

ELECTRONIC BOMBARDMENT OF METAL SURFACES

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ABSTRACT

Secondary electrons from Cu, Ag, Au, W, Pt, Pd, Mg, and Al, produced by electronic bombardment, 0 to 250 volts.—The apparatus used to study the first six metals has been described in a previous paper.¹ The last two metals and especially copper were studied with a modified apparatus constructed out of molybdenum so as to eliminate magnetic effects and permit the study of surfaces condensed from the vapor. (1) Curves are given showing the *ratio of secondary (emergent) to primary (incident) electron current* as a function of the primary velocity. These curves depend on the previous heat treatment of the metals, but after heating the higher melting point metals red-hot for some time, limiting curves were obtained which are characteristic of the different metals. Each curve (except for Cu) rises sharply from the origin but flattens out at a primary velocity of from 3 to 11 volts then rises more slowly showing perhaps a second tendency to flatten. Au and Ag also show a slight kink at 3 volts. The curve for Cu has two sharp maxima at 3 and 6.5 volts, respectively, with two other less distinct ones at about 14 and 20 volts. The secondary electron currents from Mg and Al were extraordinarily large in comparison with those of the other metals, the ratio to primary current for Al reaching a value of 1.8 at 140 volts. (2) *Velocity distribution curves* of the secondary electrons show that, in general, for low primary velocities, most of the secondary electrons have velocities nearly equal to the primary velocity. For higher primary velocities the percentage of secondary electrons having low velocities increases with the primary velocity. The primary velocity for which low velocity electrons begin to leave the surface varies somewhat with the metal but lies between 9 and 15 volts for the metals tested. Curves obtained with a special apparatus consisting of a conducting sphere at whose center the target was placed, show slight kinks indicating *inelastic collisions in copper* at 3 and 6.5 volts velocity, in agreement with the above maxima, but these results are somewhat doubtful. (3) *Variation with the previous treatment of the copper surface.* The results of various experiments show (a) that the removal of gas from the metal decreases the secondary current but does not change the form of the secondary electron curve, and (b) that the characteristic secondary electron curve with various maxima was obtained only from a crystalline surface after any amorphous layer present had been removed, and, within limits, was little affected by exposure to air. The effect of adding an evaporated film of copper was to decrease the secondary current very considerably and to cause the characteristic maxima to disappear. (4) *Effect of simultaneous exposure to radiation from a quartz mercury arc* was merely to add the photo-electric effect to that due to the bombardment.

Effect on the surface of copper of heating in vacuum.—The results indicate that the layer deposited by evaporation is amorphous and that between certain limits of temperature surface crystals of copper are formed.

I. RESULTS WITH PREVIOUSLY USED APPARATUS

THE present experiments are a continuation of a previous investigation¹ which was concerned with: (1) the magnitude of the secondary electron current from nickel as a function of the primary velocity, and (2) the velocity distribution of the secondary electrons for any given primary velocity. The results showed that the secondary electron curve depends very markedly on the previous heat treatment of the metal, but a limiting curve was obtained which did not change with further heating and was also independent of the gas (air and hydrogen) to which the metal had previously been exposed. For this reason this curve was taken to be the true curve for nickel freed from gas as much as possible. The conclusions drawn from these results were (1) that below about 9 volts primary energy, the secondary electrons consist of scattered or reflected primary electrons, (2) that above 9 volts, actual emission of electrons from nickel takes place, the number of emitted electrons increasing with the primary velocity, there being also reflected electrons present whose number decreases with increase of primary velocity.

The present experiments are concerned, first, with obtaining the secondary electron characteristics of other metals, using the same apparatus but changing the targets; and, second, with experiments made with the apparatus modified so as to permit a more detailed and varied study of conditions in certain cases.

For the first part, the apparatus previously used was evacuated and heated in an electric furnace to 400° C for several hours with the pumps working continuously. Liquid air was kept on the condensing trap continually during the time that the tube was connected to the vacuum line. The pumps (oil fore-pump and a mercury vapor pump) were kept going during the observations so that the pressure was less than 10^{-7} mm Hg. Fig. 1 shows the secondary electron curves,² i.e., ratio of the secondary to the primary current as a function of the primary velocity, for the metals indicated. These curves were obtained after heating the targets of the various metals at red heat, and represent the limiting curves obtained after heating at this temperature.³ The curves obtained after

¹ H. E. Farnsworth, *Phys. Rev.* **20**, 358 (1922)

² In the following discussion the term "secondary electron curve" will be used to denote curves of the type shown in Fig. 1 in contrast to "velocity distribution curves" as shown in Fig. 7.

