THE ANGULAR DISTRIBUTION OF THE SECONDARY ELECTRONS OF NICKEL

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Summary
The common equipment for measuring secondary emission (disk-shaped or spherical electrode within a sphere) is not suitable to obtain data about the angular distribution of the secondary electrons. To this aim an electrode system with two concentric spheres was constructed in order to obtain a really radial retarding electrostatic field with which the behaviour of the secondary electrons with different velocities could be studied. The distribution of the secondary electrons — slow genuine secondary electrons, secondary electrons with moderate velocities, and rapid reflected electrons — was measured as a function of the angle of incidence and of the bombardment voltage of the primary electrons. The construction of the measuring-tube, the method of measuring and the results obtained are discussed.

Résumé
L'équipement normalement utilisé pour la mesure de l'émission secondaire (électrode discoïdale ou sphérique à l'intérieur d'une sphère) ne convient pas à la détermination de données au sujet de la distribution angulaire des électrons secondaires. On a construit à cet effet un système d'électrodes à deux sphères concentriques dans le but d'obtenir un champ électrostatique retardateur exactement radial, permettant d'étudier la manière dont se comportent des électrons secondaires animés de vitesses différentes. La distribution des électrons secondaires — lents électrons secondaires purs, électrons secondaires animés de vitesses modérées et rapides électrons réfléchis — fut relevée en fonction de l'angle d'incidence et de la tension de bombardement des électrons primaires. L'auteur expose la construction du tube de mesure, la méthode de mesure et les résultats obtenus.

Zusammenfassung

1. Introduction
Our knowledge of the physical properties of secondary-electron emission shown by solid substances when struck by primary electrons is still
In order to obtain an insight in this matter, as many data as possible of all properties of the secondary electrons are wanted. The knowledge of these properties is also of direct practical importance for the construction of amplifying valves. Many of these valves make use of secondary emission, while for other valves special measures must be taken to suppress the harmful effect of it. For an efficient construction of these valves it is necessary to take into account all properties of the secondary electrons. One of these properties is the spatial direction in which they leave the substance.

It is striking, however, that in literature only few and incomplete data about this property can be found. Moreover, these data were published a good time ago and, according to present standards, in many respects obtained with a poor technique. Secondary emission takes place in the substance at a very low depth under the surface. To obtain reproducible results, an extremely clean surface of the examined substance and a perfect vacuum technique are required, and it is to be seriously doubted whether the old investigations have satisfied these demands.

In this field, moreover, sometimes not enough attention was paid to the influence of the deflections of the electron paths due to electrostatic fields. Necessity was felt (Baroody) to undertake these measurements anew and more complete with modern means and insights, and we have done this with a target of poly-crystalline nickel, as this is often used in the construction of electron valves.

2. The construction of the measuring-tube

As a measuring-method, the method with a radial retarding field was chosen. This form of field is necessary to be able to study separately the behaviour of the secondary electrons with different velocities. Speaking of "secondary" electrons we mean all electrons coming from the bombarded substance: the slow genuine secondary electrons, the secondary electrons with moderate velocities, and the rapid reflected electrons of primary origin. The angular distribution of these three groups with different velocities was measured separately. In order to measure the part of the secondary electrons emitted in a definite direction a rotatable collector was used.

Now it is of no use to mount this collector in the usual measuring-tube. In this tube a little disc-shaped plate of the substance to be investigated is placed in the centre of a spherical collector electrode (fig. 1). The plate is bombarded with primary electrons from an electron gun. Owing to the form of the plate the electrostatic field is not perfectly radial, so that the secondary electrons might be deflected and get a considerable deviation from their original direction. A spherical target instead of a disc-shaped one (fig. 2) would not give a solution either, as the secondary electrons
would not be dislodged in the centre of the radial field and therefore would still be deflected, and (2) the primary beam has a certain width and thus would hit the spherical target under different angles, which influences the measured angular distribution of the secondary electrons.

![Diagram 1](image1)

Fig. 1. The electrode structure of a tube for measuring secondary emission with the radial-field method. Owing to the disc-shaped secondary-emission electrode $T$, the electrostatic field is not perfectly radial, so that secondary electrons will be deflected.

The solution was found by using two concentrically mounted spherical metal electrodes (diameter 50 and 80 mm, respectively; fig. 3). The target $T$ of which the secondary emission is measured is a small plane plate (diameter 10 mm), which stands in the common centre of the two spheres $A$ and $B$. It has the same potential as the inner sphere $A$, so that the space within this sphere is field-free and thus the secondary electrons will not be deflected there. If, now, the outer sphere $B$ has a negative potential with respect to $A$, there will be a radial retarding field between both spheres.

