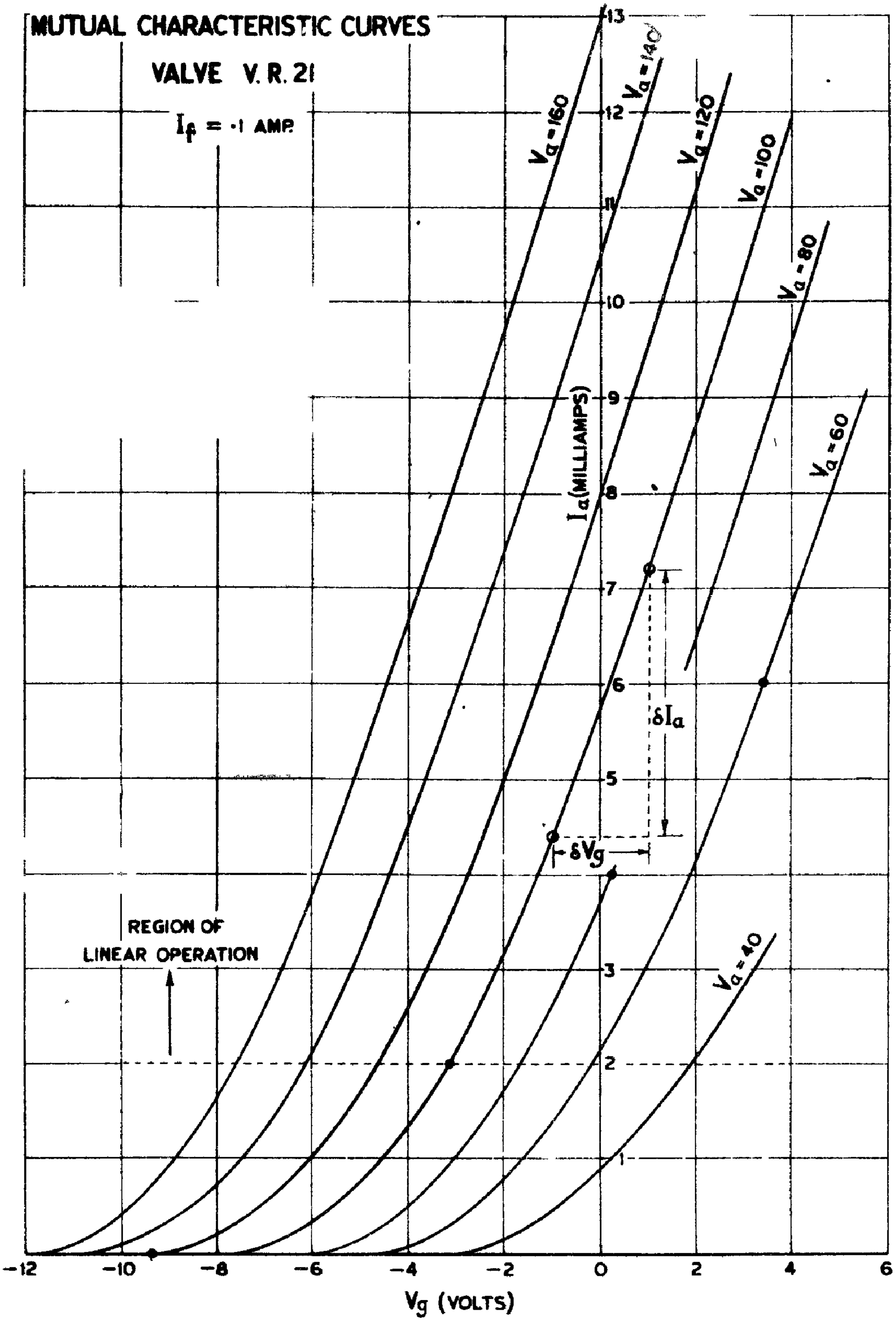


FIG. 12
CHAP VIII

milliamperes of anode current. The upper limit is not shown, because with this type of cathode there is danger of exceeding its safe emission if higher operating potentials than those shown are applied. This region of approximate straightness and parallelism is termed the region of linear operation. The effect of increasing the negative potential applied to grid is to shift the curve bodily to the right, while slightly decreasing its slope.

The anode A.C. resistance can be obtained from any curve in this family, depending upon the intended operating conditions. In order to illustrate the procedure, the operating potentials have been taken as $V_g = 0$, $V_a = 100$. The corresponding mean value of I_a is 6 milliamperes. Bearing in mind the definition of r_a, mark off on the graph a small change of V_a disposed symmetrically about the mean operating point, calling this small change δV_a. The corresponding change of I_a, called δI_a, is then ascertained, and the value of r_a follows from the definition, being the ratio $\delta V_a / \delta I_a$. In the figure $\delta V_a = 20$ volts, $\delta I_a = 2$ milliamperes, therefore $r_a = 20$ volts $\div \frac{2}{1000}$ amperes $= 10{,}000$ ohms.

The anode A.C. conductance is the reciprocal of this, i.e. $\frac{1}{10{,}000}$ siemens or ·1 milli-mho.

The I_a — V_g characteristic. Derivation of g_m

20. A typical family of these curves is shown in fig. 12, being the mutual characteristics of the valve previously discussed. A separate curve is shown for each step of 20 volts anode potential in the range 160–40 volts, these being the limits between which the valve can be usefully operated. The region of linear operation should be observed, and also that the curves for 60 and 40 volts tend to a decreasing slope, owing to the fact that when the anode potential is low and the grid potential is positive, the grid becomes a collecting as well as a controlling electrode.

The mutual A.C. conductance can be obtained from any one curve of this family ; the chosen curve should of course agree with the operating conditions previously prescribed. The procedure is shown in the figure. A small change of V_g, (δV_g), having been marked off, the corresponding change of I_a, (δI_a) is measured. By definition, $g_m = \delta I_a / \delta V_g$. In the example, $\delta I_a = 2{\cdot}7$ milliamperes, $\delta V_g = 2$ volts, hence $g_m = 2{\cdot}7 \div 2$ or $1{\cdot}35$ milliamperes per volt, (milli-siemens).

The amplification factor. Derivation of μ

21. Since $\mu = g_m \times r_a$, the amplification factor of this valve can now be determined. It is

$$g_m \times r_a = \frac{1{\cdot}35 \text{ amperes.}}{1000 \text{ volts}} \times 10{,}000 \frac{\text{volts}}{\text{amperes}} = 13{\cdot}5.$$

The significance of the amplification factor must be fully realised, since it is its amplifying property which gives the triode such a predominant importance in modern radio technique. It may be expressed by stating that in a valve of amplification factor μ one unit change of voltage between grid and filament will cause the same change of anode current as a change of μ units of voltage in the P.D. between anode and cathode. Referring again to fig. 12, with an anode potential of 100 volts and a grid potential of + 1 volt, the anode current is 7·2 milliamperes. A reduction of anode potential by 20 volts would reduce this current to 5 milliamperes. If, however, the anode potential were kept constant at 100 volts, the same reduction of anode current would be achieved by the application of a potential of —·5 volts to the grid, a change of 1·5 volts. From these figures the grid potential is approximately 13 times as effective as the anode potential in producing a change of anode current. The slight variation in the value of μ, as calculated by different methods, is of no practical significance.

The extent to which the anode current is changed by a given change of grid voltage will depend upon the extent to which the grid screens the plate from the electron flow, and also upon the degree to which the grid voltage influences the potential gradient in the space between cathode and anode. Both these factors depend upon the shape and disposition of the electrodes and therefore the amplification factor μ depends upon the geometry of the valve. This factor is large if the grid is situated comparatively near to the cathode and has a fine mesh, while a coarse grid near to the plate results in a low value for μ. In fig. 13 the alternative locations and wire diameters shown at A and B respectively will give approximately the same amplification factor.

The qualification " approximately " has been inserted because in the figure referred to it is implicitly assumed that electrons travel from filament to anode in straight lines. Fig. 14 has been developed to give a rather more accurate representation of the actual flow of electrons. The thin solid lines in this figure show the direction of the electrostatic field between anode and filament in the absence of any emission from the latter, for three different values of grid potential.

