Chapter 2

ELECTRON EMISSION

The great majority of electron tubes depend upon thermionic emission as their source of free electrons. In this emission process, electrons within a conductor or semiconductor receive sufficient energy by thermal excitation to overcome the forces tending to keep them within the solid.

Our interest in thermionic emission at this point lies in the fact that some inherent properties of thermionic emission seriously affect the design and performance of electron tubes. It is found, for instance, that the emitted electrons have small, but finite, velocities upon emission, so that in considering the shapes of the electron trajectories in the interelectrode space of a tube we must take into account the distribution of emission velocities. When we try to design an electron gun that will produce a thin beam of electrons with high current density, we find that we are seriously limited in doing so by the finite electron emission velocities.

It is also found that both the current of emitted electrons and the velocity distribution of the emitted electrons fluctuate with time. These fluctuations constitute two principal sources of "noise" in electron tubes and lead to serious limitations in the performance of many amplifier tubes.

We are further limited in designing an electron tube by the fact that each thermionic cathode material is characterized by a maximum emission current density consistent with long life of the emitter. Since the performance requirements of a tube are generally such that a certain total current must be drawn from the cathode, the maximum emission current density serves to determine the minimum area of the cathode emitting surface. In grid-controlled tubes this minimum cathode area usually determines the area of the remaining electrodes. The high-current-density beams used in klystrons and traveling-wave tubes are frequently obtained by making use of a relatively large cathode emitting surface in order to draw the required total emission current and by using electrostatic fields

to focus the electrons to a beam of smaller diameter. In later chapters we shall find that a number of the ultimate performance limitations of vacuum tubes result from the need for using a large cathode emitting surface.

Finally, some properties of the oxide-coated cathode are of concern to the tube designer and tube user. It is found, for instance, that the resistance of the oxide coating is often of the order of a few ohms across a square centimeter of coating. This resistance is effectively inserted between the cathode lead and the emitting surface. In the case of grid-controlled tubes, it serves as a negative feedback mechanism which has the effect of reducing the transconductance of the tube. Furthermore, during the processing of a tube and during the life of the tube, compounds form at the interface between the oxide coating and the base metal. These compounds place an additional impedance between the cathode lead and the emitting surface. The interface resistance is often ten or more times that of the oxide coating, and it increases with the life of the tube. End of life for many grid-controlled tubes occurs when the growth of interface resistance reduces the transconductance of the tube below a minimum useful value.

These limitations are of sufficient importance to merit further consideration of the thermionic emission process, and accordingly a major part of the present chapter will be concerned with this subject. (Discussion of noise in electron beams and its excitation by current and velocity fluctuations at the cathode will be deferred until Chapter 13, however.)

Electrons can be emitted from a solid by processes other than thermionic emission. Whenever electrons near the surface of a solid are given sufficient energy to overcome the forces tending to keep them within the solid, some of the electrons escape. Excitation of the electrons near the surface can be caused by incident electrons, photons, positive ions, or excited atoms, and each of these means of excitation can lead to electron emission. Electron emission also can be caused by the application at the surface of sufficiently high electric fields that the surface forces are reduced to the point where electrons escape. Electron emission resulting from electrons striking a surface is known as secondary emission; emission resulting from photons striking a surface is known as photoelectric emission; and emission resulting from the application of very high electric fields is known as field emission, or Schottky effect. Some characteristics of secondary emission and photoelectric emission will be described in Sections 2.5 and 2.6, respectively. Emission caused by positive ions and excited atoms striking a surface is of interest in connection with gas-discharge devices, and we shall defer discussion of it until Chapter 14. Field emission has found only limited application in electron-tube work[1] and will not be described further.

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[1] Some special-purpose cathode-ray tubes and x-ray tubes have field-emission cathodes. Certain arc-discharge processes are also known to depend upon field emission.

We shall begin by describing briefly the behavior of electrons in the interior of a metal and the forces that act on electrons at the surface of a metal.

2.1   Electrons in a Conductor, Work Function, and Contact Potential

(a)   *Electrons in a Conductor*

It is well known that the structure of metals is crystalline. Three crystal structures frequently formed by the metallic elements are illustrated in Figure 2.1-1. These are the body-centered cubic structure, the face-

	d
Na	3.67Å
K	4.62Å
W	2.74Å

VIEWED FROM ABOVE

(a)

	d
Al	2.86Å
Ni	2.49Å
Cu	2.55Å

	d	d′
Be	2.28Å	2.23Å
Mg	3.20Å	3.19Å
Zn	2.66Å	2.91Å

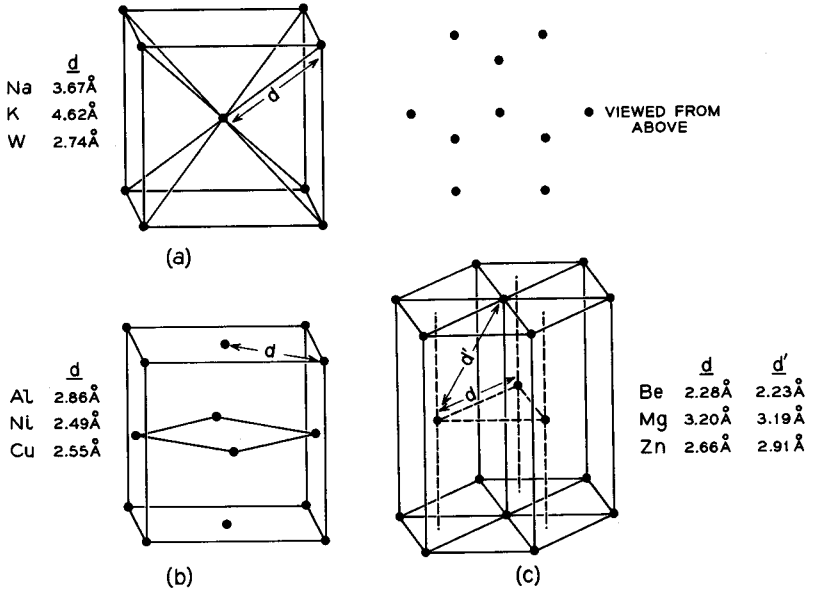(b)   (c)

FIG. 2.1-1 Three common metallic crystal structures: (a) body-centered cubic structure; (b) face-centered cubic structure; (c) hexagonal structure.

centered cubic structure, and the hexagonal structure. The atomic spacings of several metallic elements that form these structures are shown in Figure 2.1-1. Practically all nearest-neighbor spacings of the atoms in metallic crystals lie between 2 and 5 angstroms (1 angstrom = 10^{-8} cm).

Let us now look at the electronic structure of the isolated atoms. An atom is always characterized by certain discrete total energies which its electrons can have. Each electron in the atom has one of these energies and therefore is said to be in an energy state of the atom. With each energy state there is associated a certain characteristic motion of the electron

about the nucleus. For many purposes, an electron in a given energy state can be thought of as causing a cloud of charge about the nucleus. The probability of finding the electron in a given volume element about the nucleus is proportional to the charge density of the cloud at the volume element. It is found that electrons in certain energy states tend to contribute their maximum charge density at approximately the same distance from the nucleus, and consequently there are said to be shells of electrons about the nucleus. Thus, copper has two electrons in its innermost shell, eight electrons in the next shell, eighteen in the next, and one in the outer shell. Metallic atoms have one to four electrons in the outer shell. Generally, the radius at which the outer-shell electrons in the isolated atoms contribute their maximum charge density is nearly half the nearest-neighbor spacings of atoms in the metallic crystal and at least several times the radius at which the electrons in the next smaller shell contribute their maximum charge density.[2]
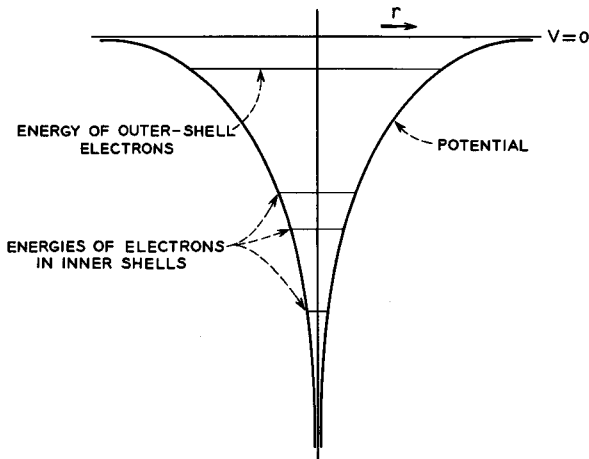

FIG. 2.1-2 The potential experienced by an atomic electron as a function of radius r from the nucleus of the atom.

Figure 2.1-2 shows qualitatively how the potential that acts on an electron in an isolated atom varies with distance r from the nucleus. As the electron travels to large distances from the nucleus, so that it is outside the charge clouds of the other electrons, it leaves behind a net charge of $+e$ on the atom and experiences a potential $-e/4\pi\varepsilon_o r$ volts. At smaller distances, such that the electron is within the charge clouds of the other electrons, its

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[2]Reference 2.1, p. 349, lists the radii at which electrons in the various energy states of the lighter atoms contribute their maximum charge density.

potential is complicated by interactions with other electrons. When the electron is inside the charge clouds of all the other electrons, its potential approaches $-(Ze/4\pi\varepsilon_o r) + C$, where Ze is the positive charge on the nucleus, and C is a constant.
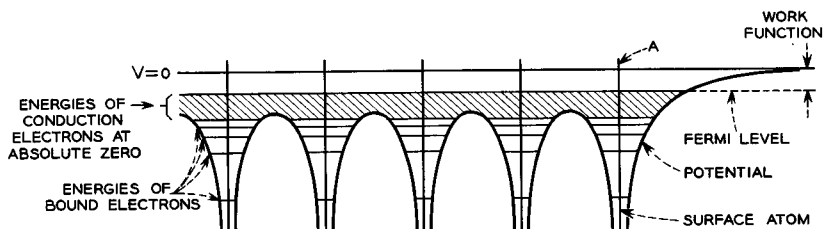

FIG. 2.1-3 The potential experienced by an electron in a metallic crystal. The potential is plotted along a line running through the centers of several of the atoms. The vertical lines in the figure indicate the locations of the atomic centers. The conduction band might extend from the bottom of the shaded region to well above $V = 0$.

Figure 2.1-3 shows qualitatively how we may expect the potential to vary along a line of atoms in a crystal. Clearly, the potential will be periodic with extreme local variations near the nuclei. The crystal may be thought of as being made of a lattice of positive charge centers with the space between the charge centers filled with a cloud of negative charge. The positive charge centers are the metal atoms minus their outer-shell electrons, and the cloud of negative charge arises from the outer-shell electrons. At the interatomic spacings that atoms assume in a crystal, the charge clouds of the outer-shell electrons overlap appreciably, whereas very little overlapping takes place for the charge clouds of the electrons in the inner shells.

The overlapping of the outer-shell charge clouds causes a broadening of the possible energies that the outer-shell electrons can have into a band of energy states, known as the conduction band. Each energy state in the conduction band can be occupied by a maximum of two electrons. In a metal not all the energy states in the conduction band are filled. At absolute zero only the lower part of the band is filled, while the higher energy states are unoccupied. If there are N outer-shell electrons in a piece of metal which is at absolute zero, the outer-shell electrons occupy the $N/2$ lowest energy states in the conduction band, there being two electrons in each state. However, when the metal is at room temperature or higher, a few of the electrons are excited to higher states by thermal excitation. (In Figure 2.1-3 the conduction band would extend from the lower part of the shaded region to well above $V = 0$.)

Excitation to the higher states also takes place when an electric potential gradient is established within the metal, and it can be shown that the existence of unfilled states just above the occupied part of the band is an essential condition for electric conduction. It is the outer-shell electrons that are responsible for electrical conductivity, for they find themselves relatively free to drift through the crystal under the influence of an applied electric field, while those in the inner shells remain bound to their atoms.