![Diagram 2](image2)

Fig. 2. When using a spherical target the secondary electrons are deflected as they are not dislodged in the centre of the radial field. Moreover, the primary beam has a certain width and thus hits the electrode under different angles, which also influences the measurements.
In order not to cause a disturbance in this radial field the (very small) gun G for the primary electrons is mounted within the inner sphere and fed by means of electrostatically screened leads. Also the gun itself was screened to keep the space within A field-free. To prevent magnetic disturbances the metal parts of the measuring-tube were made of constantan.

The earth's magnetic field was so weak at the place of the measurements that compensation was not necessary. To diminish the disturbing influence of tertiary electrons, the inside of the spheres and of the collector C was covered with a layer of woolly soot.

A part of the secondary electrons now can leave the inner sphere under various angles through a narrow slit of a width of 2 mm lying in a plane exactly perpendicular to the plane of the target (see fig. 4; N in fig. 3).
Fig. 4. The electrode system with the outer sphere $B$ and collector $C$ (fig. 3) removed. The slit $N$ in the inner sphere $A$ (fig. 3) can be seen clearly.
In the plane of the slit the collector C (fig. 3) can move. This collector is fixed insulatedly to the outer sphere B behind a gap O in the latter. B and C have equal potentials, so that at the entrance O of the collector practically no disturbance of the electrostatic field arises that might give rise to incalculable errors, as sometimes occurred in older measurements. As, however, the inner sphere has a certain charge during the measurements, the secondary electrons that pass through the slit N will undergo a slight dispersion a (fig. 5) similar to the one arising when electrons in an amplifying valve pass an opening of a positively charged grid.\(^5\). The amount of this dispersion can be calculated easily (see appendix). Now the opening of the collector was so much widened in the direction of the dispersion that practically all electrons coming from the inner sphere can pass (dimensions of the opening 2 \times 6 \text{ mm}^2).

![Fig. 5. Owing to the charge of the inner sphere A the electrons undergo as light dispersion a. The opening O through which they enter the collector is so wide that even the most deflected electrons can pass.](image)

The target T (fig. 3) is fixed on a bar \(P\) that can slide in a leading. With the aid of a magnet that works on a steel cross-beam fixed to the other end of the (constantan) bar \(P\), the target can be carried out of the spheres to be degassed separately. Much attention must be paid to this degassing, as no reproducible results can be obtained if the surface is not quite clean. Before starting the measurement it proved necessary to keep the target a considerable time at such a temperature that the nickel started evaporating. To enable \(P\) and \(T\) to slide up and down it was necessary to attach the inner sphere \(A\) to a hollow pipe \(H\) which had to be led through the outer sphere \(B\). This causes a serious disturbance in the radial field at the place of the pipe \(H\) but, as the measurement takes place on the other side of the sphere, the influence of that disturbance is negligible.

To measure the secondary-electron flow in the various directions separately, the collector \(C\) must be moved with respect to the target \(T\).
For this purpose the outer sphere $B$ was allowed to rotate in such a way that the gap $O$ behind which the collector is fixed is always exactly opposite to the slit $N$ in the inner sphere $A$. To make this rotation possible a wide slit $W$ had to be made in $B$ in order to let through the pipe $H$ of the inner sphere. This causes again a disturbance in the radial field, which is compensated by screens $S$ covering the slit $W$ and having the potential of $B$.

To measure the secondary emission in all directions within an angle of $180^\circ$, the bar $P$ with the target can be turned around its axis over $180^\circ$ with the aid of a magnet (see above).

The whole electrode system is mounted in a glass globe of 25 cm diameter. The outer sphere $B$ with the collector $C$ is fixed in its position gravitationally by means of a counterweight, while the rest of the system can be revolved in the way as shown in fig. 6. The position of the collector with respect to the target can be adjusted by turning the knob, and is read on a protractor.

3. The method of measuring

Fig. 7 shows the scheme of the measuring-installation. In order to prevent disturbances due to space charge in the inner sphere at low voltages, a primary beam current less than $10^{-8}$ ampere had to be used. Owing to the small solid angle of the collector gap the smallest variation in the collector current that must be read appeared to be about $10^{-12}$ ampere. These very small currents were measured with the aid of an amplifier operating on the method with the vibrating condenser $^{6}$), which has the advantage of being more rapid than, e.g., the method with the mirror galvanometer. With this method the collector current was determined by measuring the voltage loss across a resistance $R$ of $10^3$ MΩ (fig. 7). Therefore the insulation of the collector $C$ must be very high. It has to exceed $3.10^4$ MΩ, and this demand could be satisfied by using quartz insulators. The cathode of the electron gun consists of a tungsten filament $F$ being fed by a d.c. source. Using a tungsten filament enables us to open the tube repeatedly to exchange the target or to place it under various angles. A Wehnelt cylinder $D$ performs the focusing of the primary beam on the target (diameter of the focus 1-2 mm).