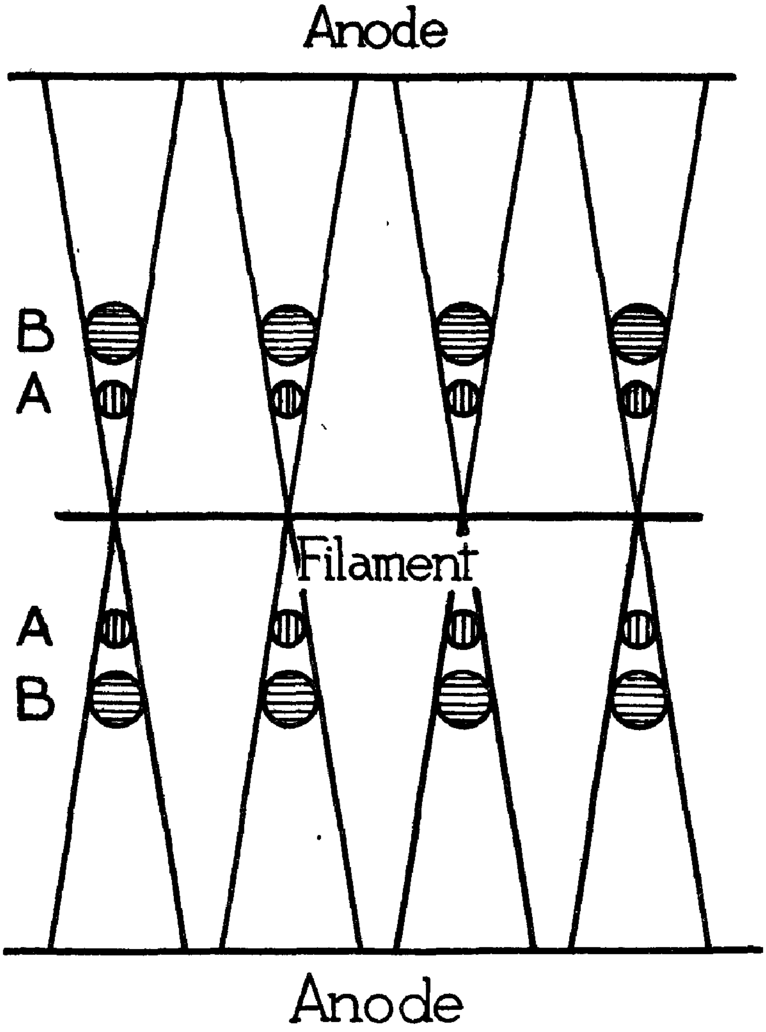
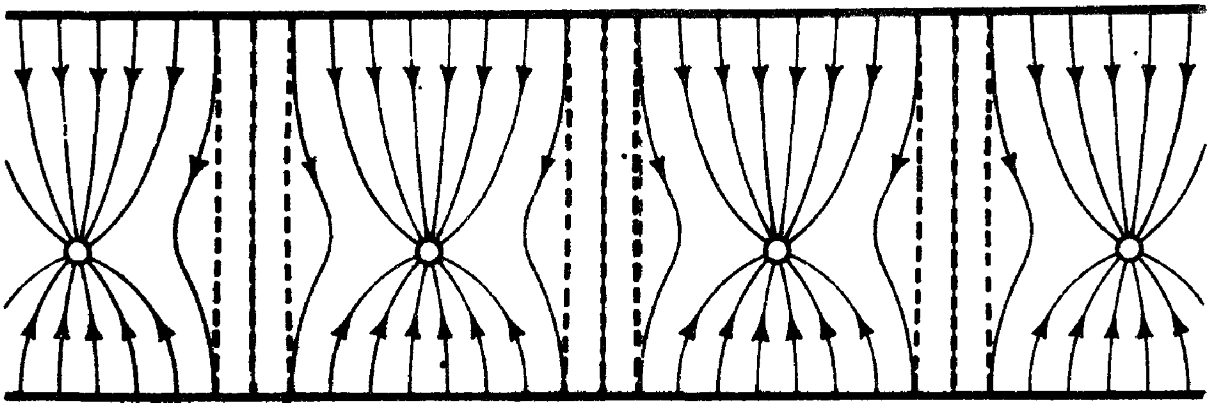


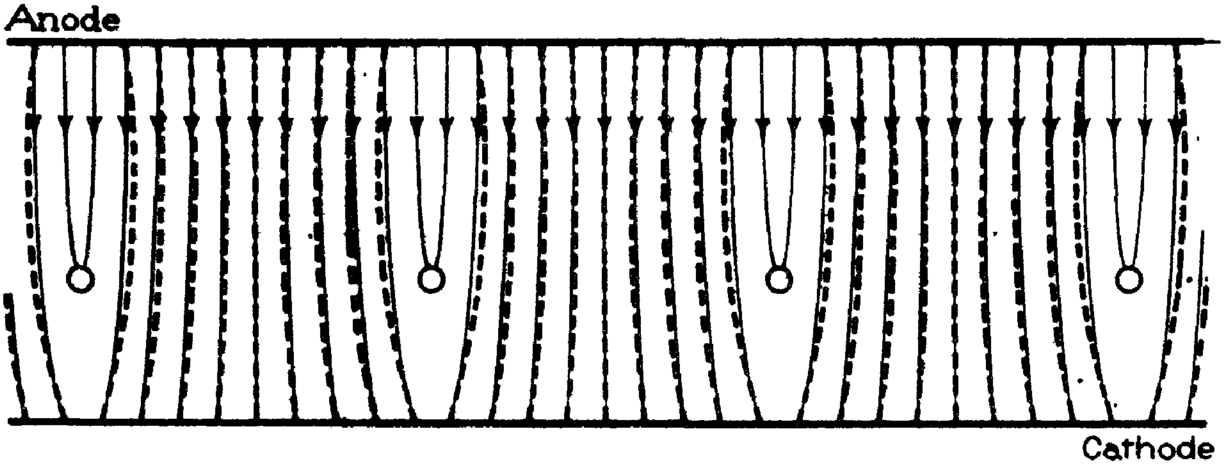
FIG. 13, CHAP. VIII.—Alternative designs of grid giving approximately equal amplification factor.

The heavy broken lines represent the paths of electrons when emission is taking place, and as the electrons flow along lines of electric force, the broken lines may also be assumed to represent the electric field under emission conditions. The effect of a positive grid potential in increasing the electron current is also shown by this figure.

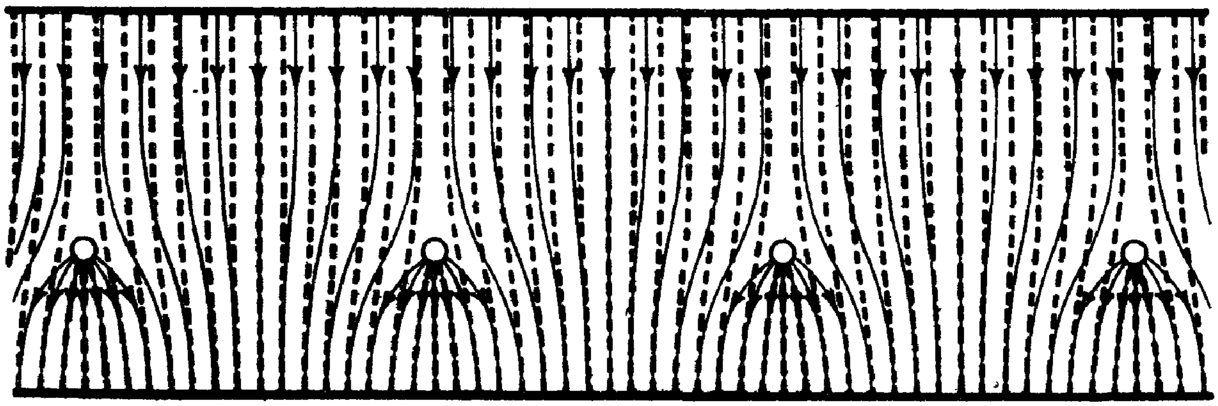
22. The principal function of the triode is therefore to act as an extremely sensitive " relay." It differs from an electro-mechanical relay in two particulars. First, it has no appreciable time lag, the change of anode current taking place almost instantaneously upon the occurrence of a grid voltage change. This is due to the almost entire absence of mass, and therefore inertia,



A - Grid Negative



B - Grid Neutral



C - Grid Positive

ELECTRIC FIELDS IN TRIODE

FIG. 14
CHAP VIII

in the moving part of the relay, the electrons themselves. Second, by suitable adjustments of the operating conditions, the valve can be made to perform its amplifying function without constituting a load upon the preceding circuit, the presence or absence of the valve and its anode circuit making no difference to the power consumption in the circuits normally connected to grid and filament. It might at first sight be thought that this is contrary to the principle of the conservation of energy, because energy is dissipated in the valve itself, but the anode circuit contains a source of energy (the H.T. supply device), and it must be realised that it is this source which supplies the energy dissipated in the valve and the anode circuit.

The I_g — V_g characteristic

23. The principal function of the grid is to act as a controller of the flow of anode current, but under certain conditions it may collect electrons, while if an appreciable quantity of gas is present in the valve, it may sometimes collect positive ions. A typical $I_g \rightarrow V_g$ characteristic curve for a soft triode is shown in fig. 15. It must be clearly understood that this is not the valve whose I_a — V_g and I_a — V_a curves have already been discussed. The general features of this curve may be explained as follows. When electrons flow through a valve, they travel with accelerated velocity, under the influence of the electric field of force set up by the H.T. battery. If gas molecules are present, collisions occur between them and the electrons, resulting in ionisation of the gas. Whether any one collision will result in the formation of a positive or a negative ion depends largely upon the velocity of the electron, or how far it has travelled since leaving the cathode before meeting the molecule, the average distance for the whole emission being called the mean free path of any electron. If the velocity of the electron on impact is low, the electron probably unites with the molecule forming a negative ion, while if it is high, the impact may cause an electron to be dislodged from the molecule, resulting in the formation of a positive ion. Negative ions move off toward the anode with comparatively low velocity, while positive ions move toward the filament. The formation of negative ions thus results in a reduction of anode

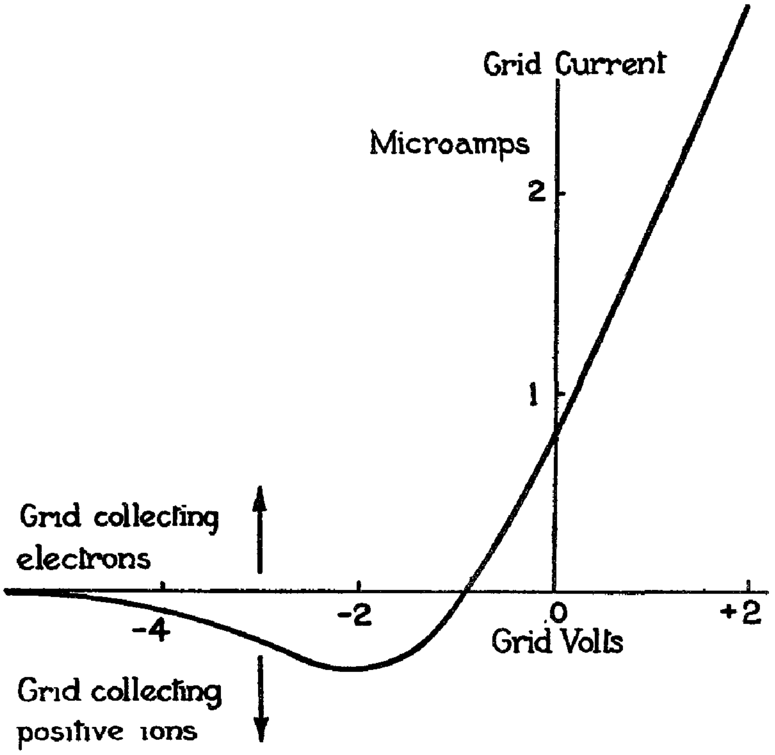


Fig. 15, Chap. VIII.—Grid current/grid volts characteristic of soft triode.

current, and the formation of positive ions in an increase. So far we have only considered the effect of the gas on the anode current. Now consider the grid. If its potential with respect to cathode is positive, the grid will collect electrons from the anode stream, while if negative it will collect positive ions provided that these are formed. If the grid is extremely negative, its repulsive force will prevent any electrons travelling an appreciable distance from the cathode, and therefore the production of positive ions is unlikely. The collection of positive ions by the grid is referred to as reverse grid current.

