CONDUCTION PROCESSES IN THE OXIDE-COATED CATHODE
by R. LOOSJES and H. J. VINK.

From the discovery of the thermionic emission of the alkaline earth oxides the modern oxide-coated cathode has been developed which is widely used in the field of electronics, for instance in radio valves, in cathode ray tubes and in gas-discharge lamps. An essential part of the emission process of this cathode is the electronic conduction of the oxide layer. Some new experiments and theoretical considerations concerning the nature of this conduction have made it possible to understand the behaviour of the oxide-coated cathode under various conditions better than has previously been the case.

Introduction

In 1903 Wehnelt discovered that a glowing strip of platinum covered with a small quantity of calcium oxide emits an appreciable quantity of electrons at temperatures where the thermionic emission of the metal itself is negligible. From this discovery in the course of time the modern oxide-coated cathode, as used, for instance, in most radio valves, has been developed, which consists of a porous sintered layer of mixed crystals of barium oxide and strontium oxide, 10-100 μ thick, on a metal core. The so-called indirectly heated cathode consists of a nickel tube coated on the outside with the oxide and surrounding a heating element (tungsten wire with an insulating coating). By means of this heating element the tube is heated to 1000-1100 °K and when the cathode is brought to a negative potential with respect to a collector electrode (anode) a strong thermionic emission takes place from the oxide coating.

At the temperatures mentioned a good oxide-coated cathode gives a thermionic emission (saturation current) of the order of 1 A/cm². The electrons emitted from the coating are restored from the metal core. From this it follows that the oxide coating itself must be conductive, and the object of the present article is to study this conduction process more closely, in the light of new experimental investigations.

Preparation of the oxide coating

As already remarked, with indirectly heated cathodes a tube of nickel is used as core for the oxide coating. For reasons which will be made clear later, the metal used is not pure nickel but an alloy obtained by adding small quantities of a readily oxidizable metal (Mg, Si, Mn, Al, Ti) to the nickel. First the metal core is coated with a thin layer of carbonates of alkaline earth metals (barium, strontium). These carbonates can be obtained, for example, by precipitation from an aqueous solution of the corresponding nitrates or hydroxides with ammonium carbonate. After being washed and dried the substance is ground for a number of hours in a ball mill with a solution of what is known as a binder (e.g. nitrocellulose dissolved in a volatile organic solvent). The resulting milkwhite suspension (size of particles 2-10 μ) is applied to the metal core, for instance, by means of a spray-gun. The solvent evaporates very quickly, leaving on the metal a porous coating of fine carbonate crystals cemented together and to the core by the binder.

The cathode is then mounted in the tube and heated in vacuo to 1100-1400 °K, whereupon first the binder decomposes and after that the carbonates decompose into oxides and carbon dioxide. The released carbon dioxide oxidizes the carbon of the binder to carbon monoxide. The gaseous products are pumped away, leaving a coating of pure oxides.

During the heating process the oxide coating sinters somewhat and adheres well enough to the core. The dissociation of the carbonate crystals requires great care. It must not be done too quickly nor at too high a temperature. If this is not properly attended to it may happen that the oxide coating sinters until it is no longer porous. Experience has taught that this is detrimental for the emission, for only a porous layer (porosity 50-60%) gives good emission. For the oxide coating mixed crystals of BaO and SrO (1 mol BaO to 1 mol SrO) are used because this material has proved to possess the best thermionic emission properties.

Activation of the cathode

The layer of earth alkaline oxides thus formed on a metal core is not capable of yielding the desired electron emission directly. To bring this about the cathode must first be "activated", and this is
generally done in the following way. The cathode is heated to 1100-1250 °K, while a voltage of some tens of volts positive with respect to the cathode is applied to the anode. Immediately after applying the voltage the emission is still very small, but it increases at first gradually and later on more rapidly. Ultimately the temperature of the cathode and the anode voltage have to be reduced in order to avoid very high emission currents, which appear to have a detrimental effect. After a few minutes a stationary state is reached and a cathode is obtained from which a continuous emission current of \(10^3-10^4 \text{A/m}^2\) (0.1-1 A/cm\(^2\)) at a temperature of 1000-1100 °K and a pulse emission current \(10^{-4} \text{sec}\) of \(2 \times 10^4\) to \(10^5 \text{A/m}^2\) can be drawn.