As a high vacuum is extremely important for getting reproducible results of the measurements, during the evacuating-process not only the usual measures — as a long annealing and getters (in a separate bulb) — were taken, but moreover an improved Penning vacuum gauge $^{7}$ was connected to the tube (see fig. 6), by which the vacuum could be improved and checked. During the measurements the vacuum amounted from $10^{-7}$ to about $10^{-10}$ mm of mercury.
Fig. 6. The electrode system is mounted in a rotatable glass globe (diameter 25 cm). By turning the knob one can adjust the position of the target with respect to the gravitationally fixed collector. In two smaller bulbs a Penning vacuum gauge and a getter are connected to the tube. In the long tube at the top the bar with the target can be moved with the aid of a magnet, to degas the target separately.
The measurements were all done on a target of electrolytically obtained nickel (99.4% Ni; order of magnitude of the crystals: 0.1 mm). To diminish the influence of the structure of the surface as much as possible, the target was first mechanically and then electrolytically polished.

Fig. 7. Scheme of the measuring-installation. A inner sphere, B outer sphere, F heater filament, D Wehnelt cylinder, T target, C collector of the secondary electrons. The collector current is determined by measuring the voltage loss over a resistance $R$ of $10^3$ MΩ with the aid of the electrometer $E^6$). $V_1$ bombardment voltage = voltage of sphere A, $V_2$ voltage of sphere B, $V_2 < V_1$. To avoid space charge the primary beam current is less than $10^{-8}$ ampere.

The measurements were performed at various velocities of the primary electrons corresponding to 25, 100 and 450 electronvolts, respectively, and under angles of 0°, 30° and 45° to the normal on the target. To this

Fig. 8. The well-known graph of the number $n$ of secondary electrons having a velocity $v$. The angular distribution was measured of the electrons with velocities lying in the intervals I, II and III (see the table in the text).
latter aim the target was put on its bar in the required position with respect to the primary beam. The secondary emission was measured continuously under all angles to the normal on the target, except within an angle of about 20° around the axis of the electron gun, as this part was spatially screened by the gun. In the given results of the measurements (figs 9-12) this part has been drawn dotted by interpolating as well as possible.

Fig. 9. Angular distribution of the rapid reflected electrons for bombardment voltages $V_1$ of 25, 100 and 450 volts at incidence angles of the primary beam of 0°, 30° and 45° to the normal on the target. For clarity, in these and the following figures no separate points of measurement have been marked. The parts of space screened by the gun are drawn dotted by interpolating. The dashes trace the part that is less reliable due to the neighbourhood of the gun.
The dashes trace the part that is less reliable due to the neighbourhood of the gun. As each figure contains several curves close to each other the separate points of measurement have not been marked.

As the purpose of these experiments is only the angular distribution of the secondary electrons and not the intensity distribution, for the sake of better comparison the areas enclosed by the given curves were made equal in each figure. The intensity distribution as a function of the incidence angle and voltage of the primary electrons can be found in many places in literature 1).

The secondary emission was measured in the following voltage intervals (see fig. 8):

Fig. 10. The same as fig. 9 for the secondary electrons with moderate velocity, for $V_1$ equal to 25 and 100 volts only.
The primary electrons: slow secondary electrons (I in fig. 8) and rapid reflected electrons (III in fig. 8) are listed for different voltages.

For the primary electrons:
- 25 volts: 1 to 6 volts
- 100 volts: 5 to 15 volts
- 450 volts: 0 to 10 volts

For the secondary electrons with moderate velocity (II in fig. 8):
- 25 volts: 10 to 15 volts
- 100 volts: 45 to 55 volts
- 450 volts: *

For the rapid reflected electrons:
- 20 to 25 volts
- 80 to 100 volts
- 360 to 450 volts

*) current density was below observation limit

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Fig. 11. The same as fig. 9 for the slow secondary electrons. For purposes of comparison a cosine distribution of Lambert is given in c (dotted circle).
4. Discussion of the measurements

It is not intended here to go deeply into the theory of secondary emission so as to try to explain the obtained curves quantitatively. We hope to return to the subject later. Only some notable properties of the curves will be mentioned here.

The electrons that are leaving the target without appreciable loss of velocity are primary electrons which in penetrating the surface atoms are bent off and scattered over different angles and are rediffused in dependence of the situation of the surface, which consists here of at random placed crystal surfaces 8). With these rapid reflected electrons it is striking that at an angle of 0° of the primary beam to the normal (fig. 9a) the reflection takes place in a smaller solid angle at a higher bombardment voltage.
At bombardment under angles of 30° and 45° to the normal there are two maxima, the larger one more or less in the opposite bombardment direction, the smaller one more or less in the reflected bombardment direction (figs 9b and c). At higher bombardment voltages the small maximum becomes smaller and the large maximum larger.