³ A magnetic field was used to focus the primary electrons during these observations. As was found later, the ratio of the secondary to the primary current when using the magnetic field was smaller than when no field was present. For instance when using no field, the value of the ratio for copper at 250 volts primary velocity was later found to be 1.14 instead of 1.04.

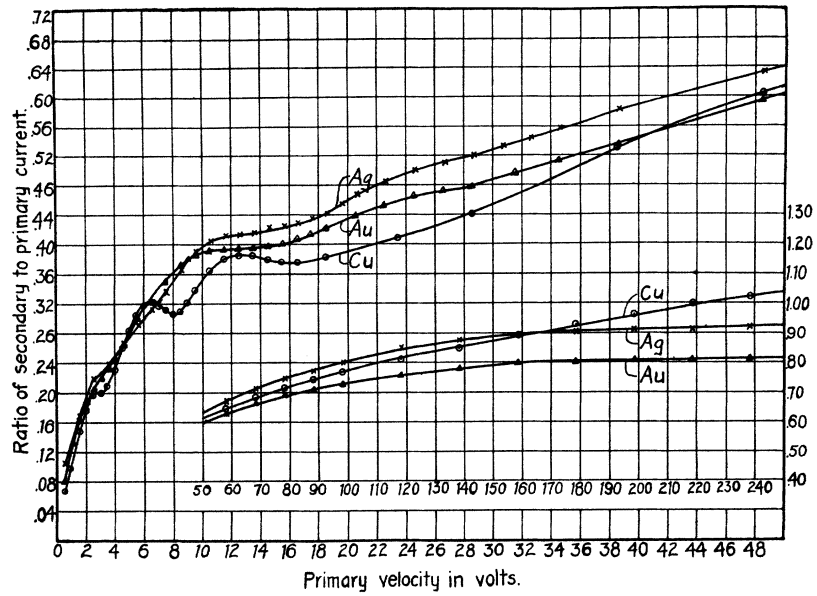


Fig. 1, a. Secondary electron curves for Cu, Ag, and Au after red-heat treatment.

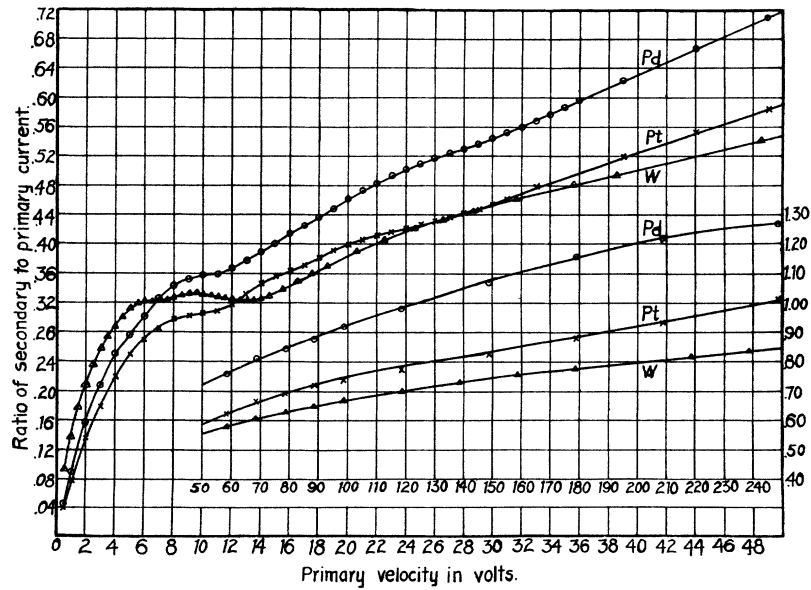


Fig. 1, b. Secondary electron curves for W, Pt, and Pd after red-heat treatment.

baking the whole apparatus at 400°C for several hours but without heating the target at red heat were in each case quite different from the final curves shown, but since this difference was taken to be due to the effect of occluded gas these curves are not given. The curves of Fig. 1 have been corrected for contact potential between the source and target.

II. DISCUSSION OF THE RESULTS

The curves for the different metals show distinct differences in form. It is therefore obvious that their interpretation will in some cases have to be more complex than that previously given for nickel. The curve for tungsten is the only one which is quite similar to the one for nickel, with the break coming at 14 instead of 9 volts, and measurements of the velocity distribution of the secondary electrons indicate that secondary electrons having very small velocities begin to leave the surface for primary velocities somewhere near 14 volts, the number increasing with the primary velocity, there being also a few per cent having velocities nearly equal to that of the primary beam up to at least 100 volts.