(b) Work Function

Next let us consider the forces acting on an electron at the edge of a metallic crystal. The letter A in Figure 2.1-3 marks the position of a surface atom. An electron moving to the right from A would at first experience a potential similar to that in an isolated atom. However, at somewhat larger distances from A, the main effect results from a force called the image force. A well-known problem in electrostatics[3] shows that a point charge $+q$ located y meters from the surface of a conducting plane is acted on by a force directed toward the plane and equal in magnitude to that which the charge would experience from an equal and opposite charge $2y$ meters away. The actual force arises from an induced surface charge $-q$ on the conducting plane. In the case of an electron y meters from a planar conductor, the potential arising from the image force is $-e/16\pi\varepsilon_0 y$ volts. If y is measured in angstroms, this becomes $-3.6/y$ volts.

As the distance y decreases and approaches the interatomic spacing d, the concept that the surface is a planar conductor becomes no longer valid, and the potential merges with that arising from the surface atoms. The location of the region over which the merging takes place depends upon the number of atoms per unit area of the crystal surface and upon the shape of the outer-shell electron clouds. Consequently, we would expect that the height to which the potential curve rises above the filled part of the conduction band will differ for crystals of different metals.

In Figure 2.1-3 we have shown the outer-shell electrons, or conduction electrons, to have energies distributed over a band having a definite maximum and minimum. Such is the case at absolute zero, and it is almost the case at room temperature. However, as already noted, when the metal is at room temperature or higher, a number of the electrons are excited to states just above the part of the conduction band that is filled at absolute zero. If the temperature is sufficiently high, a few electrons gain sufficient energy to overcome the image potential and leave the surface of the metal. This is the basis of thermionic emission.

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[3]See Problem 1.6.

The potential corresponding to the top of the part of the conduction band that is filled at absolute zero is frequently called the Fermi level. The work function of a metal is the energy that must be given to an electron at the Fermi level to enable it to escape from the metal with zero velocity. In the discussion that follows, we shall designate the work function by ϕ and assume that it is measured in electron volts. (*The work function in electron volts is numerically equal to the potential rise in volts from the Fermi level to the potential $V = 0$ shown in Figure 2.1-3.*)

The thermionic emission current density from a surface is closely related to the work function of the surface. With a large work function, the electrons must be excited to higher energy states in the conduction band in order to be able to escape, and the emission current density for a given cathode temperature will be lower.

Table 2.1-1 lists the work functions of several metals.[4] The work function

TABLE 2.1-1. MEAN WORK FUNCTIONS

Metal	ϕ (Electron Volts)	Metal	ϕ (Electron Volts)
Ag	4.28	Mo	4.27
Al	3.74	Na	2.27
Au	4.58	Ni	4.84
Ba	2.29	Pd	4.82
C	4.39	Sb	4.08
Ca	2.76	Sr	2.35
Cb	3.99	Ta	4.12
Cs	1.89	Th	3.41
Cu	4.47	Ti	4.09
Fe	4.36	W	4.50
K	2.15		

of a clean metal surface is always of the order of a few electron volts, and the energy separation between the bottom of the conduction band and the Fermi level is also of about this magnitude.

Actually, ϕ is different for different faces of a metal crystal. The variation arises in part from the fact that the density of surface atoms changes from face to face, and the distance from the surface atoms at which the image potential merges into that of the surface atoms shows a corresponding variation. In the case of tungsten, the measured values for the different faces[5] range from 4.30 electron volts to nearly 6 electron volts. The values listed in Table 2.1-1 are for polycrystalline surfaces.

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[4]Reference 2.2.
[5]Reference 2.3.

(c) Contact Potential

It can be shown that if two dissimilar metals are brought together at absolute zero, the potentials within the metals immediately become adjusted so that the Fermi levels in the two systems coincide. This situation is illustrated in Figure 2.1-4 for two metals at absolute zero. The figure would
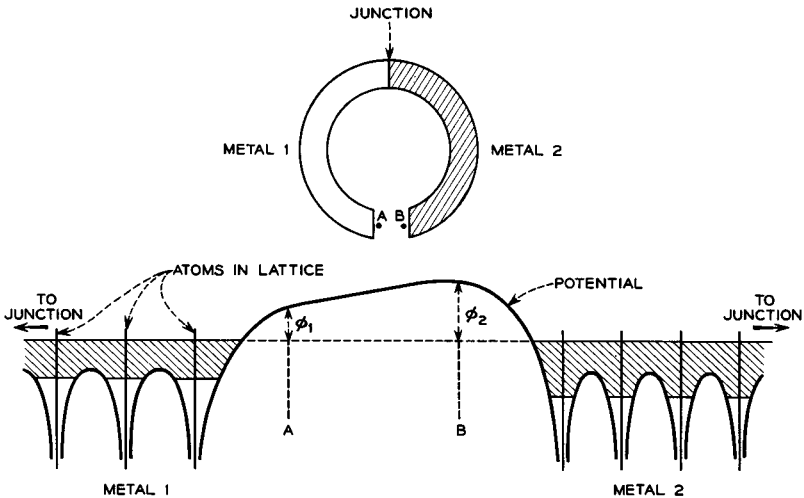

FIG. 2.1-4 Two metals joined at absolute zero. The symbols ϕ_1 and ϕ_2 indicate potential differences which are numerically equal to the work functions of the two metals.

be the same at higher temperatures except that the tops of the filled parts of the conduction bands would not be well defined, since some of the electrons are excited to higher energies. If the two metals have different work functions, the potential rises to different heights outside the two metals, and a potential difference must exist between a point just outside one metal and a point just outside the other. From the definition of the work function, we can see that this contact potential difference, as it is called, is numerically equal to the difference between the work functions of the two metals.

Since there is a potential difference between points A and B in Figure 2.1-4, this can result only from the presence of induced surface charges on the conductors. The potential in the region between the two metals is therefore a superposition of the potential caused by the image force and that arising from the induced surface charge. The surface charges result from a flow of charge between the metals that takes place when the metals

are first joined. The flow of charge is such that the material of lower work function is positively charged.

If several wires made of different metals are connected in series, the potential difference in volts between a point just outside the wire on one end and a point just outside the wire on the other end is numerically equal to the difference between the work functions in electron volts of the two end metals. Let us suppose that two parallel metal plates made of different metals form a parallel-plate capacitor and that the plates are joined by a wire. If ϕ_1 and ϕ_2 are the work functions of the plates in electron volts, the potential difference in volts between a point just outside one plate and a point just outside the other will be numerically equal to $\phi_1 - \phi_2$. We shall designate it V_{12}. If d is the spacing between the plates, the electric field intensity in the region between the plates will be V_{12}/d, neglecting edge effects, and the surface charge density σ on the two surfaces that face each other will be given by

$$\sigma = \varepsilon_o \frac{V_{12}}{d} \tag{2.1-1}$$

Evidently as the distance between the plates is varied, charge must flow along the wire joining them.

When a voltage difference is applied between two electrodes of a tube, the electric field intensity in the interelectrode space effectively results from the sum of the applied potential difference and the contact potential difference. Since the contact potential may amount to two or three volts, there are many cases where it cannot be overlooked.

If the cathode of a tube is oxide-coated, it will likely have the lowest work function of any of the electrodes. Thus, if all the electrodes in such a tube are directly connected together, the emitted electrons experience a retarding field that returns almost all of them to the cathode. Part of the "aging" or drift in the electrical characteristics of some grid-controlled tubes with life has been attributed to a change in the contact potential difference between the control grid and cathode as a result of a gradual contamination or decontamination of the grid surface.

2.2   The Richardson-Dushman Equation

A derivation of the law governing the thermal emission of electrons from a metal[6] involves results that are closely related to the physics of solids and hence represents a departure from most of the work that will be emphasized in later chapters. In brief summary, an expression can be derived for the

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[6]See Reference 2.4, p. 137.

number of electrons per unit volume of the metal which at temperature T are excited to states characterized by sufficient energy to enable the electrons to overcome the surface forces. (In Figure 2.1-3, these states would lie above the horizontal line corresponding to $V = 0$.) The current of electrons in these states striking unit area of surface from within the metal is assumed to be the emission current density and is found to be

$$J_o = \frac{4\pi m e k^2}{h^3} T^2 \epsilon^{-\phi/W_T} \text{ amps/meter}^2 \qquad (2.2\text{-}1)$$

where h is Planck's constant, k is Boltzmann's constant, T is the absolute temperature of the emitting surface, and ϕ is the work function of the metal in electron volts. W_T is the "electron-volt equivalent" of the energy kT and is given by

$$W_T = \frac{kT}{|e|} = \frac{T}{11,600} \text{ electron volts} \qquad (2.2\text{-}2)$$

where $|e|$ is a positive dimensionless constant numerically equal to the charge of the electron. Equation (2.2-1) is known as the Richardson-Dushman Equation for the emission current density. The equation can be expressed more conveniently in the form

$$J_o = A T^2 \epsilon^{-\phi/W_T} \text{ amps/meter}^2 \qquad (2.2\text{-}3)$$

where

$$A = \frac{4\pi m e k^2}{h^3} = 120 \times 10^4 \text{ amps/meter}^2(^\circ\text{K})^2$$
$$= 120 \text{ amps/cm}^2(^\circ\text{K})^2$$

To a first approximation, ϕ is independent of temperature. However, experimental evidence indicates that it has a small temperature coefficient, and hence that it can be expressed as $\phi = \phi_o + \alpha T$, where ϕ_o is the work function at absolute zero. (Measurements of the coefficient α for tungsten[7] indicate that it is of the order of a few times 10^{-5} electron volt/$^\circ K$.) Substituting $\phi = \phi_o + \alpha T$ in Equation (2.2-3), we obtain

$$J_o = A T^2 \epsilon^{-(\phi_o + \alpha T)/W_T} = A\epsilon^{-\alpha|e|/k} T^2 \epsilon^{-11,600\phi_o/T}$$
$$= A' T^2 \epsilon^{-11,600\phi_o/T} \qquad (2.2\text{-}4)$$

where use has been made of the relations $|e|W_T = kT$ joules and $W_T = T/11,600$ electron volts. A non-zero coefficient α, therefore, has the effect of modifying the constant A in the Richardson-Dushman Equation.

Experimental values[8] of $A' = A\epsilon^{-\alpha|e|/k}$ for clean surfaces of several metals

[7]Reference 2.5.

[8]Reference 2.6.

TABLE 2.2-1

Metal	A' $(Amp/cm^2(°K)^2)$	ϕ (Electron Volts)
Mo...................	55	4.27
Ni...................	30	4.84
Pt...................	32	5.29
Ta...................	37	4.12
W...................	70	4.50

are given in Table 2.2-1, along with the corresponding work functions from Table 2.1-1. (It should be noted that accurate measurement of A' is extremely difficult, since a small error in the absolute temperature T can cause a large error in A'.)

Equations (2.2-3) and (2.2-4) indicate a critical dependence of the emission current density upon both the work function ϕ and the temperature T of the emitting surface. Decreasing the work function by one electron volt increases the emission current density by $\epsilon^{11,600/T}$ for the same temperature T. Table 2.2-2 lists values of the emission current density in

TABLE 2.2-2. EMISSION CURRENT DENSITY
AMPS/Cm²

$T - °K$	$\phi = 1.0\ ev$	$\phi = 2.0\ ev$	$\phi = 3.0\ ev$	$\phi = 4.0\ ev$	$\phi = 5.0\ ev$
1000	360	3.3×10^{-3}	3×10^{-8}	—	—
1500	—	17	7.6×10^{-3}	3×10^{-6}	1.4×10^{-9}
2000	—	—	4.4	1.3×10^{-2}	4×10^{-5}
2500	—	—	230	2.1	2.1×10^{-2}

amperes per square centimeter for several values of ϕ and T assuming that $A' = 40$ amps/cm²(°K)². Evidently cathodes with a high work function must be operated at a high temperature in order to obtain an appreciable emission current density.

The emission current density given by Equations (2.2-3) and (2.2-4) is often referred to as the saturation emission current density. Under most operating conditions less current is actually drawn from the cathode. If more electrons are emitted from the cathode than are drawn to the other electrodes, negative space charge accumulates just outside the cathode. This causes a small retarding field at the cathode surface which returns some of the emitted electrons to the cathode. The current drawn from the cathode is then said to be space-charge-limited. If full saturation emission current flows to the other electrodes, the current drawn from the cathode is said to be temperature limited, since the cathode temperature then determines the magnitude of the current flowing to the other electrodes.