With the secondary electrons with moderate velocity it is striking that in contradistinction to the rapid electrons we have to do with a more regular trend of the curves. The distribution curve for bombardment under 0° to the normal is fairly a circle (fig. 10a), as is the case with the radiation of light of a radiating surface (cosine law of Lambert). Apparently, in consequence of the collisions in the matter which are also attended with a considerable velocity loss, the electrons are scattered equally distributed over different angles. At oblique bombardment the circle is slightly flattened and a little more is emitted in the bombardment direction (figs 10b and c). This might be looked at as a remainder influence of the scattering directions of the primary electrons, like the one perceived with the
rapid reflected electrons. It is also possible, however, that the cause must be looked for in the trivial fact that microscopically seen the surface of the target is never wholly smooth.

The behaviour of the slow genuine secondary electrons (fig. 11) is much like that of those with moderate velocity. We always find oval curves here (no pure cosine distribution, see the dotted circle in fig. 11c) which at bombardment under angles of 30° and 45° to the normal are also slightly deformed in the bombardment direction (figs 11b and c). The behaviour at different bombardment voltages is fairly the same here.

That the differences between both last groups are not larger can only astonish us, as both the influence of the absorption in the substance and that of the surface barrier must be greatly different for both groups.

In figs 12a-e the course of the angular distribution of the rapid, the moderate, and the slow secondary electrons is given as a function of the incidence angle of the primary electrons at bombardment voltages of 450 and 100 volts. The only remarkable thing here is that with the rapid reflected electrons (figs 12a and b) the smaller maximum becomes larger with a larger incidence angle of the primary electrons to the normal. Obviously, the angular distribution of the rapid reflected electrons is strongly and that of the other groups little dependent on bombardment voltage and incidence angle of the primary electrons.

Finally the author wants to express his thanks to Messrs Cupido and Abbenes who with much patience and care have performed the many time-taking measurements.

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Appendix

In order to get an impression of the errors that can arise from deflections in the slit of the inner sphere we can make use of calculations done on deflections of electrons passing a plane grid-shaped electrode. The maximum deflection angle $a_{\text{max}}$ in a slit of a grid is given by

$$\tan a_{\text{max}} = \frac{\pi \beta}{V'} = \frac{\pi \gamma d}{V'} ;$$

$\beta$ being the charge of a grid wire per unit of length, $\gamma$ the charge of the grid per unit of area, $d$ the pitch of the grid and $eV'$ the energy of the electrons passing the slit ($e =$ charge of an electron).

If the charges per unit of area are equal, the maximum deflection in a slit of a grid-shaped electrode will be greater than the maximum deflection in a slit of the same dimensions in a solid electrode, but of the same order of magnitude.
For the inner sphere of our electrode system the charge per unit of area is
\[ \gamma_1 = \frac{CV}{O} = \frac{R_1R_2}{R_2 - R_1} \frac{V}{4\pi R_1^2}, \]
where \( C \) is the capacity and \( V \) the potential difference between the two spheres, \( O \) the area of the inner sphere and \( R_1 \) and \( R_2 \) the radii of the inner and the outer sphere, respectively.

For a plane electrode with a slit of 2 mm wide and the same charge \( \gamma_1 \), we have for electrons with an energy \( eV \)
\[ \tan \alpha_{\text{max}} = \frac{R_2d}{4R_1(R_2 - R_1)} = \frac{40 \times 2}{4 \times 25 \times 15} \approx 0.05. \]
The voltage loss in the original direction caused by the deflection from that direction is
\[ \Delta V = V(1 - \cos^2 \alpha) = V \sin^2 \alpha \approx V \tan^2 \alpha \approx 25.10^{-4} V, \]
so that in this case (plane electrode) the accuracy of measurement will be \( \frac{1}{4} \) %. In our case of a voltage difference \( V \) between two concentric spheres we may expect the same order of accuracy.

We can also calculate the lateral displacement due to the deflection in the slit. For the case of plane electrodes the same law holds as for a missile shot off under an angle \( \alpha \) to the vertical. As can easily be calculated from the equations of motion, the maximum height \( h \) is reached at a horizontal distance \( x = 2 \tan \alpha \), so that for electrons that with \( \tan \alpha = 0.05 \) would just reach the other electrode, the distance \( x \) becomes 1.5 mm, as \( h = 15 \) mm. In the case of the two spheres the displacement will be smaller owing to the curvature of the electrodes.

Taking the value 1.5 mm for the displacements on both sides of the beam of secondary electrons emerging from the slit, and taking into account the width of the beam at the outer sphere without deflection (\( \frac{3}{8} \times 2 \approx 3 \) mm), we arrive at a total width of 6 mm of the beam with deflection. This width was taken for the opening of the collector in the direction of the deflection.

REFERENCES

5) J. L. H. Jonker, Philips tech. Rev. 5, 131-140, 1940.