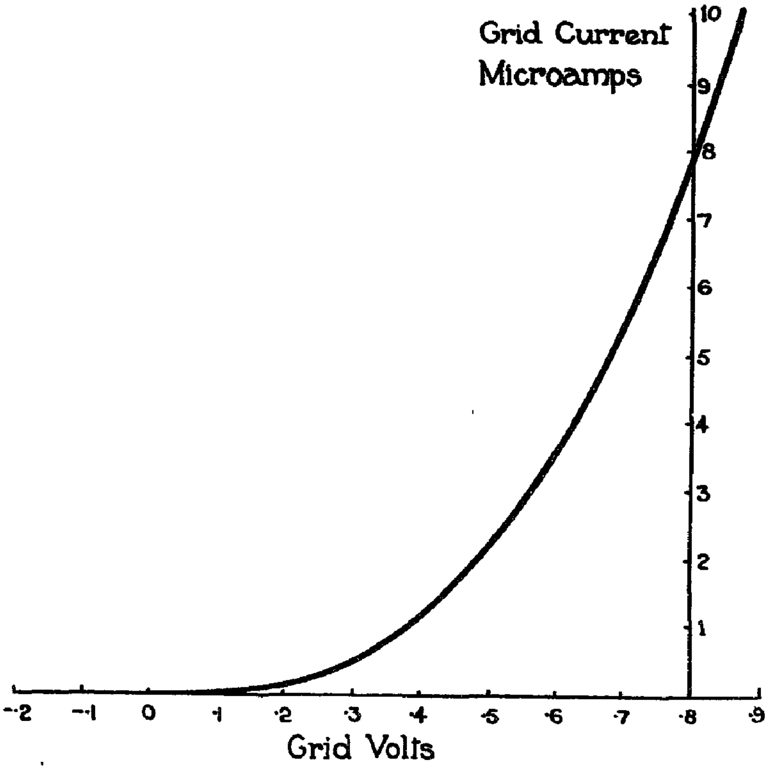


FIG. 16, CHAP. VIII.—Grid current/grid volts characteristic of Valve V.R. 21.

The $I_g - V_g$ curve for a perfectly hard triode would show no reverse grid current because no positive ions would be formed. Since a perfect vacuum is unattainable, it is usual to specify the degree of vacuum in terms of the permissible reverse grid current, a typical specification for a receiving valve being " maximum reverse grid current not to exceed two microamperes."

The $I_g - V_g$ curve of the valve previously discussed is shown in fig. 16. It is a hard valve, the reverse grid current being indistinguishable on the scale to which this curve is plotted.

The $I_g - V_g$ characteristic

24. This curve is rarely used, and it has only been mentioned in order to emphasise that the triode has four characteristics. A valve having n electrodes has $(n - 1)^2$ characteristics, but its behaviour in most circumstances can be deduced from two of them.

Simultaneous variation of V_a and V_g — dynamic characteristics

25. So far we have considered the variation of anode current under conditions in which either V_a or V_g are varied independently. In practical circuits however, V_a and V_g usually vary simultaneously. In the valve characteristic circuit, fig. 10, the resistance of the external anode circuit is utterly negligible compared with the internal resistance of the valve, but in actual

working conditions the anode circuit invariably contains an impedance of some kind, and this will modify the performance of the valve. We will first assume that the anode circuit possesses a resistance of the same order as the anode A.C. resistance of the valve.

The triode with its anode load resistance, as it is termed, is shown diagrammatically in fig. 17 in which for purposes of numerical illustration the valve may be the V.R. 21, the static characteristics of which are given in figs. 11, 12 and 16. The external anode circuit consists of a 120 volt battery and a non-inductive resistance *R* of 10,000 ohms. The grid may first be assumed to have zero potential with respect to the filament. On completing all circuits an anode current will be established, setting up a P.D. across the resistance. The P.D. between anode and filament will then be, not 120 volts, but 120 volts minus the fall of P.D. in the resistance. The effect of the latter is therefore to reduce the anode current, an effect which might be anticipated from first principles, but nevertheless is often not appreciated.

Now suppose the grid is given a positive potential. There will be an increase in the anode current, and consequently a larger P.D. between the terminals of the load resistance. The anode-filament P.D. being equal to the battery E.M.F. minus this $I\ R$ drop, the rise of anode current will be accompanied by a fall in the anode-filament P.D. On the other hand, if the grid is given a negative potential, the electron flow decreases, and the P.D. between the terminals of the load resistance will be less than when the grid potential was zero. The anode-filament P.D. therefore rises as the grid is made more negative with respect to the filament. It follows therefore that if an alternating voltage is applied between grid and filament, the changes of anode current and anode-filament P.D. are in anti-phase, an increase of I_a due to the positive half-cycle of grid voltage being accompanied by a decrease in V_a and vice-versa. Algebraically,

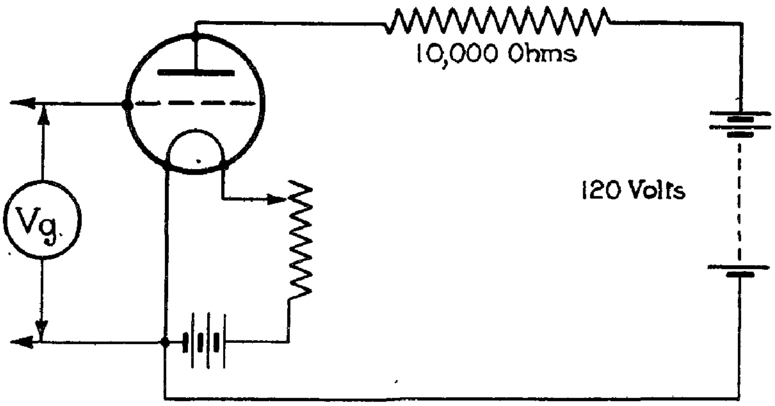


FIG. 17, CHAP. VIII.—Circuit illustrating derivation of dynamic characteristic.

$$\delta V_a = -R\ \delta I_a$$

the minus sign being inserted to denote the anti-phase relation. The curve showing the variation of anode current with variation of grid voltage, for a given load impedance—not necessarily non-reactive—is called the dynamic mutual characteristic.

26. For a given load resistance, the dynamic mutual characteristic can be derived from the family of static mutual characteristics as follows. Referring to figs. 12 and 17, the anode current is just reduced to zero by the application of — 9·5 volts to the grid. The P.D. across the load resistance is also zero, and the anode-filament P.D. equal to the E.M.F. of the H.T. battery, 120 volts. The point $I_a = 0$ on the 120 volt curve is therefore a point on the dynamic characteristic. If the negative grid voltage is reduced so that the anode current rises to 2 milliamperes, the P.D. across the load is 20 volts, and the anode-filament P.D. falls to 120 — 20 or 100 volts. The point corresponding to 2 milliamperes on the 100 volt curve therefore gives another point on the dynamic characteristic. A further reduction of negative grid voltage, allowing the anode current to rise to 4 milliamperes, causes a P.D. of 40 volts across the load resistance and the

anode-filament P.D. falls to 120 — 40 = 80 volts; the point corresponding to 4 milliamperes on the 80 volts curve gives a third point on the dynamic characteristic. These points are indicated by small circles in fig. 12 and the dynamic characteristic for a resistance of 10,000 ohms may now be drawn. To avoid confusion it has been shown in a separate diagram, fig. 18.

The slope of this curve is the dynamic mutual conductance for the given load resistance, and is measured in milliamperes per volt as in the case of the mutual characteristic. The slope may be found algebraically as follows. Since $g_m = \frac{\delta I_a}{\delta V_g}$ the change of anode current δI_a for any change of grid voltage δV_g, is $g_m \, \delta V_g$ (provided V_a is constant) and in the same manner $\delta I_a = g_a \, \delta V_a$ provided V_g is constant. If both V_a and V_g vary simultaneously, the total variation of I_a is given by the sum of the separate variations, so that

$$\delta I_a = g_m \, \delta V_g + g_a \, \delta V_a$$

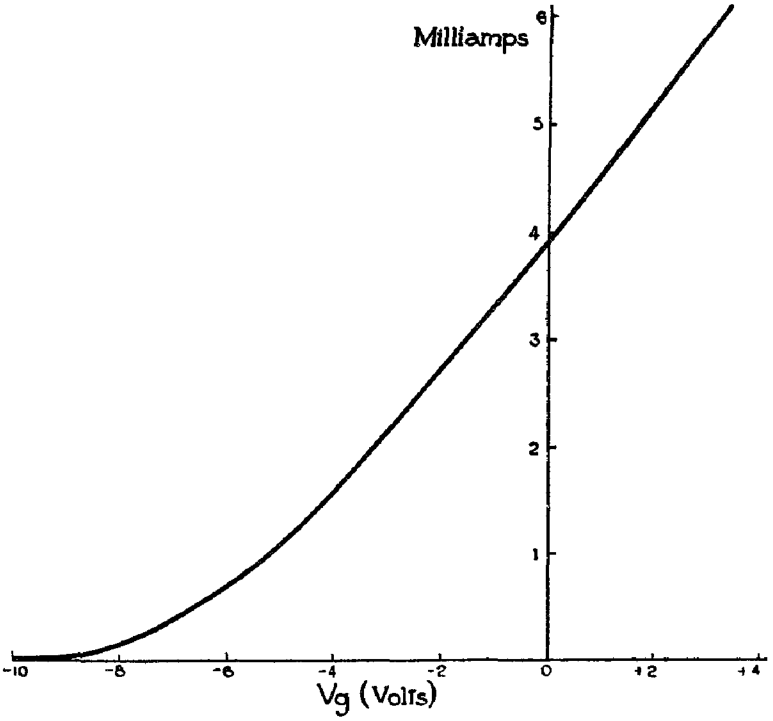


FIG. 18, CHAP. VIII —Dynamic characteristic of Valve V.R. 21 with 10,000 ohms resistance.

bearing in mind that g_m and g_a are only constant within the region of linear operation. It is often more convenient to use a different notation, in which i_a is written for δI_a, v_a for δV_a and v_g for δV_g. In this form

$$i_a = g_m \, v_g + g_a \, v_a$$

In the foregoing discussion, it was shown that, under dynamic conditions, $\delta V_a = -R\delta I_a$ which in the new notation may be combined with the last equation, giving

$$i_a = g_m \, v_g - g_a \, R i_a$$

$$(1 + g_a R) \, i_a = g_m \, v_g$$

$$\therefore \; i_a = \frac{g_m}{1 + g_a \, R} \, v_g$$

Thus $\frac{g_m}{1 + g_a R}$ or $\frac{g_m}{1 + \frac{R}{r_a}}$ is the slope of the dynamic mutual characteristic, just as g_m is the slope of the static mutual characteristic.