2.3 Cathode Materials

The choice of cathode materials to be used in a particular tube is determined by such factors as the environment in which the cathode is to be operated, the required emission current density, the tube life requirements, the temperature at which the cathode must be operated to obtain the emission density, and the power which must be supplied to heat the cathode. Generally, the choice of materials which will satisfy a particular application is quite limited.

As a first consideration, all cathode materials are characterized by a maximum operating temperature consistent with long life of the emitting surface. This means that they are characterized by a maximum emission current density consistent with long cathode life. In the case of pure metal cathodes, such as tungsten filaments, the limiting temperature is that at which evaporation of the metal starts to be appreciable. In the various other forms of cathodes to be described in this section, additional chemical and physical processes tend to limit the life of the cathode when too high temperatures are used. Since for many applications it is desirable to have available a high emission current density and since the emission current density increases rapidly with temperature, the cathode operating temperature is often determined as a compromise between requirements for high emission density and requirements for long cathode life. Of the relatively large number of possible cathode materials that have been investigated,[9] only a very few are capable of simultaneously giving appreciable emission current density and good life performance.

A second important consideration is the desirability of operating the cathode at as low a temperature as possible. A low cathode operating temperature means low heater or filament power and greater power efficiency for the tube. If less heat is dissipated in the tube, less heat is radiated and conducted from the tube, and there is less heating of the surrounding apparatus. Furthermore, as the cathode warms up, thermal expansion of the cathode and its supports frequently causes a change in the electrode spacings and hence a change in the electrical characteristics of the tube. With a low cathode operating temperature, it is much easier to minimize these changes in spacing, and greater reproducibility of the electrical characteristics from device to device can be obtained. Finally, the noise which appears in the tube output, and which results from fluctuations in the emission current and velocities, is less when the required emission current density is obtained at a lower operating temperature.

Since a cathode with a low work function can provide a given emission current density at a lower operating temperature than one with a high work
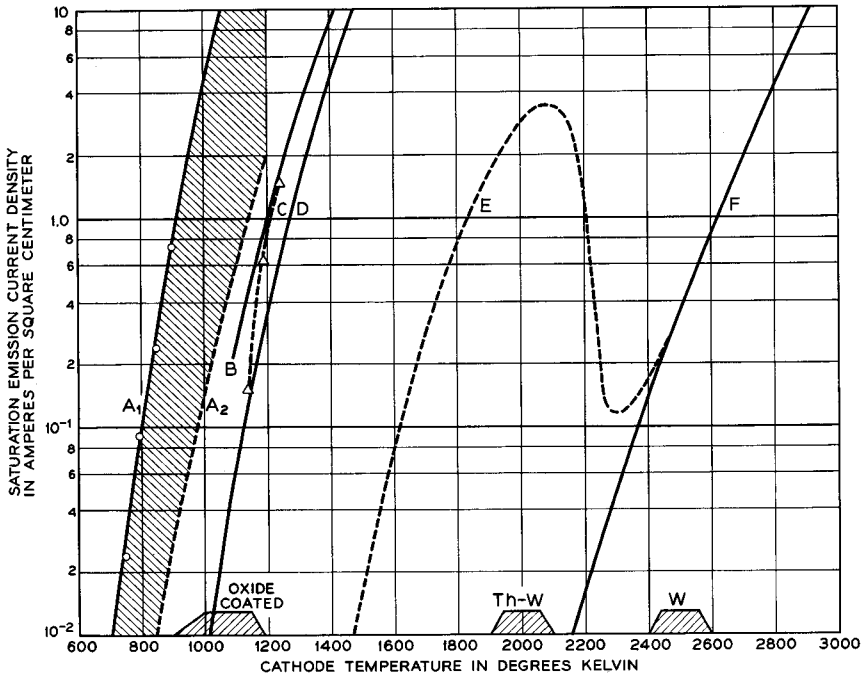
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[9]Reference 2.6.

FIG. 2.3-1 Emission current density vs. cathode temperature for several types of thermionic emitters. The shaded blocks at the bottom of the figure show the normal operating range for three of the cathodes. (a) *The oxide-coated cathode.* Curve A_1 gives the saturation emission current density under pulsed conditions. (Circular points, Reference 2.11; solid curve, Reference 2c, Volume I.) Curve A_2 gives the dc saturation emission density. The position of this curve may vary substantially with environmental conditions. DC current densities much in excess of 0.5 amp/cm² lead to relatively short cathode life. (b) *The pressed nickel cathode.* Curve B shows the dc saturation emission current density obtained from a pressed nickel cathode (Reference 2.15). (c) *The impregnated nickel cathode.* Curve C shows the saturation emission current obtained from the impregnated nickel cathode. The measurements were taken with 40 microsec pulses and a repetition rate of 60 pulses/sec (Reference 2.12) (d) *Pressed and impregnated tungsten cathodes.* Curve D shows the saturation emission current density obtained from pressed and impregnated tungsten cathodes based on $A' = 2.5$ amps/cm²(°K)² and $\phi = 1.67$ electron volts. (These constants are given in Reference 2.13. However, it is the experience of the writers that under practical operating conditions somewhat higher cathode temperatures are needed to yield a given emission current density than those indicated by curve D). *The thoriated tungsten cathode.* Curve E shows the measured saturation emission current density of an uncarbonized thoriated tungsten filament (Reference 2.9). (f) *Tungsten filaments.* Curve F shows the saturation emission current density of a tungsten filament based on $A' = 70$ amps/cm²(°K)² and $\phi = 4.5$ electron volts.

function, much effort has been devoted to obtaining cathode materials with low work functions. The oxide-coated cathode combines good emission properties and appreciable life with a particularly low work function, and consequently it is the most widely used type of cathode emitter.

Some discussion of the more frequently used cathode materials is given in Sections (a) to (d) below. Methods for heating the cathode are described in Section (e).

(a) Pure Tungsten

Filaments of pure tungsten[10] are operated at about 2500°K. At this temperature they yield a saturation emission density of 300 to 400 ma/cm^2 and radiate about 70 watts/cm^2. This high radiation per unit area means that a relatively large amount of power is required to heat the filament. If the ratio of emission current density to power radiated per unit area is taken as a measure of efficiency in obtaining emitted electrons for a given amount of heater power, tungsten cathodes are the least efficient of the commonly used cathode materials.

The vapor pressure of tungsten at 2500°K is 1.3×10^{-8}mm of Hg, which is sufficiently small that the filaments are able to survive several thousand hours of operation before failure occurs. Nearly all other common pure metals have vapor pressures much too high at temperatures at which appreciable thermionic emission takes place. (One exception is tantalum, which has found some application as a cathode material.) The melting point of tungsten is 3640°K.

Curve F in Figure 2.3-1 shows a plot of emission current density vs. temperature for a tungsten emitting surface.

Tungsten filaments find their chief application in tubes that operate with anode voltages greater than about 20 thousand volts. Other cathode materials suffer severe damage from bombardment by positive ions if used in tubes that operate at very high voltages. The positive ions are formed by the emitted electrons striking molecules of residual gas in the tube and are accelerated toward the cathode by the same field that accelerates the electrons away from the cathode. If they strike an oxide-coated cathode with sufficient energy, they may chip away part of the emitting surface. However, pure tungsten filaments show less damage as a result of such bombardment. A number of x-ray tubes, high-voltage diode rectifier tubes, and some high-voltage transmitting tubes use tungsten filaments.

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[10]The fabrication of tungsten filaments is described in Reference 2.7, Chapter 8.

(b) Thoriated Tungsten

Thoriated tungsten filaments are made by adding 1 or 2 per cent of thorium oxide, ThO_2, to the tungsten before it is sintered and drawn into filaments. After drawing, the filament is heated in an atmosphere of hydrocarbon vapor, causing the surface of the wire to be converted to tungsten carbide, W_2C, to a depth of about one tenth of the wire radius, a process known as carbonization. The normal operating temperature of the filament is about 2000°K, and at this temperature the tungsten carbide slowly reduces the thorium oxide. Free atoms of thorium thus produced diffuse through the metal and eventually reach the surface, where some are adsorbed and others evaporate onto surrounding electrodes. Under normal operating conditions, there is probably somewhat less than a mono-layer of thorium atoms adsorbed on the surface of the filament. At the same rate that free thorium atoms diffuse to the surface, other thorium atoms that were adsorbed on the surface are lost as a result of evaporation, reaction with residual gases in the tube, and positive ion bombardment.

It is found that a partial layer of thorium atoms adsorbed on a tungsten carbide surface evaporates at a much slower rate at a given temperature than it would from solid thorium. As a result, the filament can operate at a much higher temperature than would be possible for solid thorium. However, if several layers of thorium are adsorbed on the surface, the evaporation rate of the outer layers is much the same as from solid thorium, so that there is a tendency for additional layers to be lost, leaving only a single layer, or perhaps a little less than a layer.

The adsorbed atoms form a dipole layer at the surface with positive charge on the outside. This modifies the potential acting on a conduction electron at the surface of the filament causing the work function to be lower. The resulting work function is not that of thorium, but is one characteristic of thorium atoms adsorbed on a tungsten carbide surface. At 2000°K the work function is between 2.6 and 2.7 electron volts and A' is about 4 amps/cm²(°K)². The reason that A' is lower than the values measured for clean metal surfaces is not well understood.

Early thoriated tungsten filaments were not carbonized; thermal re-duction of the thorium oxide was relied upon to release free thorium. Generally, the filaments were first "activated" by heating them well above the normal operating temperature for a few minutes to effect appreciable reduction of the thorium oxide. This was followed by operation for about a half hour at a somewhat lower temperature, still above the normal operat-ing temperature, to permit diffusion of the free thorium to the surface. However, the rate of thermal reduction of the thorium oxide at the normal operating temperature was insufficient to keep up with the loss of thorium from the surface, and the filaments had to be "reactivated" from time to

time. Carbonization both increases the rate of reduction of the thorium oxide and reduces the rate of evaporation of thorium atoms from the surface of the filament.[11]

As the filament temperature is increased above 2000°K, the rate of evaporation of thorium atoms from the surface increases faster than the rate of diffusion of thorium atoms from the interior of the filament, with the result that the fraction of the surface covered with thorium atoms decreases. This causes ϕ to increase toward the value for a clean tungsten-carbide surface, and one might expect that the value of A' would likewise approach the corresponding value for a clean tungsten-carbide surface.

Curve E in Figure 2.3-1 shows the variation of the saturation emission current density with temperature for an uncarbonized thoriated tungsten filament according to measurements by Langmuir[12]. Between 2100°K and 2300°K, the emission density actually falls because of the rapid increase of ϕ with temperature. Langmuir estimated that at the maximum of the curve, the surface was covered with about 0.8 of a layer of thorium atoms, whereas at the minimum to the right, he estimated there was only about 0.15 layer of thorium on the surface.

A plot similar to curve E for a carbonized thoriated tungsten filament does not appear to be available at the time of writing. However, at 2000°K carbonized filaments give an emission current density of about 3 amps/cm², which is comparable to that indicated by curve E for uncarbonized filaments. The radiation from a carbonized filament at 2000°K is about 28 watts/cm², so that the thoriated tungsten filament offers considerable advantage over pure tungsten filaments with respect to the ratio of emission current density to power radiated per unit area.

Thoriated tungsten filaments are used in a number of moderate-voltage transmitting tubes and a class of hot-cathode gas tubes, known as tungar rectifiers. Cathodes of thoriated tungsten are also used in high-power beam-type microwave tubes, where the high emission capabilities of the thoriated tungsten cathode are an important advantage. The cathodes in this case are heated by electron bombardment.

(c) Oxide-Coated Cathodes

Although the physical processes involved in thermionic emission from an oxide-coated cathode are not well understood at present, the description of the physical processes and the interpretation of the tube processing given in the following paragraphs appear to be the prevailing thought in a somewhat simplified form.

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[11]Reference 2.8.
[12]Reference 2.9.