Although drawing current is mostly necessary for good activation, it is sometimes possible to activate the cathode without applying a voltage, i.e., without drawing current. This is particularly the case when the core contains the above-mentioned reducing materials (such as Si and Mg). Full activation can then be reached merely by heating the cathode in vacuo to a high temperature \(1100-1200 °K\).

This shows that a partial reduction of the oxide is essential for activating the cathode. It has been found that as a result of this reduction a certain quantity of free barium is formed in the coating of BaO-SrO mixed crystals. In the method of activation by drawing current described above this barium is released by electrolysis of the oxide coating, whereby Ba\(^{2+}\)-ions move in the direction of the metal core and O\(^{2-}\)-ions in the opposite direction. Finally the oxygen ions emerge from the layer in the form of free O\(_2\) and the Ba\(^{2+}\)-ions are likewise neutralized, so that ultimately a quantity of free barium is left in the coating.

The quantities of barium in question are very small (in the order of 0.01%), but this free barium is nevertheless of essential importance for the emission. The fact is that as soon as the amount of barium is reduced, for instance by a momentary increase of temperature causing the barium to evaporate, or by chemical conversion (heating in a gaseous atmosphere containing traces of O\(_2\), Cl\(_2\) or of H\(_2\)O), the emission is greatly diminished. By introducing new free barium, for instance by evaporation, the emission is increased again.

The thermionic emission of a well activated oxide-coated cathode is, of course, strongly dependent on the temperature. In the case of the thermionic emission from metals (such as tungsten) Richardson’s formula applies:

\[
J_s = A T^2 \exp \left( -\frac{\varphi}{kT} \right) 
\]  

or 1):

\[
\log J_s - 2 \log T = \log A - 0.434 \left( \frac{\varphi}{k} \right) \frac{1}{T}, 
\]  

where \(A\) represents a universal constant (= \(1.2 \times 10^6 \text{A/m}^2\text{K}^2\)) and \(\varphi\) is the work function amounting, for instance, to 4.5 V for tungsten \((\varphi\) is the energy required to liberate an electron from the metal in vacuum). If, in analogy with this, one plots for an oxide-coated cathode

\[
\log J_s - 2 \log T = -\frac{4.5V}{T}, 
\]

we find the quantity \(\varphi\), which in this case is also called the work function. For a well activated oxide-coated cathode \(\varphi\) lies between 0.9 and 1.1 V.

When emission takes place electrons leave the oxide coating. In the stationary state this loss of electrons is compensated by electrons leaving the metal core and entering the oxide coating. Obviously a continuous thermionic emission is only possible if the electrons are able to pass through the coating into vacuum, i.e., if the oxide coating is an electronic conductor.

### The oxide coating as semi-conductor

At first sight it may seem surprising that a layer of (Ba, Sr)O should be capable of conducting electrons, since it consists of transparent oxide crystals, and it is a known fact that such non-metallic substances generally behave as perfect insulators.

One would be inclined to ascribe this to electrolytic conduction of the oxides, and if the temperature is high enough the phenomenon of electrolysis indeed occurs; we have already seen from the foregoing that electrolysis plays a part in the process of activation. But the ionic conduction is far too small to account for the emission currents observed, and particularly so at the relatively low temperatures (1000-1100 °K) at which the cathode is used; it has been estimated that at such temperatures with a fully activated cathode the ionic current forms only 0.001% of the total current through the oxide coating, so that ionic conduction need not be considered.

It is known, however, that only absolutely pure crystals of stoichiometric composition are good insulators; impure crystals, contaminated in some

1) By “log” is to be understood the logarithm with the base 10.
way or other, for instance with foreign atoms or an excess of one of the constituent atoms, show conduction and are therefore called electronic semi-conductors.

The conductivity $\gamma$ of an electronic semi-conductor depends strongly on temperature. A semiconductor containing only one kind of impurity can be described by a formula of the type:

$$\gamma = K \exp \left( -\frac{E}{kT} \right), \quad \text{(5)}$$

where $E$ represents a constant with the dimension of energy and $K$ is likewise a constant which depends, however, on the amount of the impurity.