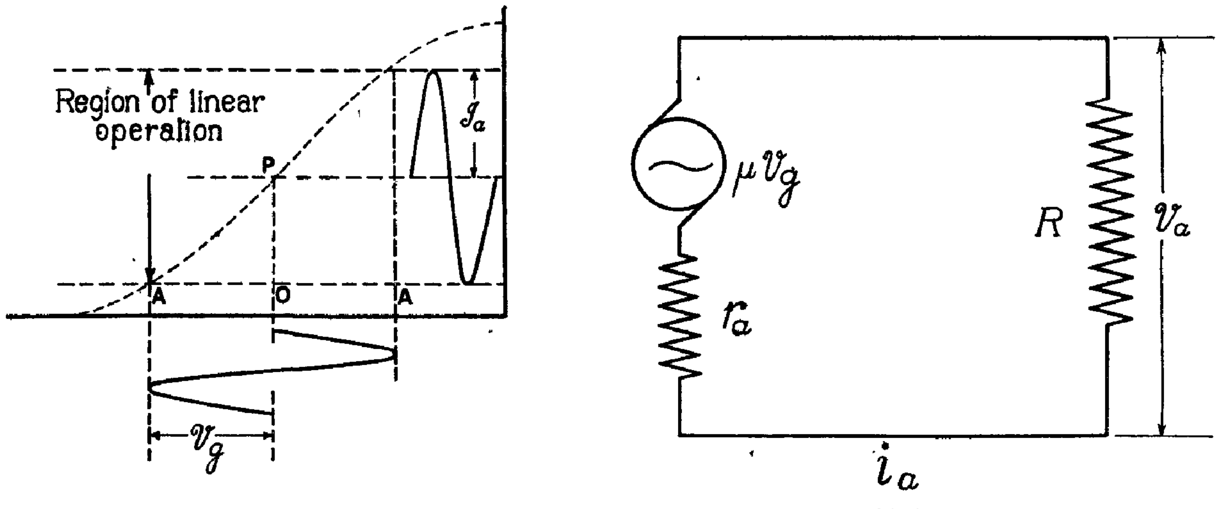
It is often convenient to write this relation in a different way. Since

$$i_a = \frac{g_m \; v_g}{1 + \frac{R}{r_a}} = \frac{r_a \, g_m \, v_g}{r_a + R}$$

$$i_a = \frac{\mu \, v_g}{r_a + R}$$

because $r_a \, g_m = \mu$

27. It has already been stated that the fundamental function of the triode is that of an amplifier, and a somewhat detailed consideration of the factors governing its employment in this capacity is given in Chapter XI. The triode is also employed as a power converter and as a rectifier in connection with radio transmitters and receivers respectively, and it is necessary to give a brief outline of the use of the valve as an amplifier before the latter applications can be appreciated. Suppose the steady anode voltage and mean grid voltage are so adjusted that the anode current is equal to one-half the saturation value, the mean anode current being that marked P on the dynamic characteristic fig. 19a. If now an alternating voltage $v_g = \mathcal{V}_g \sin \omega t$ is applied between grid and filament, the peak value of which does not exceed O A, a sinusoidal variation of anode current will take place as shown in the diagram.



(a) (b)

FIG. 19, CHAP. VIII.—Triode used as amplifier; operating conditions and equivalent circuit.

By definition of the amplification factor the voltage will produce a change of anode current equal to that which would be produced by μ times this voltage acting directly in the anode circuit, provided that the variation of grid voltage is confined within the limits of linear operation. Within this limit therefore, the valve may be considered, for purposes of calculation, to act as the generator of an alternating E.M.F. μv_g, and to possess an internal resistance r_a ohms. The valve with its associated anode circuit may be represented by the equivalent circuit fig. 19b, the anode circuit load being assumed to consist only of a resistance R.

The variation in anode current due to the sinusoidal grid-filament voltage will be

$$i = \frac{\mu \mathcal{V}_g \sin \omega t}{r + R}$$

which is greater than $\frac{\mathcal{V}_g \sin \omega t}{R}$ provided that μ is greater than $1 + \frac{r_a}{R}$. The latter condition may be fulfilled by the choice of a suitable valve for R, or, if this is fixed, by choice of a valve having suitable values of μ and r_a. The valve may thus be considered to act as a current amplifier.

The P.D. set up between the ends of the external resistances as a result of the change of grid voltage v_a is Ri_a and

$$Ri_a = \frac{R \mu v_g}{r_a + R}$$

Now $- Ri_a$ is the change of anode-filament P.D. and may be denoted by v_a as before, hence

$$v_a = -\cdot\frac{R}{r_a + R} \mu \mathcal{V}_g \sin \omega t$$

Thus v_a is a sinusoidal voltage variation also. It is again seen that v_a is larger than v_g if $\mu > 1 + \frac{r_a}{R}$ and the valve is said to function as a voltage amplifier. When the mean anode voltage V_a and mean grid voltage V_a are so chosen that the mean operating point lies near the upper or lower bends of the $I_a - V_g$ curve, the variation of anode current will not be a true reproduction of the grid voltage variation. These are the conditions in which a valve is employed as a rectifier in radio reception, and in these circumstances it is no longer permissible to employ the simple equivalent circuit for purposes of calculation.

The load line

28. Dynamic conditions can frequently be studied with greater facility with the aid of the $I_a - V_a$ characteristics. The procedure is similar to that adopted in deriving the dynamic mutual characteristic. Referring to figs. 12 and 17 we have seen that with 120 volts H.T. supply, a negative grid bias of about 9·5 volts will reduce the anode current to zero, and the anode-filament P.D will then be 120 volts. Also, on decreasing the negative bias until I_a rises to 2 milliamperes the P.D. across the load resistance is 20 volts and the anode-filament P.D. 100 volts. A further reduction of the grid bias to zero causes the anode current to rise to 4 milliamperes, and the anode-filament P.D. falls to 80 volts. These points are plotted in fig. 11, and the straight line passing through the points is called the load line corresponding to an anode load resistance of 10,000 ohms.

When an alternating P.D. is superimposed upon the steady grid bias voltage a point representing corresponding instantaneous values of anode current and anode-filament P.D. travels to and fro on the appropriate load line, and the chief advantage of this method of representation is the ease with which the power relations can be computed. First, take the conditions in the absence of the alternating grid-filament voltage, The $I_a - V_a$ curves in fig. 20 are typical of those of a small power triode; let the H.T. supply voltage be 120 volts and the load resistance be 10,000 ohms as before; the corresponding load line has been inserted in the diagram. If the grid bias is fixed at —8 volts, the anode current I_a is 5 milliamperes and the power supplied by the H.T. battery, 600 milli-watts. The anode-filament P.D. V_a is only 70 volts, and the power dissipated in the valve is $I_a V_a = 70$ volts × 5 milliamperes or 350 milli-watts. The power dissipated by the load resistance is $I_a^2 R$ or 250 milli-watts.

Now suppose an alternating voltage of 8 volts peak value is applied between grid and filament in addition to the steady bias. During the positive half-cycles of grid voltage the anode current will increase, rising to a maximum value of 8 milliamperes, and will fall during negative half-cycles, its minimum value being only 2 milliamperes. A point representing corresponding instantaneous values of anode current and anode filament P.D. therefore travels to and fro between the points A and B. (fig. 20). Owing to the presence of this alternating component of anode current in the resistance R, the power losses in the latter will be increased. If $\mathcal{I}_a$ is the peak value of the alternating component, its R.M.S. value is $\frac{\mathcal{I}_a}{\sqrt{2}} = \frac{3 \cdot 0}{\sqrt{2}}$ milliamperes and the power dissipated in the load resistance is $\frac{\mathscr{I}_a^2 R}{2}$ = 45 milli-watts. This of course is in addition to the amount calculated above, due to the steady anode current.

The average value of the current, however, is still 5 milliamperes, and the power delivered by the H.T. battery is unchanged. The power expended in the valve is the difference between the total power supplied and that dissipated in the load resistance, and this is less than before, i.e. 350 – 45 or 305 milli-watts instead of 350 milli-watts.