General. The oxide-coated cathode is used in nearly all general-purpose tubes, many low-voltage transmitting tubes, and most hot-cathode gas tubes. It consists of a thin coating of a mixture of metallic oxides applied to a base of nickel or some nickel alloy.[13] The oxides most frequently used are those of the alkaline earths, barium, strontium, and calcium, (i.e., BaO, SrO, and CaO). Since these oxides are unstable in the presence of atmospheric moisture, the coating is applied to the base in the form of the corresponding carbonates ($BaCO_3$, etc.), and during the processing of the tube the cathode is heated to decompose the carbonates and release CO_2.

To prepare the carbonates for application to the cathode, they are first ground into a fine powder and mixed with an organic binder and a suitable solvent. Often nitrocellulose serves as the binder and amyl acetate as the solvent. The resulting mixture is then applied to the cathode, often by spraying, although filamentary cathodes are frequently dipped in the mixture or drawn through it. The coated cathode is then dried in room air.

While the tube is being pumped, the envelope and electrodes are heated, generally by applying rf induction to the metal parts. Sometimes an oven is also placed over the tube for a period before the rf induction is applied. This heating of the envelope and electrodes drives off appreciable amounts of gases that are adsorbed on the inside surfaces of the tube. It also causes the organic binder in the cathode coating to decompose into volatile gases, which are pumped away. When the envelope and electrodes are suitably "outgassed," the cathode temperature is raised to approximately 1000°K for about a minute. This causes the carbonates in the cathode coating to decompose into carbon dioxide and the metal oxides, a process known as "breakdown." The carbon dioxide is evolved as a gas and is pumped away.

A coating of the pure oxides is an insulator, and as such is capable of supporting very little sustained emission. To become suitable for thermionic emission, the coating must first be "activated." In this process, barium oxide is partially reduced, given rise to free barium atoms within the coating, which in turn aid in making the coating a semiconductor and increase its emission capabilities. Cathode activation is accomplished by heating the cathode to a temperature above the normal operating temperature. Sometimes current is drawn from the cathode while at this elevated temperature. (Often the normal operating temperature lies between 1000°K and 1150°K.) The heating of the cathode above the normal operating temperature causes impurity atoms in the base nickel to diffuse through the nickel, with the result that some reach the interface between the coating and the nickel, where they reduce the oxides in the coating. It

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[13] One exception is fluorescent lamps in which tungsten is used for the base.

is found that the impurity atoms principally react with the barium oxide, so that the reactions at the interface lead to the release of free barium atoms. The passage of current through the coating probably also causes some electrolytic dissociation of the coating.

Most cathodes are activated partly while the tube is being pumped and partly after the tube is removed from the pump. Usually the cathodes of general-purpose tubes are raised to a temperature of 1200° to 1450°K for about 30 seconds during pumping and then "aged" for a length of time after removing the tube from the pump. Often a series of aging steps is used in which both the cathode temperature and the anode current are varied from step to step. The aging time may range from 10 minutes to several days, depending largely on the quality of the tube being made. Tubes intended for applications needing high reliability are generally aged for a longer period of time at a lower cathode temperature.

The activated coating is white in appearance, its thickness is of the order of 0.5×10^{-2} cm (0.002 inch), and it is highly porous, having a density of about one quarter that of the solid oxides. Its electrical properties are those of an n-type semiconductor.[14]

In some tubes a mixture of barium, strontium, and calcium oxides is used, the molecular proportions consisting of 10 to 14 per cent calcium oxide and about equal percentages of barium and strontium oxides. However, there has been a trend in the tube industry toward the use of "double-carbonate" coatings containing barium and strontium oxide in about equal molecular proportions. The "triple-carbonate" coating (barium, strontium, and calcium oxides) has been found to give faster activation and consequently is attractive from a manufacturing standpoint. However, the adherence of the coating to the base nickel is somewhat poorer, and failure due to peeling of the coating is more likely. In addition, some recent studies of the life capabilities of grid-controlled tubes made with double- and triple-carbonate coatings indicate that greater life can be achieved with the double-carbonate coating. The use of barium oxide alone has been found to give particularly unreproducible results,[15] whereas an active coating of strontium oxide has a higher work function than that of a mixture of barium and strontium oxides.

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[14]At room temperature and higher, electrons are excited to the conduction band of the coating by donors which are distributed throughout the coating. At the cathode operating temperature, a few of the conduction electrons gain sufficient energy to overcome the work function of the coating and escape from the surface. The current of escaping electrons is the thermionic emission current. At present there is some difference of opinion as to what constitutes the principal donor in the coating; possibly it is the free barium atoms.

[15]It is thought that the barium oxide dissolves into the barium carbonate forming a solution which melts at about 1175°K. (Reference 2c, Vol. I, p. 62.)

At the cathode operating temperature, barium oxide has an appreciably higher vapor pressure than either strontium oxide or calcium oxide. Consequently, the barium oxide in the outermost part of the coating gradually becomes depleted, and evaporated barium oxide deposits on the surfaces surrounding the cathode throughout the operational life of the tube.

Equation (2.2-3), which gives the emission current density from a metal, does not apply to emission from a semiconductor and hence does not apply to emission from an oxide-coated cathode. However, it is found that the variation of emission density with temperature for an oxide-coated cathode is governed principally by the factor $\epsilon^{-|e|\phi/kT}$ as in the case of emission from metal surfaces. Experimental values of ϕ for commonly used coatings lie between 1.0 and 1.3 electron volts.

The cathodes of many general-purpose tubes are operated at temperatures in the range from 1000° to 1150°K. At 1050°K, the heat radiation from an oxide coating[16] is about 3 watts/cm², and mean cathode current densities of a few hundred milliamperes per square centimeter are found to be consistent with reasonably long life of the cathode, perhaps 10 to 30 thousand hours. However, if the cathode temperature is raised in order to increase the emission current density beyond 500 ma/cm², the life of present types of oxide-coated cathodes is found to decrease rapidly with increasing temperature and cathode current density. When particularly long life is desired from a tube, lower operating temperatures are used, and the emission density must be correspondingly less. The oxide-coated cathodes used in repeater tubes for recently developed underwater telephone cables operate at 940°K, and are expected to have an average operational life in excess of 40 years. The mean current density drawn from the cathodes in this case is only 10 ma/cm².

The Base Nickel. During operation of the cathode, free barium atoms in the coating diffuse through the coating, eventually reaching the outer surface, whereupon many evaporate onto surrounding electrodes and the walls of the tube. Since an excess of barium atoms in the coating is necessary for the coating to be an active emitter, impurity atoms in the base nickel must continually reduce the barium oxide and release free barium atoms. For this reason, much attention has been given to the impurity content of nickels used as the base material. A nickel too rich in reducing agents will cause short cathode life, whereas a very pure nickel will lead to insufficient emission. In addition, most reducing agents form compounds at the interface between the coating and the nickel, and these compounds often have the effect of placing an electrical impedance between the cathode lead and

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[16]Black-body radiation at this temperature is nearly 7 watts/cm².

the emitting surface. In grid-controlled tubes, such an impedance is likely to cause adverse effects on the electrical performance of the tube.

The principal reducing agents found in cathode nickels are listed in Table 2.3-1. Those elements near the top of the table are found to be more active reducing agents than those near the bottom of the table[17]. Zirconium

TABLE 2.3-1. CONCENTRATION OF REDUCING AGENTS IN PER CENT
BY WEIGHT IN AN ACTIVE NICKEL AND A PASSIVE NICKEL

Reducing Agent	Atomic Number	Type A (Active)	Type B (Passive)
C	6	0.06	< 0.01
Mg	12	0.04	< 0.01
Al	13	0.006	< 0.005
Si	14	0.03	< 0.01
Ti	22	0.02	< 0.005
Zr	40	None	None
W	74	None	None

and tungsten are found in cathode nickel only if they have been intentionally added to the nickel. A nickel relatively rich in reducing agents is said to be an "active" nickel and has the property that shorter times are required to activate and age the coating. The concentration of reducing agents in such a nickel might be as indicated for Type A in the table. A nickel such as Type A is frequently used in the manufacture of commercial grid-controlled tubes. However, because of the relatively rapid rate of reduction of the barium oxide and because the formation of interface compounds (see below) may be appreciable, the life of the coating may be less than might be obtained with smaller amounts of reducing agents.

A nickel that is nearly free of reducing agents, such as Type B in the table, would be considered to be a "passive" nickel. Such a nickel would be incapable of supporting substantial emission from an oxide cathode over an appreciable length of time because the rate of diffusion of impurity atoms through the nickel to the oxide coating would be too slow. In the manufacture of tubes requiring particularly long life there has been a trend in the industry toward the use of nickels that are more passive than Type A. Recently, studies have been carried out on the performance of cathodes in which the base consists of a passive nickel to which one or two reducing agents are added in controlled amounts. One "single-additive" nickel which appears to perform satisfactorily contains about 0.1 per cent zirconium. The zirconium both increases the mechanical strength of the nickel and

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[17]Part of this undoubtedly results from the fact that the elements near the top of the table are lighter and hence diffuse faster.

acts as the reducing agent to provide long-term activity of the cathode. A "double-additive" nickel which has also given good results contains 0.01 to 0.03 per cent magnesium and 2 to 4 per cent tungsten. The magnesium makes possible the initial activity of the cathode, but it is soon lost from the nickel by reaction with the coating and evaporation from the surface. The tungsten makes possible the long-term activity and considerably increases the mechanical strength of the nickel.

It is believed that the nickel itself does not reduce the oxides in the coating. Other impurities which are sometimes present in the nickel and which probably have little effect upon the coating activity are[18] cobalt, iron, copper, and molybdenum. One nickel-cobalt-iron alloy which is sometimes used in oxide-coated filamentary cathodes contains about 19 per cent cobalt and 2 per cent iron. The addition of the cobalt and iron gives greater mechanical strength to the filament and increases its resistivity over that which can be obtained with pure nickel.

Interface. Next let us consider the events that take place at the interface between the base metal and the coating. When carbon atoms reach the interface, they react with the oxide to form CO and free barium. The CO is evolved as a gas, some of which contributes to the residual pressure in the tube, some is absorbed by the getter material, and some becomes adsorbed on the inside surfaces of the tube. Other reducing agents in the base form solid compounds upon reacting with the barium oxide. Various workers have reported finding one or more of MgO, $BaAl_2O_4$, Ba_2SiO_4, $BaTiO_4$, and Ba_3WO_6 at the interface. Often the layer of compounds is referred to as "interface."

The presence of such a layer between the coating and the base has the effect of placing an electrical impedance between the cathode lead and the emitting surface. An approximate equivalent network[19] for the impedance consists of a resistance shunted by a capacitance as shown in Figure 2.3-2. Values of the resistance often range from a few tenths of an ohm to a few tens of
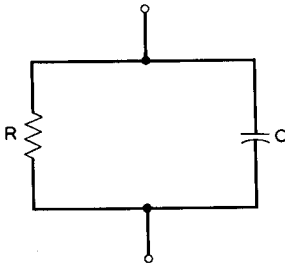

FIG. 2.3-2 Approximate equivalent network for the interface impedance. A more accurate network would include an additional resistance and capacitance in series which would shunt the network shown in the figure.

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[18]Manganese and sulfur are known to have adverse effects on cathode activity.

[19]A more accurate network would include an additional resistance and capacitance in series which would shunt the network shown in Figure 2.3-2.

ohms for one square centimeter of emitting surface.[20] The capacitance shunting the layer gives the parallel RC combination a time constant of about a microsecond. In the case of base nickels containing greater than 0.05 per cent silicon, by far the greater part of the interface resistance results from Ba_2SiO_4, whereas base nickels having less than 0.01 per cent silicon lead to particularly small interface resistances. Often the interface resistance increases when the cathode is held at operating temperature for extended periods with no current being drawn. In cases where the silicon content of the base nickel is high, interface resistances as high as 1000 ohms and more have been observed after such operation.

The coating also exhibits a resistance, often of the order of a few ohms across the thickness of a square centimeter of coating. This resistance and the interface resistance add in series and are effectively inserted between the cathode lead and the cathode emitting surface. Such a resistance R in series with the cathode lead of a grid-controlled tube reduces the low-frequency transconductance of the tube. In a triode, the transconductance is reduced by the factor $1/(1 + g_mR)$, where g_m is the transconductance in the absence of the resistance R. For $R = 100$ ohms and $g_m = 10,000$ micromhos, the transconductance is reduced by 50 per cent. At higher frequencies, of the order of a megacycle or more, the interface resistance is bypassed by the capacity shunting it, with the result that the transconductance approaches the value it would have in the absence of interface resistance.