Theory of electronic semi-conductors

Let us now consider the conduction and the thermionic emission of electronic semi-conductors more closely. According to the modern atomic theory (the quantum theory) electrons in the periodic field of the crystal lattice cannot have all possible energies. On the contrary, the possible energy levels are restricted to so-called allowed energy bands, whilst the intermediate values are prohibited. In a crystal some of the allowed energy levels are always occupied by electrons while others are not. The lowest allowed bands are "filled", while the higher bands are "empty". Sometimes there is a half-filled band between the full and the empty ones, and this is the case with metals, the conductivity of which is due to this fact, since in this case the electrons in the half-filled band can be raised to a higher level in that band at the cost of very little energy taken from an external field, which means that an electric current flows through the metal.

If an entirely filled band is followed by an entirely empty band then the substance is an insulator, because the electrons cannot then be raised to a higher energy level, i.e. in the empty band, at the cost of little energy. This is only possible when there are partly filled levels between the filled and empty bands, as is the case with the above-mentioned crystals containing foreign atoms or, in the case of the oxide coating, with an excess of barium. These additional energy levels are usually at a small distance $E_o$ (in the order of 1 to 2 eV) below the empty band (fig. 2). Now it is possible that under the influence of the thermal agitation electrons are raised from the impurity levels to the empty band and become conducting electrons. Putting the number of impurity levels occupied by electrons (at $T = 0$°K and per unit volume) as $N$, then according to the theory the number of electrons per unit volume ($n$) in the empty band at the temperature $T$ is given by

$$n = 2 N^\frac{1}{2} \left( \frac{2\pi mkT}{h^2} \right)^{3/4} \exp \left( -\frac{E_o}{2kT} \right), \quad \text{(7)}$$

where $m$ is the electron mass ($9 \times 10^{-31}$ kg) and $h$ is Planck’s constant ($6.6 \times 10^{-34}$ W sec). For the conductivity we find:

$$\gamma = b n e, \quad \text{(8)}$$

where $b$, the mobility of the conducting electrons, may be regarded as a temperature-independent

---

constant. When log $y$ is plotted as a function of $1/T$ in a certain, fairly narrow, temperature range then one obtains a straight line, since the term with $T^{3/4}$ has little effect compared with the exponential function. In this range $y$ can therefore be represented by the function

$$y = K \exp \left( -E/(kT) \right) , \quad \ldots \quad (9)$$

where $E$ differs but little from $E_0/2$.

![Fig. 2. Energy bands and additional levels of an electronic semiconductor with an excess of metal atoms.](image)

A semiconductor can also emit electrons. The foregoing theory is able to account for this and can describe the emission properties of the oxide-coated cathode. For a thermionic emission not only the energy separating the electrons in the impurity levels from the lower boundary of the empty energy band has to be overcome, but also the energy difference $W$ between this lowest empty energy level and the “zero level” (corresponding to an electron with zero velocity in vacuo). For the thermionic emission of the semiconductor one finds theoretically the formula

$$J_s = cne \left( \frac{kT}{m} \right)^{1/2} \exp \left( -W/kT \right) , \quad \ldots \quad (10)$$

where $c$ represents a numerical constant, viz. $(2/\pi^2)^{1/4}$. From the formulae (10) and (7) it follows that $\exp'$ (see (4)) differs little from $\frac{1}{2} E_0 + W$.

In what follows it will be investigated whether the conduction of the oxide coating can be explained from what is known about electronic semi-conductors. The results of the experimental investigation to be described will show that this is not fully the case.

**Experimental investigation of conduction**

Many investigations have been carried out regarding the conductance of the oxide coating, but hitherto it had not been possible to derive a coherent picture from the data obtained. What had been definitely established, however, was that almost exclusively electronic conduction takes place in the oxide-coated cathode.

For the investigations of this conduction carried out in the Philips Laboratories at Eindhoven a cathode was used as employed in cathode ray tubes. This cathode consists of a hollow cylinder of nickel (6 mm x 8 mm) closed at one end and containing a heating element. The coating of Ba-Sr carbonate, 50 $\mu$ thick, covers the flat outer face of the closed end. Two of these cathodes, coated as smoothly as possible but otherwise quite normal, were pressed together with the carbonate coatings facing each other (fig. 3) and held in that position by springs. Thus between the two metal cylinders there was a carbonate coating $2 \times 50 = 100 \mu$ thick, which could be homogeneously heated by means of the two filaments. The temperature was measured with a chromel-alumel thermocouple.