In fig 20, O F is the mean anode current I_a ; O C the H.T. battery voltage E_a ; O G the anode-filament P.D. V_a ; A Q the peak value of the alternating component of anode current, $\mathscr{I}_a$; P Q the peak value of the alternating voltage across the anode load resistance $\mathscr{V}_0$. Then O G = $I_a r_a$, G C = $I_a R$ and the rectangle O C D F = $I_a^2 (R + r_a)$ and is equal in area to

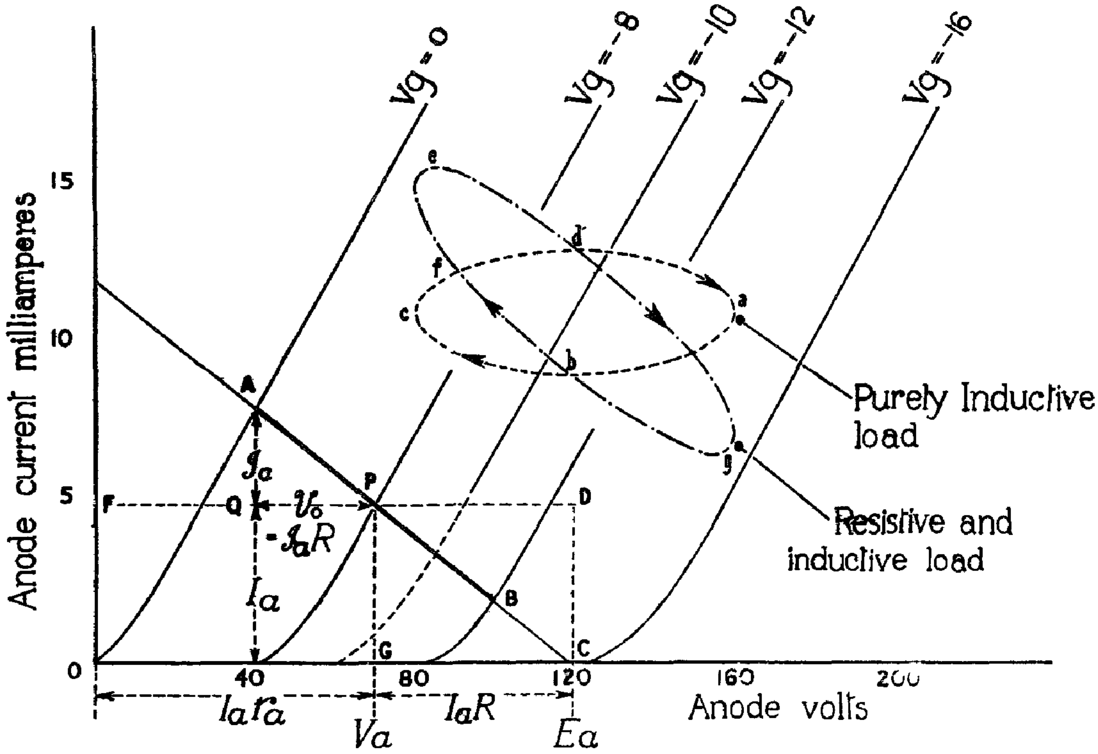


FIG. 20, CHAP. VIII.—$I_a - V_a$ characteristics of small power triode, showing load lines for resistance, reactance and impedance loads.

the power supplied by the H.T. battery. The area G C D P is equal to the steady power dissipation $I_a^2 R$ in the resistance R. The area O G P F is equal to the power dissipated in the valve itself, $I_a^2 r_a$, and the triangular area P Q A to the alternating power dissipated in the load resistance $= \frac{\mathscr{I}_a \mathscr{V}_0}{2} = \frac{\mathscr{I}_a^2 R}{2}$.

29. If the anode circuit contains a purely reactive impedance, e.g. an inductive coil of negligible resistance, the change of P.D. corresponding to a given change of anode current will lag on the latter by 90° and the load line becomes an ellipse upon which the representative point travels in a clockwise direction once per cycle. Taking the same valve as before and referring to fig. 20 let the H.T. supply voltage be 120 volts and the mean grid bias —10 volts. If the anode load is an inductive reactance of 20,000 ohms and the alternating grid voltage has a peak value sufficient to cause a P.D. of 40 volts between the load terminals, the peak value of the alternating

component of anode current will be 2 milliamperes. Since the P.D. lags by 90° on the current change, the anode current will be of normal value, 11 milliamperes, at the instant when the anode-filament P.D. is 40 volts above normal, i.e. 160 volts, giving the point *a* on the load ellipse. At the instant when the anode-filament P.D. is normal the anode current will be 2 milliamperes below normal, i.e. 9 milliamperes, giving the second point *b*. Similarly, when the P.D. falls to 80 volts the anode current will rise to normal, giving the point *c*, and finally when the anode-filament P.D. reaches normal again, the anode current will reach its maximum value during the cycle, namely 13 milliamperes, point *d*. The complete elliptical load line thus traced out is shown by a dotted line in the diagram.

When the anode impedance possesses both resistive and reactive components, the load line is an ellipse inclined to the vertical, its mean slope corresponding to the effective resistance. Suppose the operating conditions to be as in the last instance, except that a resistance of 10,000 ohms is connected in parallel with the inductive load. The load line is then found by taking the algebraic sum of the currents in the two branches of the external impedance during the whole cycle, giving the ellipse *e, d, g, b, f* (fig. 20). It is however seldom necessary to consider load lines of this nature.

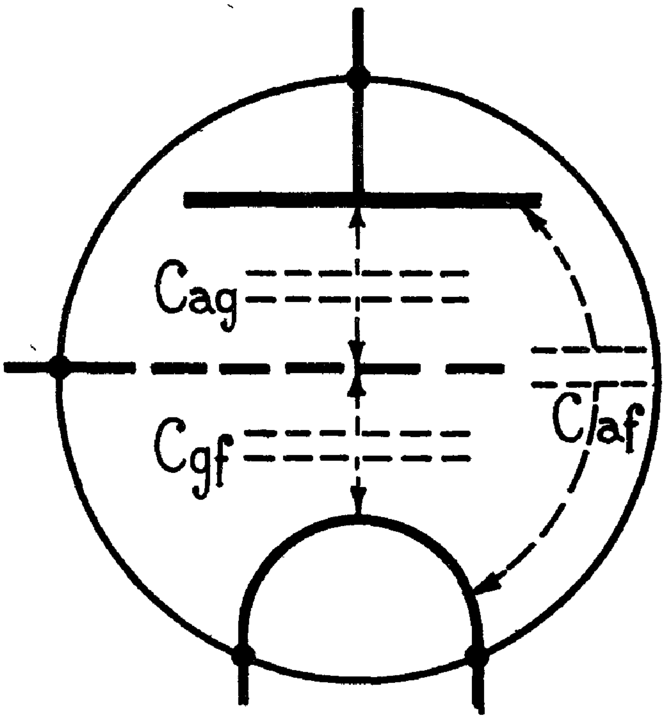
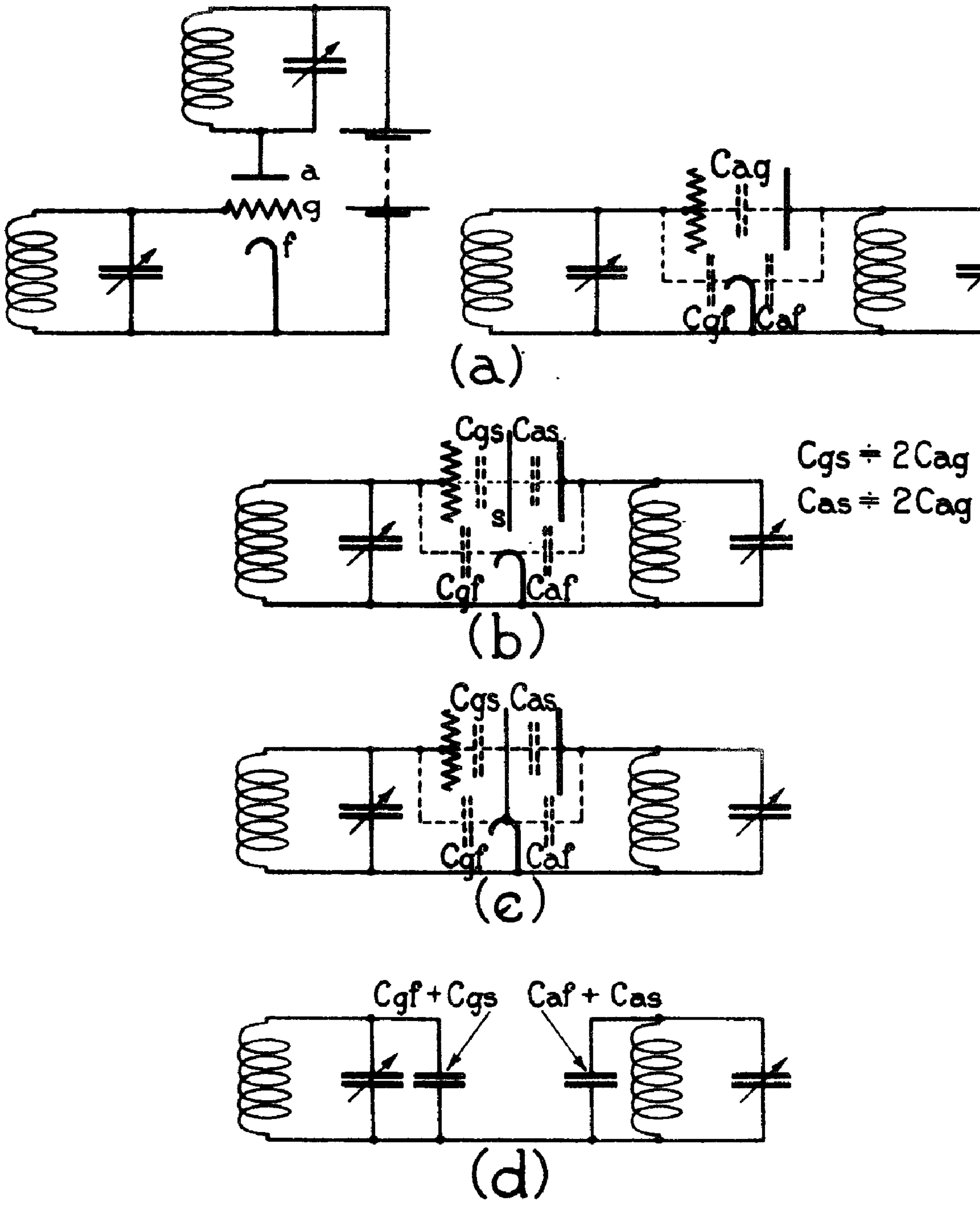


FIG. 21, CHAP. VIII.—Diagrammatic representation of inter-electrode capacitance.