During the life of a tube, the interface resistance increases because of the formation of additional quantities of interface compounds. This causes a further reduction in the transconductance, partly because of the factor $1/(1 + g_mR)$, and partly because an increase in R causes the cathode current to decrease, and this in turn reduces the transconductance. Often the two effects contribute comparable amounts to the decrease in transconductance, and together will account for the failure of a tube.[21]

Since much smaller interface resistances are obtained with base nickels having low silicon content, there has been increasing use of such nickels in grid-controlled tubes and other tubes where minimum interface resistance is desirable.

Pulsed and DC Emission Current Densities. It is found that the saturation current density drawn from an oxide-coated cathode under pulsed conditions with pulse lengths of the order of a few microseconds and a low-duty cycle is often of the order of 10 times that which can be drawn under dc conditions. However, as the pulse length is increased to a few milliseconds,

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[20]Sometimes the coating tends to blister or peel, and this adds to the apparent interface resistance.

[21]Frequently end of life of a grid-controlled tube is assumed to take place when the transconductance falls below about 65 per cent of its initial value.

or a second, the amplitude of the current pulse decays toward the end of the pulse. Figure 2.3-3 shows the decay of current density drawn from a particular diode when a step-function voltage is applied to the anode. Two
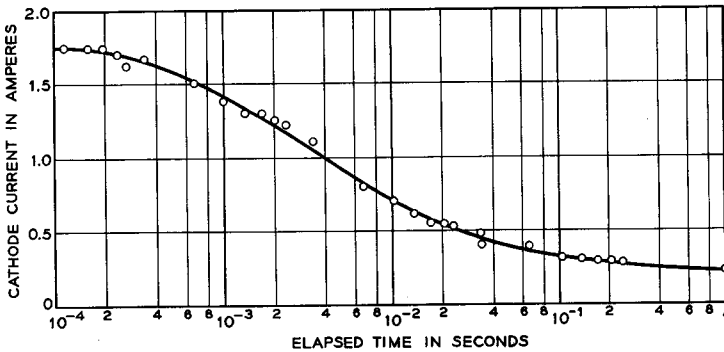

FIG. 2.3-3 The decay of the saturation emission current density drawn from a particular diode when a step-function voltage is applied to the anode. The abscissa indicates time elapsed after application of voltage to the anode. (From L. S. Nergaard, *RCA Rev.* **13**, 464, December 1952)

effects are thought to be principally responsible for the decay of the pulsed emission current when the pulse length is increased to times of the order of a millisecond or a second:

1. Gas released from the anode and other electrodes struck by the electrons tends to destroy cathode activity by oxidizing the impurity centers in the coating. The gas is released both as a direct result of electron bombardment and as a result of heating caused by the kinetic energy of the incident electrons. It is known that O_2, CO_2, SO_2, H_2O, and CO are all effective in destroying the impurity centers.

2. Under the influence of the potential gradient established in the coating when current is conducted through the coating, the impurity centers tend to migrate toward the nickel base leaving a layer of oxide near the surface that is partially depleted of impurity centers.[22]

In Figure 2.3-1, curve A_1 shows the saturation emission current density that can be drawn from an oxide-coated cathode in a very clean environment under pulsed conditions. Curve A_2 shows the dc saturation emission current that might be obtained under normal operating conditions. The position of curve A_2 depends much on the environment in which the cathode is operated.

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[22]Reference 2.10.

Causes of Failure. Finally, let us list the principal causes of failure of oxide-coated cathodes. These are:

1. Formation of excessive interface.
2. Peeling or blistering of the coating.
3. Destruction of the coating by ion bombardment.
4. Evaporation of the coating.
5. "Poisoning" of the cathode by residual gases or foreign matter within the tube.
6. Depletion of the activating agents in the base nickel.

Of course, in filamentary cathodes mechanical failure of the filament itself is still another cause of failure.

(d)   The L-Cathode; Pressed and Impregnated Cathodes of Tungsten and Nickel
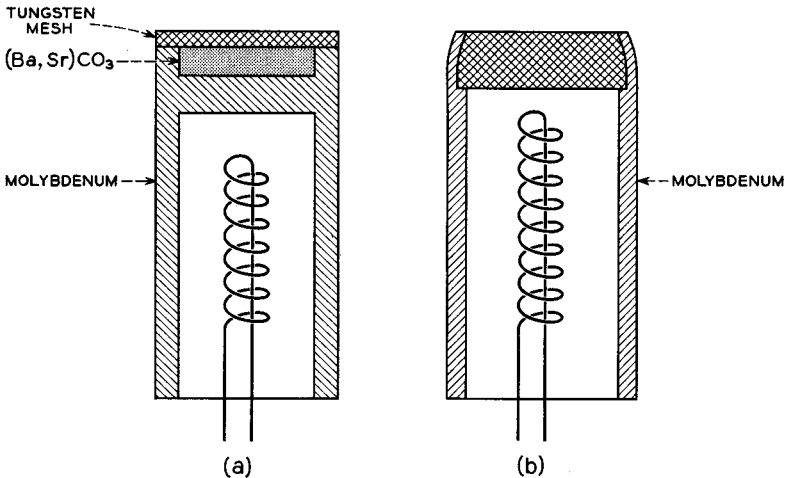
FIG. 2.3-4 The construction of the Philips cathodes: (a) the L-Cathode; (b) the pressed or impregnated cathode. The heaters are shown schematically. (From A. Venema *et al., Philips Tech. Rev.* **19,** 177, 1957)

Several forms of cathode in which emission takes place from the surface of a porous tungsten body, which is covered with adsorbed barium and oxygen atoms, have been developed by the Philips Laboratories.[23] One of these,

known as the L-Cathode, is illustrated in Figure 2.3-4(a). Here the emitting surface consists of a porous tungsten body of approximately 27 per cent porosity which is welded to a nonporous molybdenum support. A chamber between the tungsten and molybdenum initially contains (Ba, Sr)CO_3 in solid solution. However, breakdown of the cathode causes the carbonates to be reduced to a solid solution of (Ba, Sr)O. During operation of the cathode, evaporated BaO diffuses and migrates through the tungsten pores, and some of it is reduced by the tungsten. As a result, the outer surface of the tungsten body becomes covered with adsorbed barium and oxygen atoms, perhaps nearly a monolayer of oxygen covered with a monolayer of barium.[24] The emission constants for such a surface as measured by Philips Laboratories are approximately $\phi = 1.67$ electron volts and $A' = 2.5$ amps/cm^2($^\circ$K)^2. Curve D in Figure 2.3-1 shows a plot of emission current density vs cathode temperature based on these constants.

In two other cathodes developed by the Philips Laboratories, the oxides are contained within the pores of the metal body rather than in a reservoir beneath it. In one of these, known as the pressed cathode, a powdered mixture of $CaCO_3$, $BaCO_3$, and Al_2O_3 is mixed with a powdered tungsten-molybdenum alloy containing 75 per cent molybdenum, and the resulting mixture is pressed together in a die. The compact is then removed from the die and sintered at 1850°C. The resulting metal body has a porosity of about 40 per cent. It is mounted in a molybdenum support as shown in Figure 2.3-4(b). Emission properties of the cathode are similar to the L-Cathode, but the rate of evaporation of BaO from the pressed cathode is somewhat higher. The use of Al_2O_3 serves to increase the stability of the cathode in the presence of atmospheric moisture.

In still another Philips cathode, known as the impregnated cathode, a porous tungsten body of about 17 per cent porosity is first machined into the desired geometry. Then a powdered mixture of $CaCO_3$, $BaCO_3$, and Al_2O_3 is brought in contact with the tungsten body and heated until the powder melts and is drawn into the pores by capillary action. The resulting cathode shows a lower rate of evaporation of BaO than the pressed cathode and has generally found favor over both the pressed cathode and the L-Cathode. (The L-Cathode requires a relatively long activation cycle, and difficulties are experienced in welding the porous tungsten body to the molybdenum holder so that there are no cracks through which the BaO can evaporate.) The emission properties of all three Philips cathodes are about the same.

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[24]Reference 2.14.

Several advantages of the Philips cathodes are:

1. High emission capability consistent with reasonably long life. Emission of a few amperes per square centimeter can be obtained with a cathode life of the order of several thousand hours when the cathode is operated in a relatively clean environment.

2. The emitting surface is physically strong and can be shaped very accurately.

3. The surface is capable of withstanding strong ionic bombardment.

4. There is negligible potential drop across the cathode.

The cathodes have the disadvantage of requiring a higher operating temperature than either the oxide-coated cathode or the pressed or the impregnated nickel cathodes discussed below.

Philips cathodes have found application in a number of beam-type tubes, including cathode-ray tubes and certain microwave tubes. They have also been used in some magnetron applications.

Pressed and impregnated cathodes can also be made with the porous metal body made of nickel. Such cathodes combine most of the advantages of the Philips cathodes with a somewhat lower operating temperature for a given current density. The pressed cathode is made by pressing together a mixture of powdered $(Ba, Sr)CO_3$ and powdered nickel in a die and sintering the resulting compact at 1000°C. The nickel body then has a porosity of about 50 per cent. Curve B in Figure 2.3-1 shows measurements[25] of the dc saturation emission current density vs. cathode temperature for the pressed nickel cathode. Pressed nickel cathodes are used in a number of beam-type microwave tubes.

Most magnetron oscillators use either pressed or impregnated nickel cathodes. The magnetron cathode is cylindrical in shape with the emitting surface on the outer side of the cylinder. During operation of the tube, many of the emitted electrons are returned to the cathode with appreciable velocity after traveling some distance through the tube. This "back bombardment" tends to destroy an oxide-coated cathode, but pressed or impregnated cathodes show little effect from the returning electrons. Generally, a molybdenum sleeve provides a base for the cathode, molybdenum having greater strength at the cathode operating temperature than nickel. However, because the coefficient of expansion of the outer nickel body is somewhat different from that of molybdenum, one or more intervening layers of porous nickel or nickel-molybdenum alloy are used to help absorb the difference in expansion. The structure of a typical impregnated

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[25]Reference 2.15.

cathode is illustrated in Figure 2.3-5. Next to the molybdenum, there is a layer of nickel-molybdenum alloy followed by a coarse porous nickel layer onto which is sintered the finer outer layer. The porosity of the outer layer
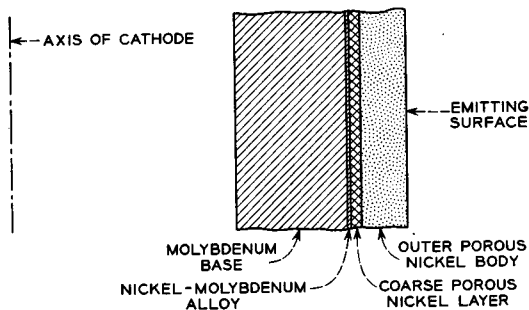

FIG. 2.3-5 A cross-sectional view of a portion of an impregnated magnetron cathode

is about 50 per cent. The outer layer is generally impregnated by bringing it in contact with a colloidal suspension of $(Ba, Sr)CO_3$. This is drawn into the pores by capillary action. Curve C in Figure 2.3-1 shows measurements of the saturation emission current density from the impregnated nickel cathode as a function of cathode temperature.

(e)   Heating the Cathode

Most oxide-coated cathodes are indirectly heated. Often the cathode emitting surface in grid-controlled tubes has the shape of a circular or elliptical cylinder, and the heater consists of a coiled or folded tungsten wire which is inserted inside the cathode. To prevent the heater from making electrical contact with the cathode or short-circuiting to itself, a coating of aluminum oxide is applied to the heater after forming the wire into its final shape. The coated heater is then fired in an oven at about 2000°K to sinter the aluminum oxide. The resulting coating is hard and insulating and can withstand a moderate amount of abrasion during assembly of the tube. The normal operating temperature of the heater is about 400°C above that of the cathode.