The cathodes pressed together in this way were mounted in a glass bulb and this connected to a high-vacuum pump. Of course both the bulb and the cathodes were subjected to a thorough degassing process, so that ultimately, after dissociation of the carbonates and degassing of the whole unit, the bulb could be sealed with a vacuum of $10^{-5}$ mm Hg. In order to improve and maintain the vacuum, just before sealing the bulb a quantity of barium was evaporated as “getter”, care being taken that this barium did not reach the cathode.

![Fig. 3. Arrangement employed for measuring the conductance.](image)

The core of the cathode consisted of ordinary “cathode nickel” containing Mg and Si, so that the oxide coating could be thermally activated. By carrying this out at relatively low temperatures it was possible to prolong the activation process over a number of hours, so that it could be interrupted at any moment to allow of measurements being taken in successive stages of the process. The conductance of the oxide coating approxi-
mately 100 μ thick was measured in various stages of activation as a function of temperature. These measurements were made with alternating current in a bridge circuit ("Philoscope" 3)), the voltage across the unknown resistance being about 1 V. At the same stages of activation current-voltage characteristics of the coating were recorded with the aid of short current pulses, the peak value of the voltage amounting to about 10 V.

**Discussion of the results of the measurements**

We shall first deal with the results obtained by measuring the conductance at low voltage: in fig. 4 a graph is reproduced representing for a given oxide coating the logarithm of the resistance $R$ ($-\log R$ is equal to $\log \gamma$ except for an additional constant) as a function of $1/T$ for various successive states of activation. It is clearly seen that as the activation increases, i.e. with increasing quantity of free barium in the coating, the conductance likewise increases and becomes less dependent on temperature. Further, in fig. 5 another similar graph has been plotted, which shows that this curve can be divided into three distinct parts: part I (600-800 °K), only slightly dependent on temperature, part II (800-1000 °K), more strongly dependent on temperature, and part III ($>1000$ °K), again less dependent on temperature. Disregarding part III, one would be inclined to explain the conduction mechanism as being that of a semi-conductor in which two kinds of foreign atoms occur, for instance two kinds of barium atoms placed differently in the lattice, so that the conductivity could be represented by formula (6). The fact that the curves become less steep as the activation increases agrees with what has already been said about the effect of the number of impurity atoms on $E$. When the quantities $E_1$ and $E_2$ are calculated from the curves in accordance with formula (6) we find the following values for the successive stages of activation:

<table>
<thead>
<tr>
<th>Stage</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_1$</td>
<td>0.22</td>
<td>0.14</td>
<td>0.12</td>
<td>0.11</td>
<td>0.10</td>
<td>0.09 eV</td>
</tr>
<tr>
<td>$E_2$</td>
<td>0.98</td>
<td>1.14</td>
<td>1.24</td>
<td>0.96</td>
<td>0.96</td>
<td>0.94 eV</td>
</tr>
<tr>
<td>$e\phi'$</td>
<td>1.07</td>
<td>1.10</td>
<td>0.90</td>
<td>1.02</td>
<td>0.87 eV</td>
<td></td>
</tr>
</tbody>
</table>

It appears that for all stages of activation $E_2$ is equal, within the limits of the accuracy of the measurements, to the product $e\phi'$ of $e$ and the work function at the respective stage. Now with indisputably real semi-conductors $E_2$ has always been found to be much smaller than $e\phi'$, so that the assumption of two kinds of impurity levels is improbable. Neither can the occurrence in part III of the $\log \gamma - 1/T$ characteristic be explained by the semi-conductor theory.