The dissipation line

30. The application of an anode-filament potential and consequent flow of anode current results in a loss of power due to the heat developed in the valve, and as previously stated transmitting and power amplifying valves are rated according to the power they are capable of dissipating in this manner. The power dissipated (in milli-watts) is given by the expression $P = V_a I_a$ where V_a and I_a are in volts and milliamperes respectively. For any given valve, the permissible dissipation is constant and the equation represents a rectangular hyperbola, which may be drawn on the $I_a - V_a$ characteristics as follows. Taking the valve, receiving, V.R. 21 as an example, and assuming that it is capable of dissipating 200 milli-watts, the following co-ordinates viz. (10 m.a., 20 volts), (5 m.a., 40 volts), (2·5 m.a., 80 volts), (2 m.a., 100 volts), (1·25 m.a., 160 volts),



EFFECT OF SCREEN BETWEEN GRID AND ANODE

FIG. 22
CHAP. VIII

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(1 m.a., 200 volts), etc., are all points on the 200 milli-watt dissipation line, which has been plotted from these values in fig. 11. The mean anode current under working conditions must lie on or below this line, otherwise the power dissipated by the valve will be in excess of the rated power. It is not customary to give the power rating of a receiving valve, and the foregoing assumption of 200 milli-watts for the valve V.R. 21 was made purely to demonstrate the method of drawing the curve.

Inter-electrode capacitance of the triode

31. The electrodes of a valve and the connecting leads to the external circuit are in somewhat close proximity, and therefore each pair of electrodes possesses a capacitance which although comparatively small may have a profound influence upon the behaviour of the valve, particularly when used at the higher radio-frequencies. Fig. 21 indicates the notation generally adopted in writing of these capacitances, the usual magnitudes of each being of the order of from 5 to 10 micromicrofarads in ordinary triodes. The inter-electrode capacitance is never absolutely constant since the space between the electrodes contains free electrons, which influence the effective dielectric constant. The most important inter-electrode capacitance is that denoted by C_{ag} in fig. 21 because in practice, the alternating grid-filament P.D. is often that developed between the terminals of the inductance of a tuned circuit, while the anode load impedance consists of a parallel-resonant circuit tuned to the same frequency. The anode-grid capacitance C_{ag} then takes the place of the coupling condenser in a well-known form of capacitance-coupled circuit (Chapter VI), the actual circuit and its electrical equivalent being shown in fig. 22a. The complications arising from this coupling in the case of radio-frequency amplifiers are dealt with in Chapter XI, but it may here be stated that the effect is to limit severely the amplification obtainable at frequencies above about 1,000 k.c/s. Many attempts have been made to overcome this difficulty by special circuit arrangements, but these cannot be considered entirely satisfactory for use in receivers, in which the circuit adjustments must often be changed with rapidity and accuracy. The screen-grid valve and its later development the radio-frequency pentode were evolved in a successful attempt to attack the problem at its source, by a reduction in the effective value of the coupling capacitance.

SCREEN-GRID AND PENTODE VALVES

The screen-grid valve

32. This type of valve has four electrodes and is therefore sometimes referred to as a " tetrode." The electrodes consist of a cathode or electron emitter, control grid, screening grid and anode or collecting electrode. The function of the control grid is exactly the same as in the triode, namely, to control the flow of electrons so that the valve will act as a relay. The screening grid acts as an electrostatic screen between the control grid and the anode, thus effecting a considerable reduction in the effective grid-anode capacitance referred to in the preceding paragraph. A consideration of fig. 22 will make this clear ; at (*a*) the tuned input and output circuits of a triode are shown, coupled together by the inter-electrode capacitance C_{ag}. If a metal plate (s) is interposed between grid and anode as at (*b*), one condenser C_{gs} is formed by the grid (g) and plate (s) and another, C_{as}, by the plate (s) and anode (a), the capacitance of each being larger than the original capacitance C_{ag}, but as the two are in series between grid and anode, the total effective capacitance of these electrodes is unaltered. The coupling effect of the grid anode capacitance is therefore not affected by an insulated screen. If the screen is connected to the filament (f) as in (*c*), the condenser C_{gs} formed by the grid and screen is in parallel with the capacitance C_{gf} while the condenser C_{as} formed by the screen and the anode is in parallel with the capacitance C_{af} (fig. 22d). There is therefore no effective capacitance whatever between the grid and the anode and consequently the input and output circuits are not coupled together, that is, energy can no longer be transferred from one to the other. It must be borne in mind that a single connecting conductor does not constitute coupling in the electrical sense.

In practice the screening cannot be perfect, since it is necessary to use a screen in the form of a gauze or mesh in order that electrons may pass through it on their way from filament to anode. Some lines of electric force from the anode inevitably terminate upon the grid, and hence there must be some residual anode-grid capacitance. By correct design this can be reduced to a value about one-thousandth of the anode-grid capacitance of a triode having similar dimensions.

33. The introduction of such a screen directly connected to the filament would modify the characteristics of the valve in such a manner as to render it unsuitable for practical use, in particular the anode A.C. resistance would be extremely high. This disability is overcome by the application of a positive potential to the screening electrode, its value being generally variable within the limits of one half to five-eights that of the anode potential. This does not nullify the screening properties, provided that the screen is connected to the cathode by a low impedance path, and it is usual to ensure this low impedance (for the frequency at which the valve is to function) by connecting externally a condenser of about ·5 microfarad between screen and filament terminals.

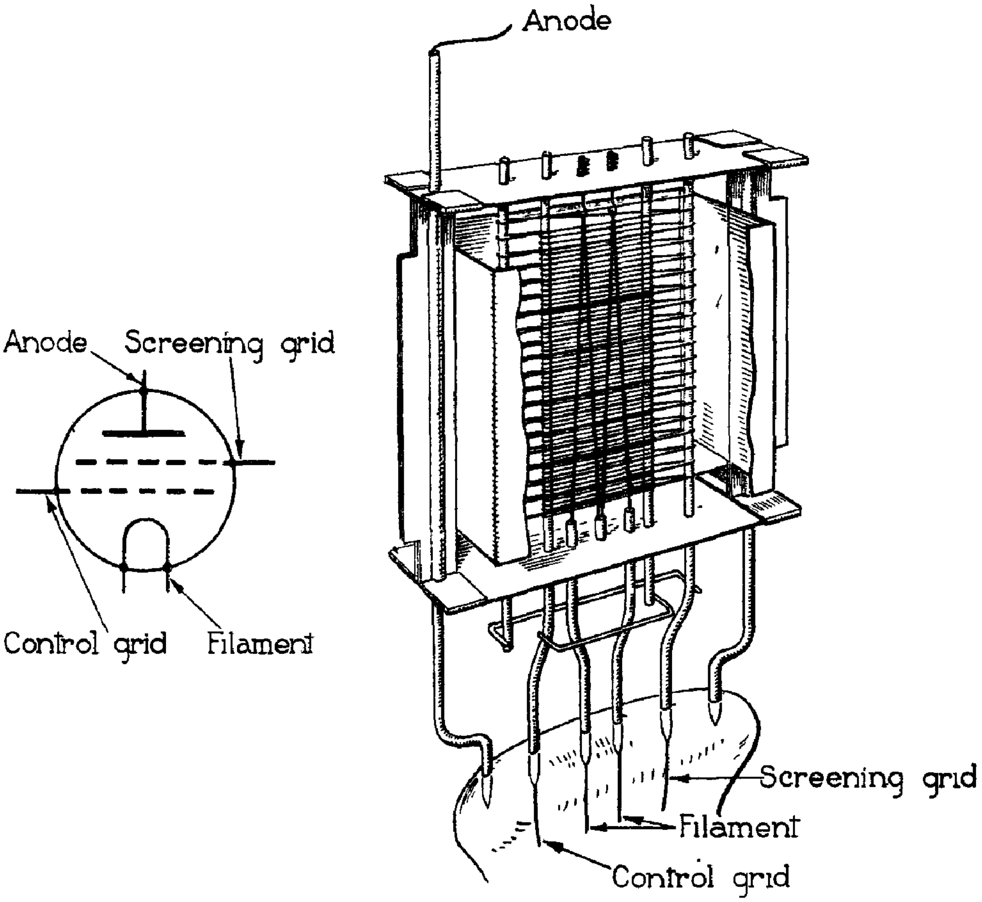
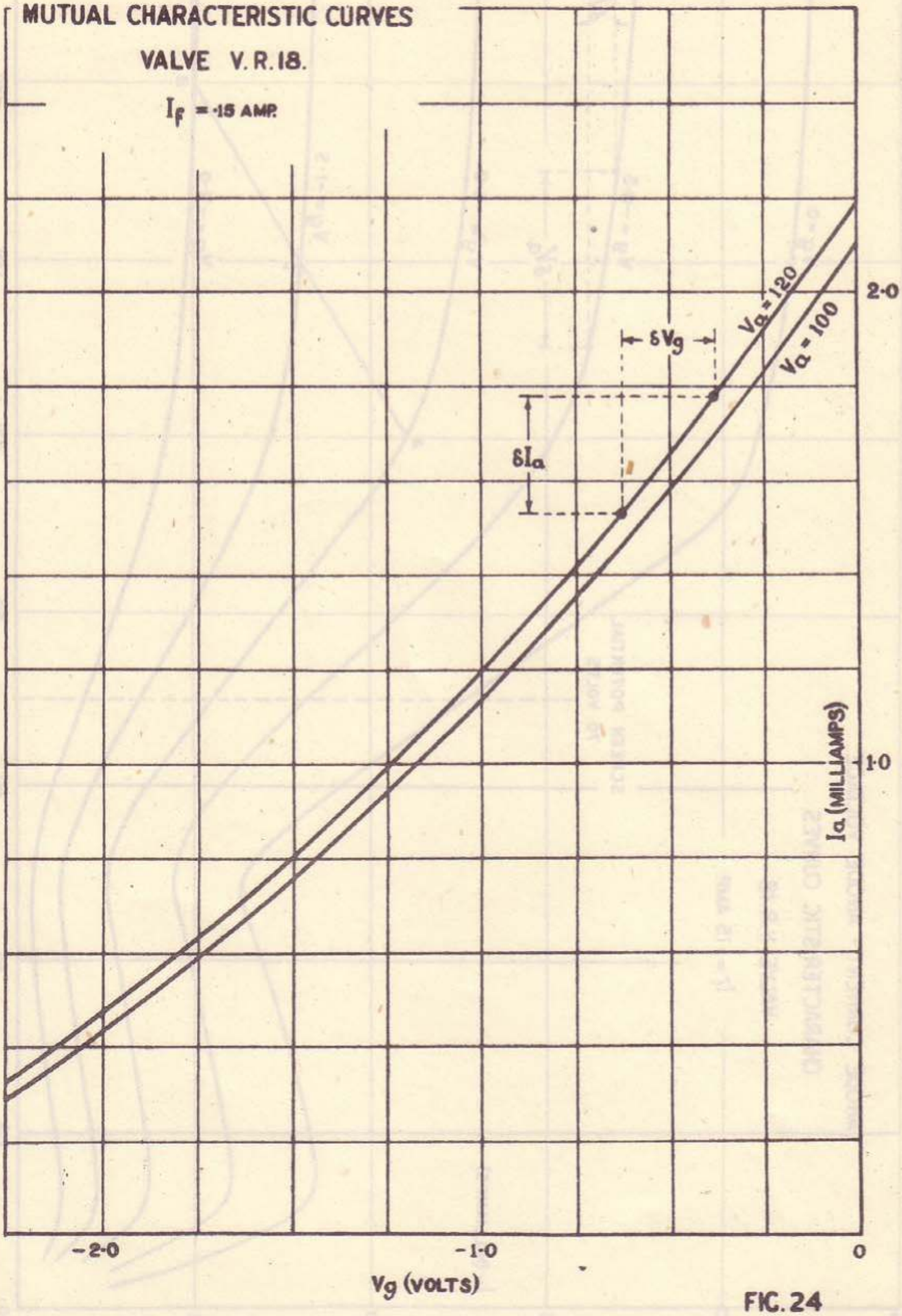