In the case of copper, however, no correlation could be found between the form of the velocity distribution curve of secondary electrons and the maxima or minima of the secondary electron curve. As for the curves for silver and gold, the fact that they are nearly identical suggests that the mechanism producing the effect is similar in the two cases. In each case there seem to be two poorly defined maxima at about 11 and 23 volts.

Since, according to the Bohr hypothesis, palladium and platinum have the same electronic arrangement as silver and gold, respectively, except for one valence electron, it is interesting to note that the secondary electron curves of palladium and platinum are very similar.

The velocity distribution of secondary electrons from all these metals is in general similar, low velocity electrons being detected somewhere between 9 and 15 volts in each case, the number increasing with the primary velocity, but since the rate of increase for the lower primary velocities is very slow, it is difficult to determine accurately the voltage at which these low-velocity electrons begin to leave the surface. In each case, a few per cent had velocities nearly equal to the primary velocity up to at least 100 volts.

These results are sufficient to show that the phenomena in question are not as simple as was originally supposed (see references given in previous paper¹) and that the characteristics vary from metal to metal, as might well be expected.

Although the results reported thus far give the secondary electron characteristics for the lower primary velocities, they do not decide the

question as to whether the phenomenon observed is strictly an atomic one or whether it depends upon the mass structure of the metal. Therefore a modified apparatus was constructed.

III. MODIFIED APPARATUS

The modified form of apparatus is shown in Fig. 2. This apparatus consists, as before, of (1) an equipotential, nitrate-coated platinum cathode *S*, heated by radiation from a tungsten spiral filament; (2) a

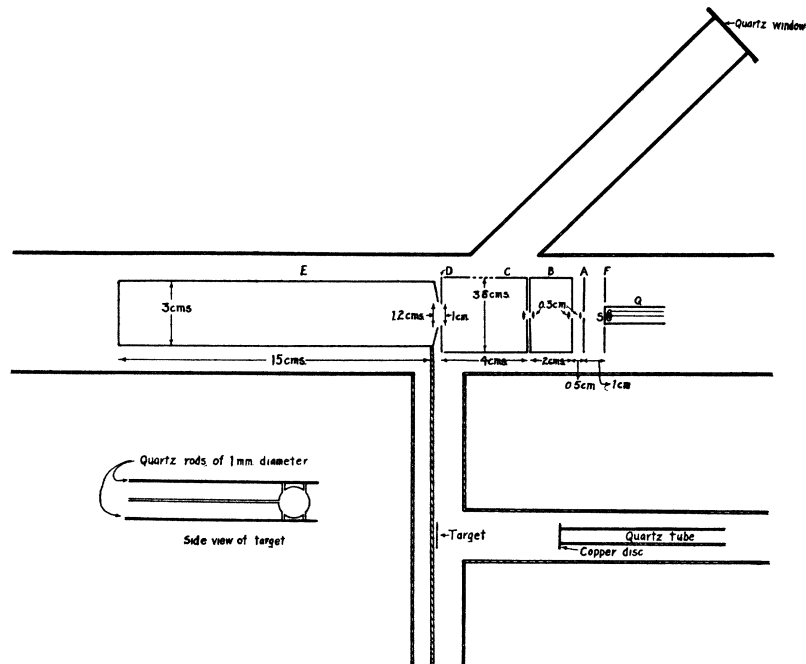


Fig. 2. Modified form of apparatus.

series of insulated diaphragms used to limit the primary electrons and to determine their velocities and those of the secondary electrons; and (3) a Faraday cylinder *E* in front of which the target to be studied can alternately be interposed and withdrawn. The metal parts of this apparatus are constructed of molybdenum instead of nickel, to eliminate any possible magnetic effects. The target can be withdrawn, by means of a magnetic control, into the side-tube where it can be separately outgassed by high-frequency induction and where an evaporated film may be deposited onto it by heating a metal disk in another side-tube. The target and disk are both mounted on quartz so that no other metal becomes hot when these are heated. (The quartz window is platinized

around the edge, then copper plated and soldered to the glass tube with Wood's metal. One end of the main tube is closed by soldering a piece of plate glass over the end of the tube with Wood's metal. This direct seal from Wood's metal to glass proves very satisfactory if proper precautions are taken to clean the glass and metal before soldering.)

The procedure is the same as that used with the former apparatus. With *B*, *C*, *D*, and *E* at the same potential, the secondary electron current, for any given primary velocity, is determined from the difference between the current to the Faraday cylinder *E*, and that to the interposed target. The velocity distribution of the secondary electrons is obtained by placing a variable retarding potential on *C* and *D* and measuring the secondary electron current as a function of this potential in the usual way.