Something similar is encountered when studying the current-voltage characteristics, an example of which is given in fig. 6, from which it may be seen
that with the $J-V$ characteristics the same temperature ranges can be distinguished as those which played a part in the log $\gamma-1/T$ curves. Up to 700-800 °K the characteristics are straight, whilst between 800 and 1000 °K they curve towards the $V$-axis. Around 900 °K the curvature begins to diminish and above 1000 °K the characteristics are again straight. Now it is possible to explain a curved $J-V$ characteristic by electronic conduction. For this it has to be assumed that rectifying contacts (barrier layers) exist at the boundary between the metal and the oxide coating. It is unlikely, however, that electrons of one kind of impurity levels ($E_1$) whose influence is preponderant at low temperatures ($< 800$ °K) do not exhibit this effect, whilst those of another kind ($E_2$) whose influence predominates at higher temperatures ($> 800$ °K) do show it. Whereas, therefore, there is nothing against ascribing that part of the conductance represented by the first term (the term with $E_1$) of formula (6) to real electronic conduction, for the behaviour represented by the second term (the term with $E_2$) some other explanation has to be found.

A new supposition regarding the causes of conductance

Attention has already been drawn in the foregoing to the fact that a good oxide-coated cathode has to be highly porous and that a closely sintered, non-porous cathode has poor emission. It is therefore surprising that hitherto so little attention has been paid to this question of porosity in trying to account for the phenomena in the oxide coating. It is our belief that the conduction by means of electrons present in the pores plays an important part in the phenomena observed. It is not illogical to suppose the existence of an electron gas of a certain density in the pores. For a long time it has in fact been accepted that owing to their emitting power the outermost grains of the oxide coating set up a cloud of electrons in a layer immediately adjacent to the surface of the cathode. If the outermost grains can do that, then why not the grains inside the coating too? The pores in the coating would then be filled with an electron gas coming from the electron clouds of the surrounding grains. As early as in 1918 von Laue¹ investigated theoretically the electron density in a space bounded by walls emitting electrons. He proved that at low temperatures the density varied with temperature in the same way as the emission. At higher temperatures, and thus with increasing emission, owing to the mutual repulsion of the electrons, the density of the electron gas in the centre of the cavity diminishes as compared with the density close to the emitting surface. As a matter of fact the density in the centre of the cavity increases only in direct proportion to the temperature, whilst that close to the wall always increases according to the same exponential law as the emission itself. We shall revert to this presently, but here we can already find support in von Laue's results for our conceptions regarding the part played by the pores in the conduction process. The pores referred to above should not be imagined as being cavities separated from each other, because then the electrons would always have to pass through a semi-conducting layer to move from one cavity to the next. The cavities are to be regarded more as a coherent sequence, so that winding channels are formed in the material, leading from the metal core to the free cathode surface. We shall now see what effect this has on the conduction.

In these channels the electrons move with a mean free path $l$, which is of the order of magnitude of the cross section of the channel, i.e. of the diameter of the grain. When a field $F$ is applied, during the time $t$ taken by the electrons to travel their mean free path $l$ these electrons (with charge $e$ and mass $m$) undergo an acceleration

$$ a = \frac{eF}{m} \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots

During this time the average increase in velocity in the direction of the field is
\[ \overline{\Delta v} = \frac{eF}{2m} t. \]

We now distinguish between two cases:
1) The average velocity \( \overline{v} \) is great compared with \( \Delta v \). In this case \( t = l/\overline{v} \) and therefore
\[ \overline{\Delta v} = \frac{eF}{2m} \cdot \frac{l}{\overline{v}}. \] (12)

Since the acceleration is destroyed after the electrons have traversed the mean free path, \( \overline{\Delta v} \) represents at the same time the average velocity of the electron in the direction of the field, so that for the current density we find:
\[ J = ne \overline{\Delta v} = ne \frac{eF}{2m} \cdot \frac{l}{\overline{v}}. \] (13)

where \( n \) represents the number of electrons per unit volume. A similar formula was derived long ago by Drude to explain the electronic conduction of metals. Since \( J \) is proportional to the field strength \( F \), and this in turn is proportional to the applied voltage \( V \), this formula yields a rectilinear \( J-V \) characteristic (Ohm's law).

2) The average velocity \( \overline{v} \) is small with respect to \( \Delta v \). This is the case if \( l \) or \( F \) is sufficiently large. Then one can write for \( t \): \( t = l/\overline{\Delta v} \) and thus
\[ \overline{\Delta v} = \sqrt{\frac{eF}{2m} \cdot l} \]
and
\[ J = ne \sqrt{\frac{eF}{2m} \cdot l}. \] (14)

Since \( F \) is proportional to the potential difference applied, Ohm's law no longer holds, in this case and we get a parabolic \( J-V \) characteristic, curved towards the \( V \)-axis.