FIG 23, CHAP. VIII.—Electrodes of screen-grid valve.

The appearance of the electrodes of a typical screen-grid valve with directly heated cathode is shown in fig. 23 in which also the external connections are indicated. It should be noted that the anode is connected to the top terminal, the pin connection which serves as anode connection in a triode being allotted to the screen. In order that the screening may be complete, the bulb is generally metallised, the metallising being connected to the negative filament pin as usual. It is also necessary to ensure that the input and output circuits are effectively screened from each other, otherwise the object of the valve is defeated.



MUTUAL CHARACTERISTIC CURVES

VALVE V.R.18.

I_f = ·15 AMP.

FIG. 24
CHAP VIII

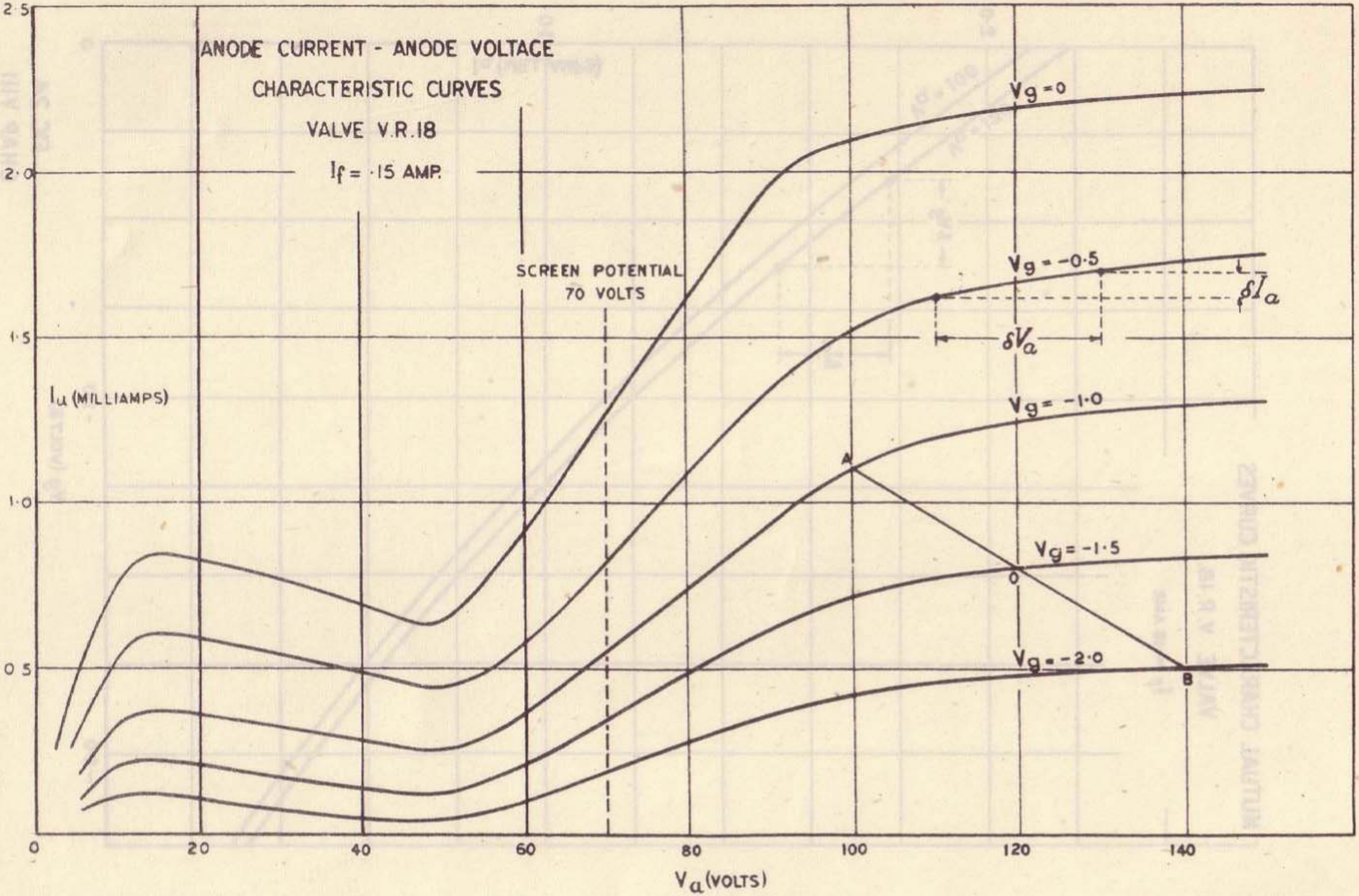


FIG 25
CHAP VIII

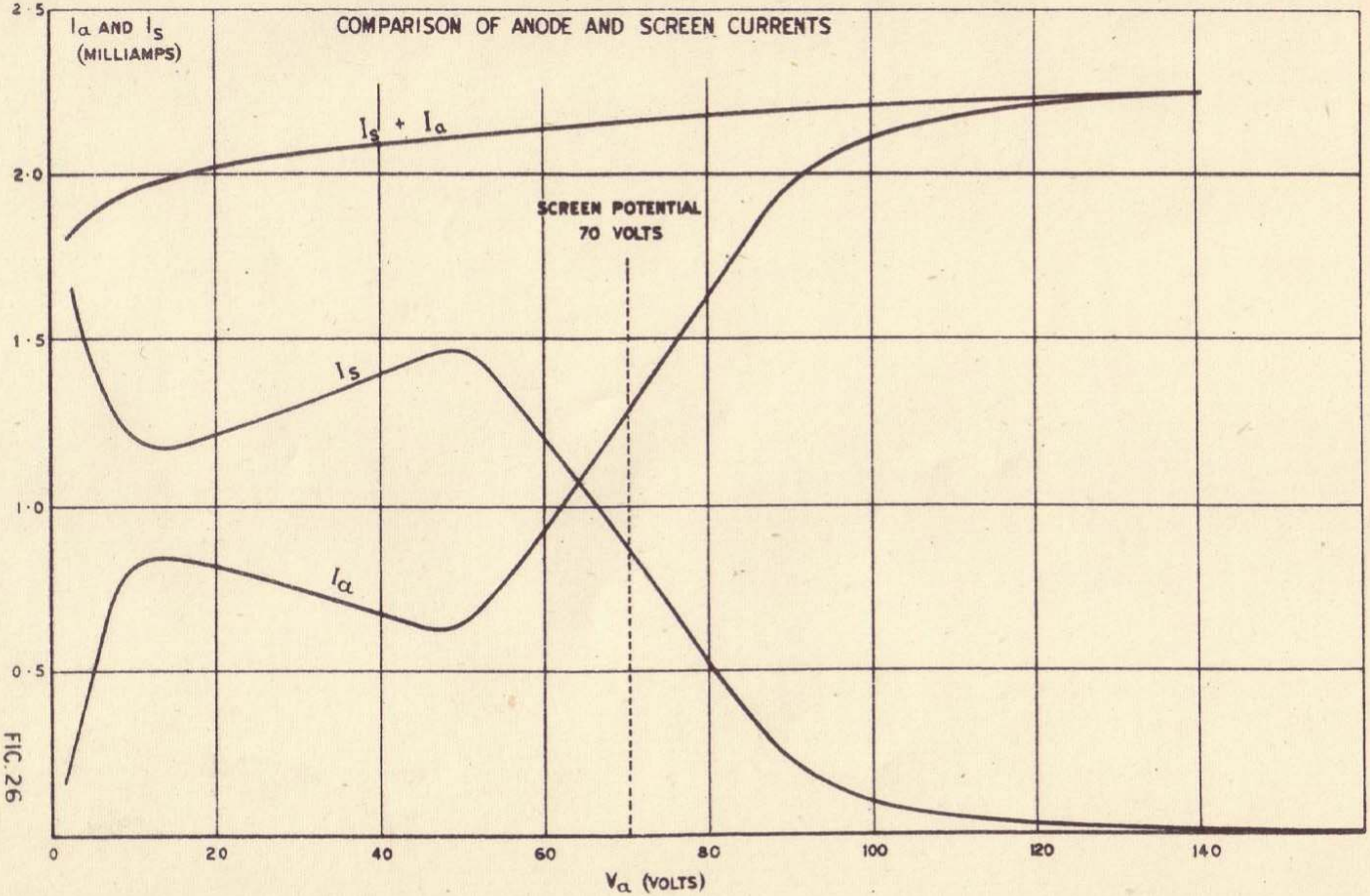


FIG. 26
CHAP VIII

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Characteristic curves

34. The static mutual characteristics of a service S.G. valve (V.R.18) are given in fig. 24. It will be seen that they are similar to those of a triode in general character. As the mutual conductance of any valve of given emission depends chiefly on the design of the control grid, tetrodes and triodes with identical cathodes and control grids have similar if not identical values of mutual conductance. The individual curves of the $I_a - V_g$ family lie much closer together for the tetrode than for the triode which implies a higher anode A.C. resistance. This feature is due to the influence of the positive potential of the screen in assisting the production of an electron current. Slight variations of the anode potential make very little difference to the anode current because practically no lines of electric flux extend from anode to cathode, owing to the effective screening between the two electrodes. The point may be illustrated by reference to the anode current-anode voltage curves fig. 25 in which it can be seen that provided the anode potential is at least 30 volts above that of the screen an increase of anode voltage produces only a very small increase of anode current. The value of r_a for this particular valve calculated from the $I_a - V_a$ curve is 266,000 while the value of g_m (from the mutual characteristic) is 1 milliampere per volt. The amplification factor is 266, which is much greater than that of a triode.