Filamentary cathodes have the advantage over indirectly heated cathodes of being quicker to reach the operating temperature and of requiring somewhat less power. However, they have a number of important limitations which preclude their use in many vacuum-tube applications. Principal among these are:

1. The cathode emitting surface has the shape of a long slender wire.

2. The voltage drop across the filament is often comparable to the interelectrode voltages.

3. Mechanical motion of the filament as it warms up generally precludes the use of filamentary cathodes in tubes where close electrode spacings are needed.

4. The filament is mechanically weak at the operating temperature and hence must be supported at one or more points over its length in order to prevent it from contacting the other electrodes. If the supports are conductors, they must be insulated from the other electrodes.

5. Direct current must be used to heat the filaments of high-gain amplifier tubes, since an ac filament current would introduce hum in the output of the tube.

Oxide-coated filamentary cathodes have found application in a number of diode rectifiers, where the voltage drop across the filament and variations in the electrode spacings do not have an important effect on the tube performance. They are also used in portable radio applications, where low power consumption is desirable, and in proximity fuses and other military applications where extremely fast warmup times are needed.

Cathodes that operate at temperatures above about 1400° or 1500°K are generally directly heated, either as filaments or by electron bombardment. Indirect heating would require sufficiently high heater temperatures that the aluminum-oxide coating on the heater would melt or evaporate.

A number of high-power klystron amplifiers which require an ampere or more of beam current use thoriated tungsten cathodes to take advantage of the high emission capabilities of thoriated tungsten. The cathode emitting surface is in the form of a concave disc and is heated by electron bombardment from the reverse side. A bombarding current of several hundred milliamperes is obtained from an auxiliary oxide-coated cathode which is held a kilovolt or more negative with respect to the thoriated-tungsten cathode. The bombarding electrons generate sufficient heat in the thoriated tungsten cathode to raise it to an operating temperature of about 2000°K.

2.4 Thermionic Emission Energies

The equations given in Section 2.2 for the emission current density can be used to predict the distribution of emission energies in the direction normal to the emitting surface. If the work function ϕ of a metal is increased by W_n electron volts, it follows from Equation (2.2-1) that the emission current density at temperature T is changed by the factor ϵ^{-W_n/W_T}. Consequently, this fraction of the emitted electrons is able to overcome a work function W_n electron volts greater than that actually present. It follows that the electrons comprising this fraction have more than W_n electron volts of kinetic energy associated with their motion normal to the cathode at the time of

emission. Similarly, the fraction of electrons that leave the cathode with greater than $W_n + dW_n$ electron volts of kinetic energy in the direction normal to the cathode is $\epsilon^{-(W_n+dW_n)/W_T}$, and the fraction of electrons that leave the cathode with normally directed energy in the range W_n to $W_n + dW_n$ electron volts is

$$dP(W_n) = \epsilon^{-W_n/W_T} - \epsilon^{-(W_n+dW_n)/W_T} = \epsilon^{-W_n/W_T}[1 - \epsilon^{-dW_n/W_T}] \qquad (2.4\text{-}1)$$

If dW_n is small compared with W_T, Equation (2.4-1) can be written as

$$dP(W_n) = \epsilon^{-W_n/W_T}\frac{dW_n}{W_T} \qquad (2.4\text{-}2)$$

This expression gives the probability that the part of the emission energy associated with motion normal to the cathode lies in the range W_n to $W_n + dW_n$. It can be used as a weighting factor to calculate the average emission energy in the direction normal to the cathode. Thus,

$$\text{average normally directed energy} = \int_0^\infty W_n dP(W_n) = W_T \text{ electron volts} \qquad (2.4\text{-}3)$$

If u_n is the electron velocity corresponding to a kinetic energy of W_n electron volts, then $W_n = mu_n{}^2/(2\,|\,e\,|)$, where $|\,e\,|$ is a positive dimensionless constant numerically equal to the charge on the electron. Substituting for W_n in Equation (2.4-2), we find that the probability that the emission velocity of an electron has a component normal to the cathode surface in the range u_n to $u_n + du_n$ is given by

$$dP(u_n) = \frac{mu_n}{kT}\epsilon^{-mu_n{}^2/2kT}du_n \qquad (2.4\text{-}4)$$

It can further be shown[26] that the emitted electrons have an average kinetic energy associated with their motion parallel to the cathode surface of W_T electron volts, and the probability that the part of the emission energy associated with motion parallel to the cathode surface lies in the range W_t to $W_t + dW_t$ electron volts is

$$dP(W_t) = \frac{1}{W_T}\epsilon^{-W_t/W_T}dW_t \qquad (2.4\text{-}5)$$

where the subscript t refers to motion in the "transverse" direction. If u_t is the electron velocity corresponding to an energy of W_t electron volts, the probability that the emission velocity has a component parallel to the cathode surface in the range u_t to $u_t + du_t$ is

$$dP(u_t) = \frac{mu_t}{kT}\epsilon^{-mu_t{}^2/2kT}du_t \qquad (2.4\text{-}6)$$

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[26]Reference 2.4, p. 141.

It will be helpful to combine Equations (2.4-4) and (2.4-6) to determine the distribution of total emission velocities and the angular distribution of the emission velocities. Multiplying the left-hand sides and right-hand sides of the two equations, we find that the probability that the emission velocity simultaneously has a component normal to the cathode surface in the range u_n to $u_n + du_n$ and a component parallel to the cathode surface in the range u_t to $u_t + du_t$ is given by

$$dP(u_n, u_t) = dP(u_n)dP(u_t) = \left(\frac{m}{kT}\right)^2 u_n u_t \epsilon^{-mu^2/2kT} du_n du_t \qquad (2.4\text{-}7)$$

where $u^2 = u_n{}^2 + u_t{}^2$. If the emission velocity u makes an angle θ with the normal to the surface, then $u_n = u \cos\theta$, and $u_t = u \sin\theta$. (See Figure 2.4-1.)
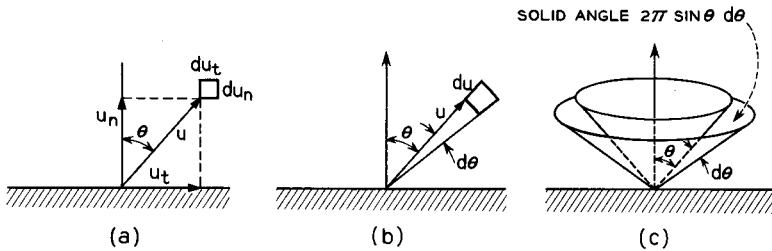

FIG. 2.4-1 The relationship between u, u_n, u_t, and θ.

The probability that the emission velocity lies in the range u to $u + du$ and makes an angle with the normal in the range θ to $\theta + d\theta$ can therefore be expressed as

$$dP(u, \theta) = \sin\theta \, \cos\theta \left(\frac{m}{kT}\right)^2 u^3 \epsilon^{-mu^2/2kT} du \, d\theta \qquad (2.4\text{-}8)$$

Integrating this expression with respect to θ from 0 to $\pi/2$, we find that the probability that the emission velocity lies in the range u to $u + du$ is given by

$$dP(u) = \frac{mu^2}{2kT}\epsilon^{-mu^2/2kT} d\frac{mu^2}{2kT} \qquad (2.4\text{-}9)$$

Substituting $W = mu^2/2 \, | \, e \, |$ in this, we obtain the probability that the total emission energy lies in the range W to $W + dW$, or

$$dP(W) = \frac{W}{W_T}\epsilon^{-W/W_T} d\frac{W}{W_T} \qquad (2.4\text{-}10)$$

Figure 2.4-2 shows a plot of this probability function vs. W for a cathode temperature of 1000°K. The average total emission energy is $2W_T$.

From Equation (2.4-8) we can also obtain the angular distribution of the emission velocities. By integrating the equation with respect to u from 0 to
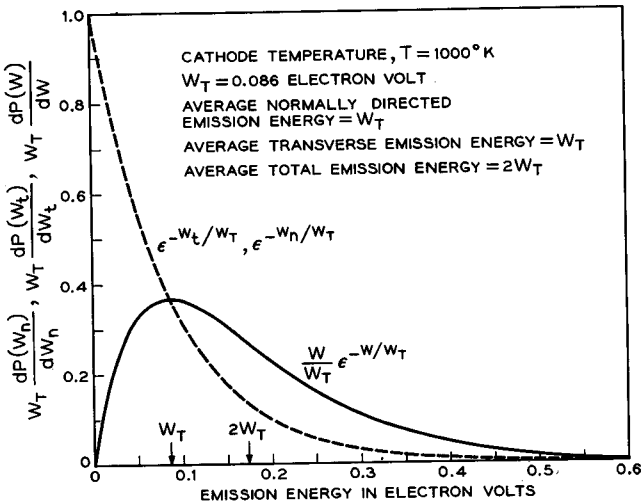

FIG. 2.4-2 The probability functions $W_T dP(W_n)/dW_n$, $W_T dP(W_t)/dW_t$, and $W_T dP(W)/dW$ are plotted vs. W_n, W_t, and W, respectively.

∞, the probability that the direction of the emission velocity lies in the range of angle θ to $\theta + d\theta$ with respect to the normal is found to be

$$dP(\theta) = 2 \sin\theta \cos\theta \, d\theta \qquad (2.4\text{-}11)$$

Since the range of angle θ to $\theta + d\theta$ with respect to the normal defines a solid angle $2\pi \sin\theta \, d\theta$, which is subtended at the surface of the emitter, the current density emitted per unit solid angle at an angle θ with respect to the normal is

$$J_o \frac{dP(\theta)}{2\pi \sin\theta \, d\theta} = J_o \frac{\cos\theta}{\pi} \qquad (2.4\text{-}12)$$

where J_o is the emission current density.

In light optics a source of brightness B is said to emit according to Lambert's Law if the radiation per unit area per unit solid angle in the direction θ with respect to the normal is $B \cos\theta$. The total radiation from unit area of the surface is then

$$\int_0^{\pi/2} B \cos\theta \, 2\pi \sin\theta \, d\theta = \pi B \qquad (2.4\text{-}13)$$

A thermionic cathode is therefore said to emit according to Lambert's Law, and the quantity J_o/π is analogous to the "brightness" of the emitter, where J_o is the emission current density.

Appendix IV gives a summary of the important relations presented in this section. We shall make use of these relations in Section 4.4, where the effects of the electron emission velocities in electron guns are discussed.

It is interesting to note that the total kinetic energy of an emitted electron plus the energy required to overcome the work function of the metal must come from heat energy supplied by the cathode heater. Thus, in addition to making up for heat that is radiated and conducted away from the cathode, the heater must supply an amount of power given by $I_o V_{\phi+2W_T}$ to the emitted electrons, where I_o is the net current drawn from the cathode,
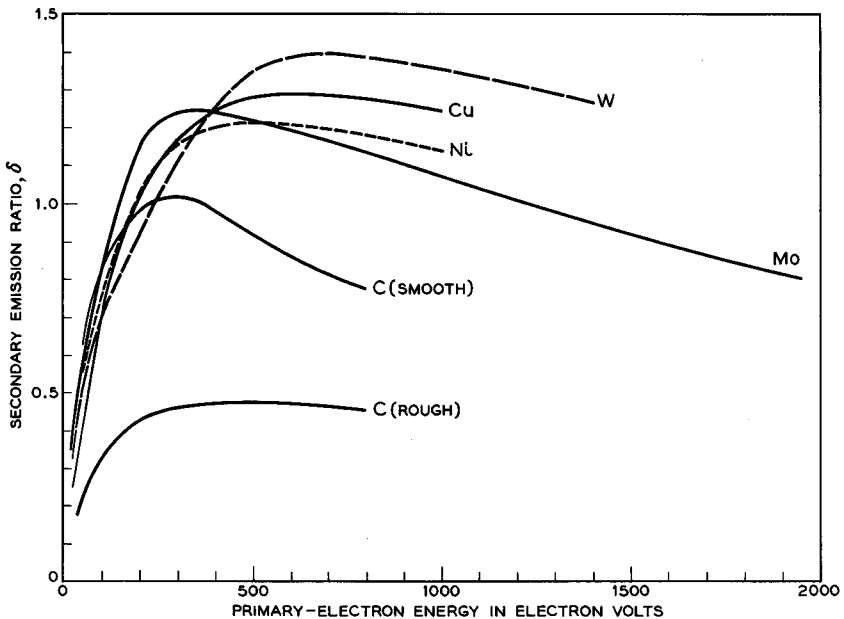

FIG. 2.5-1 Secondary emission ratio vs. primary-electron energy for clean surfaces of several metals. (Cu — Reference 2.16; C, Ni — Reference 2.17; Mo, W — Reference 2.18.)

and $V_{\phi+2W_T}$ is a voltage numerically equal to $\phi + 2W_T$ electron volts. If several amperes are drawn from the cathode, this power amounts to several watts.