The possibility of this being the case with the oxide-coated cathode may be seen from the following consideration. With a potential difference of 10 V across a coating 100 \( \mu \) thick the increase of the kinetic energy per mean free path (of the order of magnitude of the grain, thus 2-10 \( \mu \)) is 0.2-1 eV. This is very much greater than the average thermal kinetic energy \( (\frac{3}{2} kT) \), which at 800 °K amounts to 0.1 eV. The fact that at very high temperatures (> 1000 °K) the characteristic again straightens out can be explained by the theory of von Laue, according to which the electrons are driven out of the centre of the cavities (fig. 7) owing to the space charge. As a result the electrons move mainly in a thin layer along the wall of the pores, because an electron leaving the wall does not travel across the cavity but is reflected by the space charge back to the wall on the same side. Thus the free path is greatly reduced and we then again have the case of formula (11), the characteristic becoming straight again. Since, moreover, the average density in the layer referred to is less than the boundary density, which is proportional to the saturation current, it also follows that with increasing temperature the conduction in the pores within this temperature range does not increase so much as it does in the temperature range where the space charge is still negligible and where, therefore, the conduction increases with the emission.

In order to ascertain whether the explanation given for the curved \( J-V \) characteristic is correct we calculated \( J \) as a function of \( V \) according to formula (14) for a cathode which at 1000 °K should have an emission of \( 8 \times 10^4 \) A/m² with \( \varphi' = 1.1 \) V. The electron density is taken for a simple case (two infinite, parallel, flat plates at a short distance from each other). For a distance of 2 \( \mu \) we found \( J = 9.0 \times 10^3 \sqrt{V} \) A/m² and for a distance of 5 \( \mu \) \( J = 8.5 \times 10^3 \sqrt{V} \) A/m². These current densities are of the same order as those found experimentally.

Summarizing it may therefore be said that in the porous oxide coating the conduction by the electron gas between the grains is of essential importance. Without taking this conduction into account it is not possible to give a satisfactory explanation of all the phenomena found experimentally. The conduction by the electron gas and the electronic conduction of the crystals of the oxide coating are

In every field of science or technical engineering there is a need not only of a detailed handbook for the specialist but also of a more concise source of information serving as a general guide for the student and at the same time as a book of reference for others indirectly concerned with the subject matter. Without being written in such a popular language as to make it unnecessarily superficial, such a book must nevertheless be comprehensible and, moreover, bring forward all the essential points in a logical manner.

For the author of the book discussed here on the fundamentals of radio valve technique this difficult task was perhaps made somewhat easier by reason of his working in surroundings where he was continually in contact with various classes of people engaged in this particular field of practical science. In those very same surroundings it appeared that a book such as this is appreciated not only by young technicians but also by those who are mainly interested in chemistry and physics and who need to know something about electronic systems in connection with their own particular work.

This book deals exclusively with radio receiving valves and their application in radio receivers, thus not with transmitting valves, cathode ray tubes, and so on.

The first three chapters are devoted to the fundamental principles upon which the working of electronic valves is based. Chapters IV and V go deeper into the matter of the thermionic emission. The next three chapters are concerned with the technology of the valves, a subject which has been gone into at some length, and rightly so, because also in the application of radio valves this technology influences the possibilities and limitations.

Following upon a review of the various functions of the electronic valve in a radio receiver and of the types of valves that have been developed for reception purposes, in chapters XII to XVI the author deals with the characteristic properties of these valves, whilst in the next seven chapters it is explained how these properties can be utilized in the various functions, such as low-frequency amplification, high- and intermediate-frequency amplification, detection, etc. Thus a complete insight is given into the working of a radio receiver, without, however, dealing in detail with other components like capacitors, inductors, loudspeakers, etc.; this limitation has undoubtedly contributed towards the sound treatment of the subject matter.

The advantage that the author had from his close contact with a large factory making radio valves and receivers is manifest from the space that has been reserved in this book to the treatment of phenomena of interferences such as noise, hum, microphony, secondary emission and the ageing of valves. These are points which certainly have to be taken into account in the designing and developing of receivers, and the reader will find, in a somewhat condensed form, a great deal of information about these phenomena which will enable him to evaluate for himself the extent of all sorts of effects.