35. Another notable feature of the $I_a - V_a$ curves is the region of negative slope when the anode potential is below that of the screen. Fig. 26 shows the anode current, screen current and their sum, plotted against anode potential, the screen potential being fixed at 70 volts. When the anode potential is zero, all the electrons passing the control grid go to the screen, and the screen current is correspondingly large. On raising the anode potential some of the electrons pass through the screen to the anode. The total number of electrons flowing is not greatly increased, and the rise of anode current is largely at the expense of the screen current, with a resultant decrease of the latter. When the anode potential exceeds 15 volts the anode current starts to decrease with an increase of anode voltage, the screen current increasing proportionally. This phenomenon is due to the emission of electrons from the anode.

In the opening paragraphs of this chapter secondary emission was described as the production of emission from a body by bombardment with electrons. In the region under consideration the electrons reach the screen with considerable velocity, and passing through it, impinge on the anode with such force that electrons are set free from its surface ; as many as twenty electrons may be emitted for each one arriving. The emitted electrons travel in the direction of the strongest attractive field, that is toward the screen, and an electron current is established from anode to screen. The anode current is then the difference between the rate at which electrons reach it, and the rate at which they leave, while the screen current is the sum of the rate at which electrons arrive from the anode and rate at which electrons arrive from the cathode. The result is that an increase of anode potential causes a fall of anode current and a rise of screen current. When the anode potential approaches equality with that of the screen, the field surrounding the anode exerts a force on the secondary electrons which overcomes the attraction of the screen, so that any secondary electrons emitted are immediately reattracted to the anode. The anode current then rises with an increase of anode potential, until the latter exceeds that of the screen, when the anode current becomes nearly constant and independent of the anode potential.

36. From the load line drawn in fig. 25 it is evident that the valve suffers from certain limitations. Assuming a working anode potential of 120 volts, and grid bias $-1 \cdot 5$ volts, the given load line represents a dynamic resistance of 64,000 ohms, a not unlikely figure for the tuned circuit generally used. The distance OA being equal to OB, there will be little or no distortion if the input voltage is not allowed to exceed $\cdot 5$ volt. The power expended in the anode load will then be $\frac{\cdot 625 \text{ m.a.} \times 40 \text{ volts.}}{8} = 3 \cdot 125$ milli-watts. This is the order of the maximum undistorted power obtainable from this valve and therefore it is unsuitable for use as an " output " or power valve, its use being practically confined to radio-frequency amplification. Further limitations of the S.G. valve, when used as a radio-frequency amplifier for R/T reception, are dealt with in Chapter XII. For this function the tetrode has been largely replaced by the radio-frequency pentode.

The pentode

37. This type of valve has five electrodes, which are termed the cathode, control grid, auxiliary grid, earthed grid and anode, their relative positions being indicated by fig. 27. The auxiliary grid and anode are connected externally to sources of high positive potential, and the earthed grid is connected internally to the cathode. In service valves the auxiliary grid external terminal is mounted on the side of the base. Other terms used for the auxiliary grid are " suppressor grid " and " anti-secondary."

The design of the pentode arose from the inability of the usual form of screen-grid receiving valve to handle more than a few milli-watts without considerable distortion, which makes it unsuitable for, e.g. the output stage of an amplifier supplying power to a moving coil loud speaker.

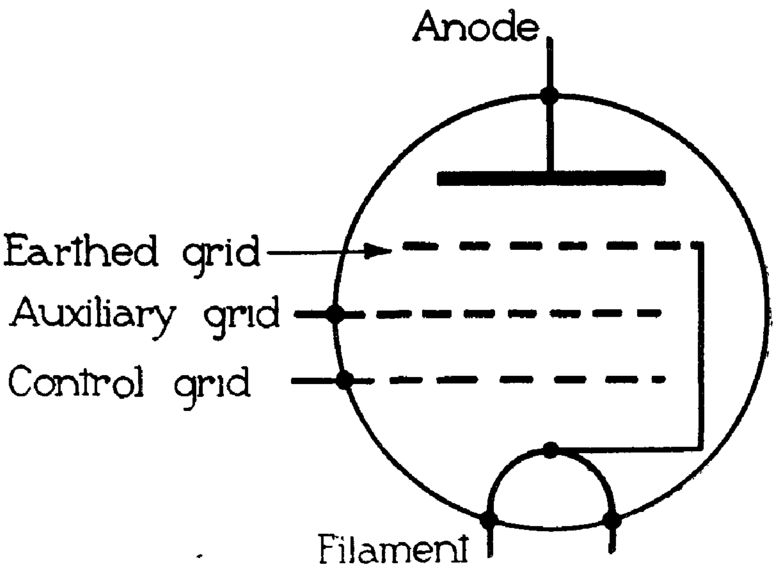

FIG. 27, CHAP. VIII —Electrodes of pentode valve.

This is due, in part to the limited variation of anode voltage which can be accommodated on the (comparatively) straight portion of its characteristics ; a limitation which could be reduced if the region of negative slope were eliminated. The auxiliary grid is retained because as we have seen in the case of the tetrode, an additional electrode with high positive potential has the effect of increasing the anode A.C. resistance and consequently the amplification factor.

When the pentode is designed for low frequency purposes, the auxiliary grid is of comparatively coarse mesh, because the effects of inter-electrode capacitance are not so detrimental as in radio-frequency circuits. The function of the earthed grid is to eliminate the negative slope of the $I_a - V_a$ curve. It will be remembered that this is due to secondary emission from the anode causing an electron current in the direction of the attractive field of the screening grid. In the pentode, the interposition of the earthed grid between the auxiliary grid and the anode screen these secondary electrons from the influence of the auxiliary grid, so that no region of negative slope occurs.

Typical mutual characteristics and $I_a - V_a$ characteristics are given in fig. 28 for comparison with those of the triode and tetrode. The constants of commercial types of pentodes used for power purposes are of the following order :—

Anode A.C. Resistance.	Amplification Factor.	Mutual Conductance.
30,000 ohms.	75	2·5 m.a. per volt.

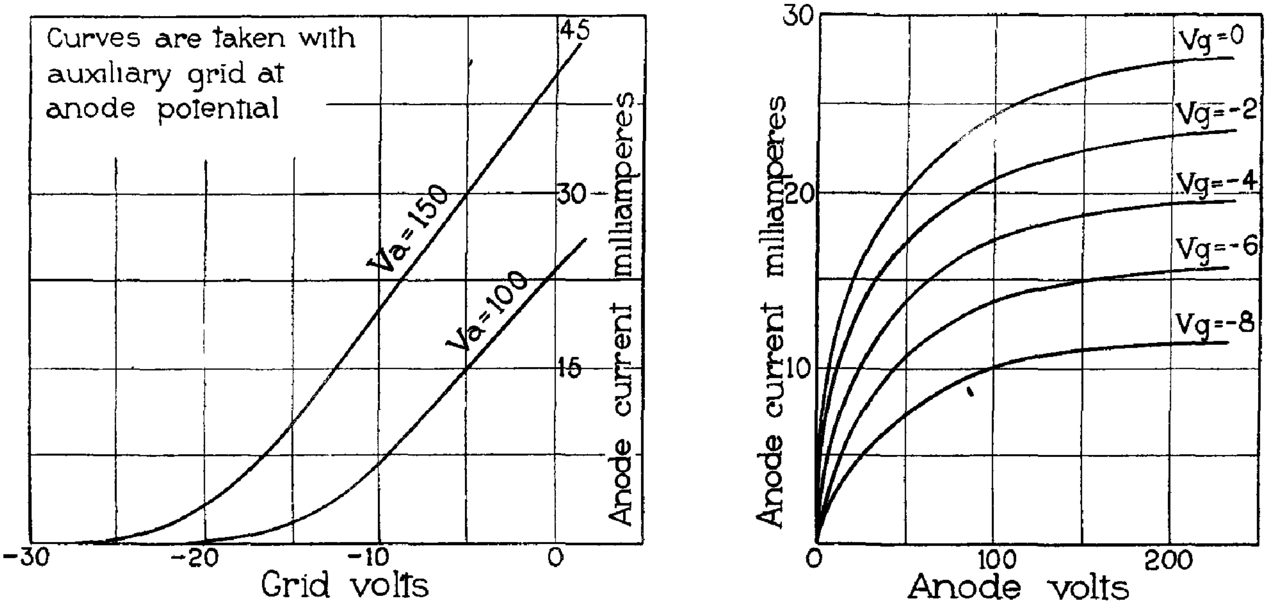

FIG. 28, CHAP. VIII.—Characteristic curves of pentode valve.

Multi-electrode valves

38. Many types of valves have been developed for special purposes, in particular as frequency changers in super-heterodyne receivers. These introduce no new principles, and such as are likely to be found in service radio apparatus will be described with reference to their special function.

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