2.5   Secondary Emission

All solid surfaces, both conducting and insulating, are capable of secondary electron emission. The secondary-electron yield for a given bombarding energy is found to be directly proportional to the current of primary electrons incident upon the surface, and for metals the yield is nearly independent of the temperature of the emitting surface.

Two important characteristics of the secondary emission from a surface are the total yield of secondary electrons as a function of the incident electron energy, and the distribution of secondary-electron energies for a given primary-electron energy. Figure 2.5-1 illustrates the results of measurements of the first of these quantities for electrons incident upon clean surfaces of several metals. Plotted in the figure is the ratio of secondary electrons to primary electrons (often designated as δ) as a function of the primary-electron energy. The same general shape of curve is found to apply to a large number of pure metals. In all cases, the curve rises to a maximum at a particular primary-electron energy and then falls off slowly with increasing primary energy.
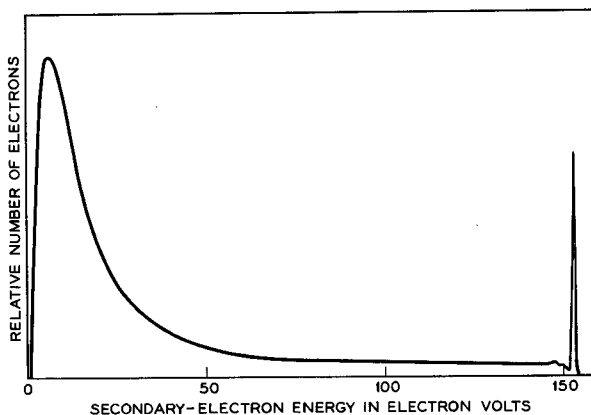

FIG. 2.5-2 Distribution of energies of secondary electrons from a gold target when 155-volt primary electrons are incident upon the surface. (From E. Rudberg, *Phys. Rev.* **50**, 138, 1936)

Figure 2.5-2 illustrates the distribution of energies of secondary electrons from a gold target when 155-volt primary electrons are incident upon the surface. The majority of emitted electrons have energies less than 30 electron volts. However, a few have energies ranging all the way up to that of the incident electrons. It is probable that the true secondary electrons are emitted with kinetic energies less than 50 electron volts, and that most of

the electrons emitted with energies between 50 electron volts and the primary energy are actually inelastically reflected primary electrons. The spike at the right of Figure 2.5-2 results from elastically reflected primaries. For the majority of metals, the most probable emission energy of the true secondary electrons lies between 1.3 and 6 electron volts.

Next let us say a few words about the interactions that occur within a clean metal target when primary electrons with energies of a few hundred electron volts are incident upon the surface. Generally, the primary electrons travel through many atomic layers of solid before their kinetic energy is reduced to that of the conduction electrons in the metal. It is believed that the primary electrons lose their kinetic energy through excitation of both individual electrons and through electron plasma excitations.[27] With each excitation the primary electron abruptly loses an amount of energy equal to that imparted to the excited electron or electron plasma.

The excitation energy of an electron plasma is a discrete quantized value which is characteristic of the particular metal target. In most cases this energy lies between 5 and 30 electron volts. After a very short time interval the electron plasma excitation energy is in turn imparted to one or more electrons in the form of kinetic energy.

It is the electrons that are excited nearest the surface of the metal that have the greatest chance of escaping from the surface and being observed as secondary electrons. Measurements of the depths from which secondary electrons are emitted from a platinum target[28] indicate that, for 500-volt primary electrons, some of the emitted electrons receive their excitation energy as far as 15 atomic layers beneath the surface, and for 1000-volt primary electrons, some of the emitted electrons receive their excitation energy as far as 30 to 35 atomic layers beneath the surface.[29]

Of course, many of the excited electrons never reach the surface, and others lose sufficient energy before reaching the surface that they are unable to overcome the work function and escape. To evaluate the effect of change in work function on the secondary emission yield, McKay[30] evaporated somewhat less than a monolayer of sodium onto a tungsten surface, thereby reducing the work function of the surface to about half that of clean tungsten. He found that the secondary-electron yield at the primary energy giving maximum δ increased by about 60 per cent. Since the amount of secondary emission from the sodium was probably very small, he assumed

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[27]Reference 2.20.

[28]Reference 2.21.

[29]Elastic reflection of primaries probably takes place from the first one or two atomic layers. However, some inelastic reflection undoubtedly takes place from appreciably greater depths.

[30]Reference 2.22.

that this increase resulted almost entirely from the change in work function of the surface.

The interactions between the primary electrons and the electrons of the solid, while best described by means of quantum mechanics, effectively result from interactions between the coulomb fields of the electrons. The excited electron receives an impulse that can be expressed as an integral of force × time. If the primary electron travels faster, the time of interaction is shorter, so that the impulse is smaller, and the probability of excitation is correspondingly less. This picture can be used to explain the shape of the curve giving secondary-electron yield vs. primary-electron energy. At low primary energies, the yield of secondary electrons increases with increasing primary energy, because the primary electrons expend more energy in slowing down and hence cause a greater number of excitations. At appreciably higher primary energies, the primary electrons are less effective in causing excitations in atomic layers close to the surface (where the escape probability is greatest), since they travel faster, and the time of interaction is shorter. Consequently, the secondary-electron yield at higher primary energies falls off with increasing energy.

Table 2.5-1 lists values of δ_{max}, the maximum secondary-electron yield, and the corresponding primary-electron energy for a number of metals.[31]

TABLE 2.5-1*

Metal	δ_{max}	Corresponding Primary Electron Energy (Electron Volts)
Al	1.0	300
Au	1.46	750
C	1.0	300
Cu	1.3	600
Mo	1.25	375
Ni	1.3	550
Pt	1.8	800
Ti	0.9	280
W	1.4	700
Zr	1.1	350

*From H. Bruining, *Physics and Applications of Secondary Electron Emission*, Pergamon Press, London, 1954.

The values given in the table apply only to clean surfaces of the metals. However, since the electrode surfaces in an electron tube are generally contaminated with adsorbed gases, oxides, and material evaporated from the

[31]Reference 2f, p. 39.

cathode, the secondary-electron yield from the electrodes is likely to differ substantially from that for a clean metal surface. An appreciable amount of oxide on a metal surface often increases the secondary-electron yield by a factor of 2 or more.
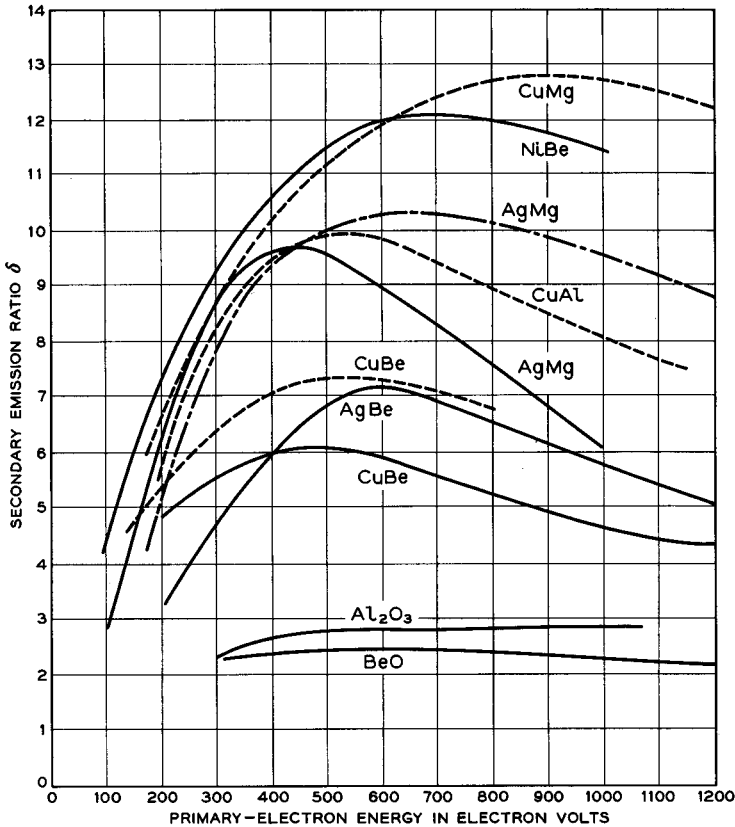

FIG. 2.5-3 Secondary emission yield vs. primary-electron energy for several compound surfaces. (After R. Kollath, *Handbook of Physics*, Vol. 21, p. 232, Springer Verlag, Berlin, 1956)

Certain compound surfaces have been found to give particularly high secondary-electron yields. Values of δ_{max} ranging as high as 10 or 12 have been reported in some cases. Several surfaces which have found application in electron tubes as good secondary-electron emitters are: a film of Cs_3Sb deposited on a metal electrode, magnesium oxide on the surface of a silver-

magnesium alloy, beryllium oxide on the surface of a copper-beryllium alloy or a nickel-beryllium alloy, and cesium oxide partially reduced on a base of silver. Table 2.5-2 lists values[32] of δ_{max} and the corresponding primary-

TABLE 2.5-2

Metal	δ_{max}	*Corresponding Primary Electron Energy (Electron Volts)*
Cs_3Sb........................... 8.0		500
AgMg........................... 9.8		500
CuBe........................... 3.5–5.5		500–700
NiBe...........................12.3		700
Ag-CsO_2-Cs..................... 5.8–9.5		500–1000

electron energy for these surfaces. Figure 2.5-3 shows a plot of the secondary-electron yield for several compound surfaces as a function of the primary-electron energy. The values of δ_{max} obtained for these surfaces depend markedly on the manner of preparation of the surface, wide variations being possible.

If a surface is very rough, the escape probability of the emitted electrons may be substantially reduced, since electrons emitted from the bottom of a hole or valley may strike other projecting parts of the surface and be recaptured. In cases where it is desirable to reduce the secondary emission from an electrode, the electrode is often coated with fine carbon granules. Bruining[33] found that optimum reduction in the secondary-electron yield occurs when the carbon granules are about 30 angstroms in diameter and form a fine labyrinth. A plot of Bruining's measured secondary-electron yield for carbonized nickel is shown in Figure 2.5-1 (curve "C(rough)"). The carbon can be deposited on an electrode either by spraying the electrode with a suspension of lamp black or by passing it through a flame that is generating carbon.

Curves giving the secondary-electron yield vs. primary-electron energy for an insulator are similar in shape to those given in Figure 2.5-1, but the values of δ_{max} are often appreciably greater. Figure 2.5-4 shows a plot of the secondary-electron yield from mica. In experiments to measure the secondary emission from an insulator, care must be taken to avoid charging the surface of the insulator, or the primary-electron energy will be indeterminate. Several experimenters have devised pulsed techniques which overcome this difficulty.

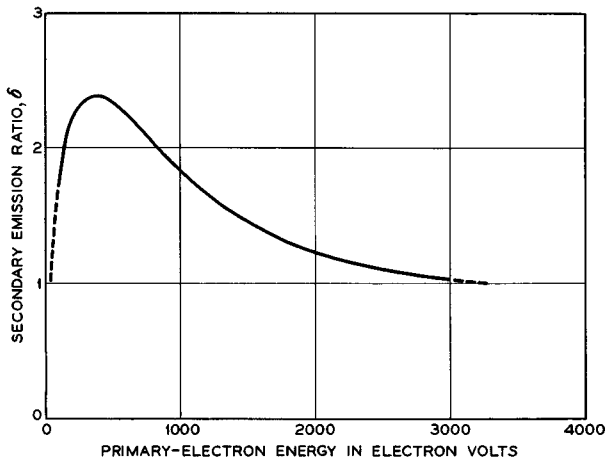[32]Courtesy Allen B. Dumont Laboratories, Clifton, N.J.
[33]Reference 2.17.

FIG. 2.5-4 Secondary emission yield vs. primary-electron energy for mica. (After H. Salow, *Z. Tech. Physik* **21**, 8, 1940)

Secondary emission is of interest in electron-tube work, sometimes as a useful effect and sometimes as an undesirable effect. In photomultiplier tubes a number of high-yield secondary emitting surfaces ("dynodes") are operated in cascade with the result that very high overall gains are obtained. In tubes using 10 dynodes, overall gains of the order of 10^5 or 10^6 are often obtained.

In a magnetron many of the emitted electrons are accelerated by the rf field and then driven back against the cathode with appreciable velocity. The resulting secondary-electron emission probably accounts for a majority of the total emission from the cathode, although thermionic emission is generally also needed to keep the device in operation.

On the other hand, secondary emission often adversely affects the characteristics of certain multielectrode tubes. One such tube is the tetrode vacuum tube, described in Chapter 5. If the screen grid of a tetrode is more positive than the anode, secondary electrons emitted from the anode are drawn to the screen grid; and over a range of the operating parameters, the anode current of some tubes decreases with increasing anode voltage.

Sometimes circuits employing grid-controlled tubes have been found to be bistable because of secondary emission from one of the grids. In one state a grid connected through a resistance to a fixed positive supply acts as an electron collector, δ being less than 1.0. In this case, the potential of the grid is biased to a value less than that of the fixed supply. In the other state the grid potential is above that of the fixed supply, with the result that the electrons arrive with more velocity causing δ to be greater

than 1.0, and the grid acts as an electron emitter. To obtain this second state there must be another electrode nearby at a still higher potential in order to collect the emitted electrons.

2.6   Photoelectric Emission

Photoelectric emission results from the interaction of photons incident upon a solid and electrons within the solid. The interaction is such that an individual photon imparts all its energy to a single electron within the solid. If the photons are incident upon a conductor or semiconductor and if the photon energy is greater than the work function of the surface, a fraction of the photons will be effective in causing the emission of electrons from the surface.

The energy of a photon is given by $h\nu = hc/\lambda$, where h is Planck's constant, ν is the frequency of the radiation, c is the velocity of light, and λ is the wavelength of the radiation. Expressed in electron volts, the photon energy is equal to $12.4 \times 10^3/\lambda$ electron volts, where λ is measured in angstrom units. (The visible spectrum extends from about 3800 to 7600 angstroms corresponding to photon energies ranging from 3.3 to 1.6 electron volts, respectively.)

At room temperature very few electrons in a conductor are in energy states above the Fermi level, and hence the maximum energy of the escaping electrons is very nearly given by $h\nu - \phi$, where ϕ is the work function of the surface. If the work function is greater than 3.3 electron volts, only ultraviolet radiation will cause photoelectron emission from the surface.

Figure 2.6-1 shows plots of photoelectric emission from clean surfaces of several metals, semimetals, and one semiconductor as a function of the energy of the incident photons. The ordinate in the figure indicates the fraction of the photons incident upon the surface that cause emission of a photoelectron. This fraction is called the quantum efficiency of the surface. Since visible light corresponds to photon energies in the range between 1.6 and 3.3 electron volts, we see that some surfaces respond only to ultraviolet light. Thus a clean platinum surface requires photon energies in excess of 4.6 electron volts to cause electron emission. The quantum efficiencies of clean metal surfaces are generally extremely low, of the order of 10^{-4} or 10^{-5}, and consequently clean metal surfaces have found little application in photoelectric devices.

Much better photoelectron yields are obtained from certain compound surfaces.[34] Figure 2.6-2 shows the relative photoelectric emission of several

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[34] The preparation of high-yield photoemissive surfaces is described in Reference 2k, Chapter 1.
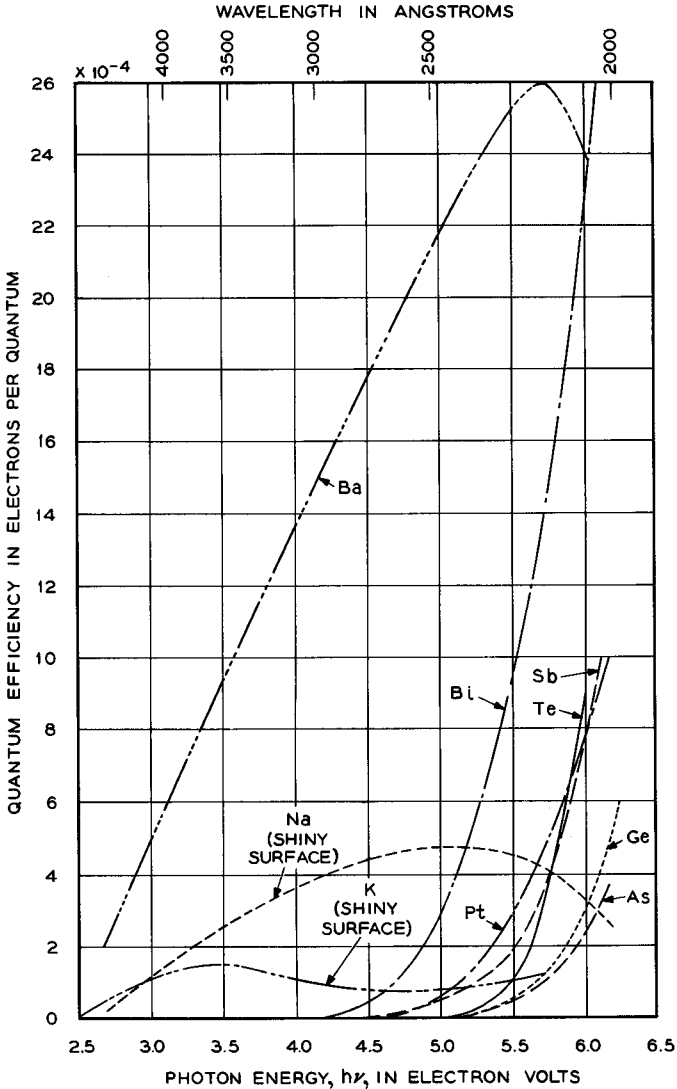
Fig. 2.6-1 Quantum efficiency of clean surfaces of several metals, semimetals, and one semiconductor as a function of the energy of the incident photons. (After *Phys. Rev.* **74,** 1462, 1948; **76,** 270, 1949; **84,** 508, 1951; **81,** 612, 1951)

frequently used compound surfaces as a function of the wavelength of the incident light. The S-11 surface is a cesium-antimony film so processed that

it is largely Cs_3Sb. Often the film is deposited as a layer several hundred angstroms thick on a part of the glass envelope of the tube.[35] Light is shone through the glass at the photoemissive surface, and the photoelectrons are drawn from the opposite side, or vacuum side, of the surface. Electrical contact to the photoemissive surface is made through an evaporated film
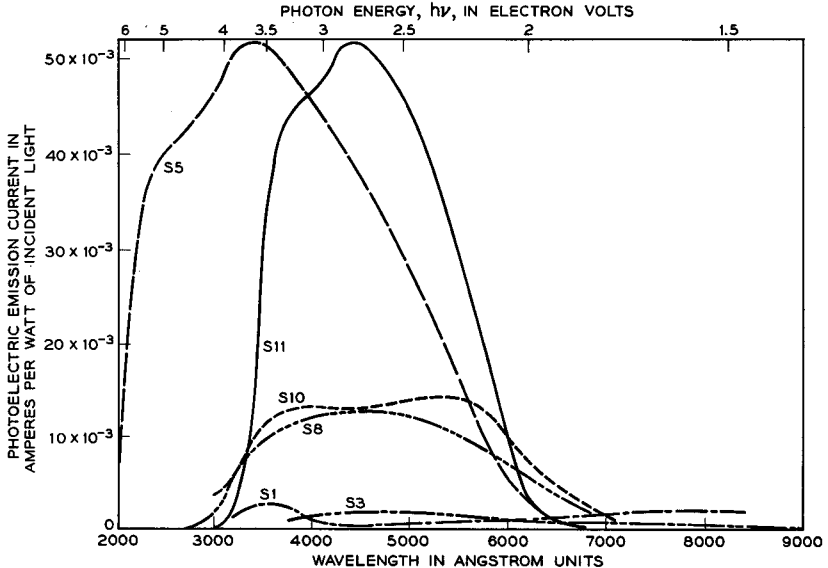

FIG. 2.6-2 Photoelectric emission current from several frequently used compound surfaces as a function of wavelength of the incident light. The curves are for equal values of incident radiant flux at all wavelengths. (Courtesy Allen B. DuMont Laboratories, Inc., Clifton, N.J.)

of metal which is deposited on the glass around the edge of the region through which the light is shone. The S-5 surface is also a cesium-antimony surface, the processing being somewhat different from that for the S-11 surface. The high response of the S-5 surface in the ultraviolet region is obtained by making the tube envelope of a glass which is transparent to ultraviolet light.

The S-8 and S-10 surfaces are compound surfaces prepared from silver, bismuth, and cesium. Cathodes having the S-3 response have compound surfaces of silver, rubidium oxide, and rubidium, whereas those having the S-1 response have compound surfaces of silver, cesium oxide, and cesium.

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[35]Sometimes a layer of manganese oxide is first deposited on the glass.

Both the S-3 and S-1 surfaces have relatively low photoelectron yields but are capable of emission at wavelengths extending well into the infrared region. The upper limit of sensitivity for the S-3 surface occurs at about
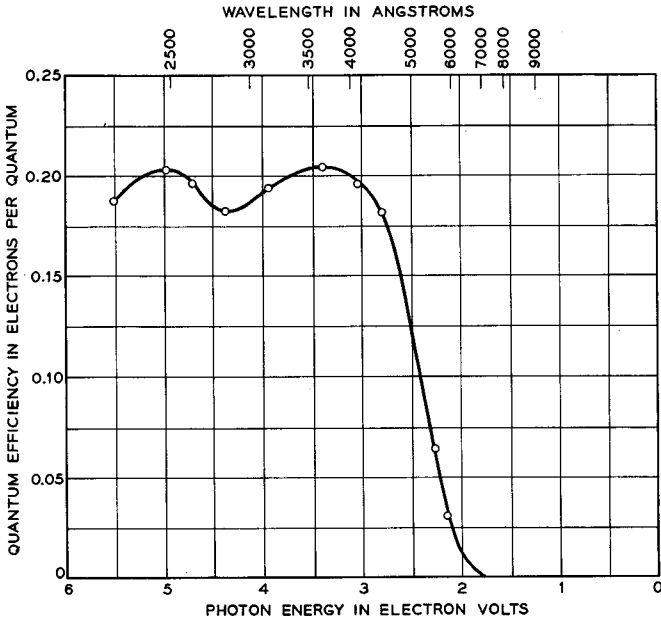

FIG. 2.6-3 Quantum efficiency of a thick film of Cs₃Sb as a function of photon energy in electron volts. The data refer to electron emission on the same side of the film as that on which the light was incident.

9000 angstroms, and that for the S-1 surface occurs at about 12,000 angstroms.

The ordinate in Figure 2.6-2 is amperes per watt of incident light, which is numerically equal to coulombs per joule or electrons per electron volt. Hence multiplying the ordinate of the curve by the photon energy in electron volts (i.e., electron volts per photon) gives the quantum efficiency in electrons per photon. Thus the S-11 curve has a maximum of nearly 52×10^{-3} amp/watt at a wavelength of 4400 angstroms. The corresponding photon energy is 2.8 electron volts, and the quantum efficiency of the surface for photons of this energy is $52 \times 10^{-3} \times 2.8 = 0.15$ electron/photon. Figure 2.6-3 shows results of measurements of the quantum efficiency of a thick film of Cs₃Sb when light is incident upon the same side

of the film as that from which the emission takes place. Over a range of wavelengths from 2200 angstroms to 4000 angstroms, about one quantum in five is effective in causing the emission of a photoelectron.

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