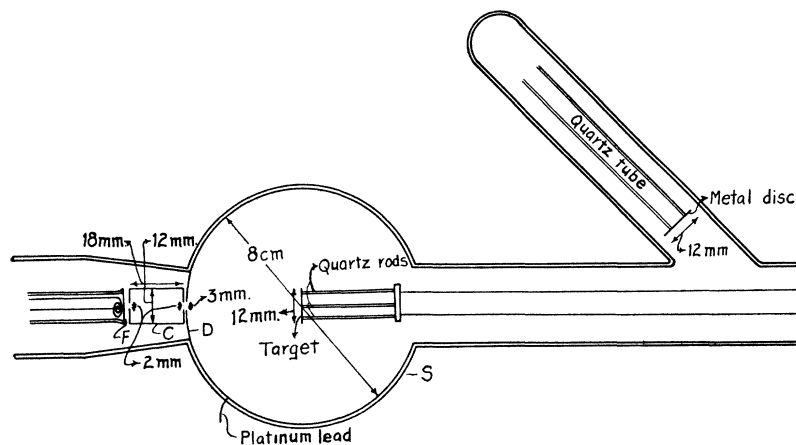


Fig. 3. Apparatus for measuring velocity distribution of secondary electrons.

Before proceeding with the results, a description of another form of apparatus will be given. The apparatus as shown in Fig. 2 is not suitable for an accurate determination of the velocity distribution of the secondary electrons because of the distorted field which exists near the edges of the target when a retarding potential is applied to *C* and *D*. To obtain a more accurate knowledge of the velocity distribution, the apparatus shown in Fig. 3 was constructed. The essential feature is the conducting sphere at whose center the target can be placed, thus insuring a uniform radial field when a retarding potential is applied to the sphere. The primary stream of electrons enters the sphere through a 3 mm hole in a platinum diaphragm *D* sealed into the glass. The inner surface of the glass sphere is made conducting by sputtering with platinum; this also makes contact between it and *D*. The target may be removed into the

side-tube by means of a magnetic control, where it may be outgassed by high frequency induction and where an evaporated film may be deposited onto it by heating a metal disk in the side-tube inclined at 45° . A diaphragm is automatically raised in the tube between the sphere and target when the target is pulled back, thus preventing any evaporated metal from contaminating the sphere. The target is mounted on three quartz rods which are fastened to a molybdenum framework that slides on glass tracks. It is thus possible to heat the target without heating the framework. The source of electrons is the same as that previously described. The cylinder *C* is made of molybdenum lined with platinum, with platinum diaphragms on the ends to limit the primary beam. The accelerating potential is applied between the source *F* and the cylinder *C*. It is found that the primary beam can be kept from spreading before reaching the target, by maintaining the potential of the cylinder *C* about 3 volts positive with respect to the sphere. It is also necessary to use large Helmholtz coils to compensate the earth's magnetic field in all of the experiments.

Although this apparatus was originally intended only for observations on velocity distribution of secondary electrons, it is found that results on the ratio of the secondary to the primary current are in good accord with those obtained with the previous apparatus. The current to the sphere is taken as a measure of the secondary current and the total current to the sphere and target as the primary current. This method, of course, neglects multiple reflection between the sphere and target but the fact that the results obtained were so nearly in accord with those from the former apparatus, Fig. 2, is good evidence that any such errors are negligible.

IV. DETAILED STUDY OF COPPER

After the reconstruction of the apparatus as shown in Fig. 2, several months were spent in a detailed study of copper. This metal was chosen because, of all the metals investigated, the various maxima and minima in its secondary electron curve are more sharply defined than for the other metals, and also because the low melting point of copper enables the surface to be readily evaporated off or a film to be deposited (by heat treatment) from another plate of copper.

The following work on evaporated films was done in an attempt to determine to what extent the characteristics of copper are determined by crystal structure and to what extent by gas content of the metal. Curve 1, Fig. 4, is a typical curve for copper. It is of the same form as that obtained with the former nickel apparatus, except that the maximum

now observed at 20 volts was not then noticeable. This is probably because in the earlier form of apparatus it was not possible to heat the target to such high temperatures as were later used. A curve similar to curve 1 was obtained after the target had been heated for only a few minutes at red heat, but curve 1 was obtained after the target had been heated for about 45 minutes at bright red heat, when the pressure indicated by the McLeod gauge was less than 10^{-6} mm Hg. During this heating the surface of the target had evaporated so that the target appeared very crystalline with a bright copper color. Curve 2 was obtained after copper had been evaporated from a copper disk onto the

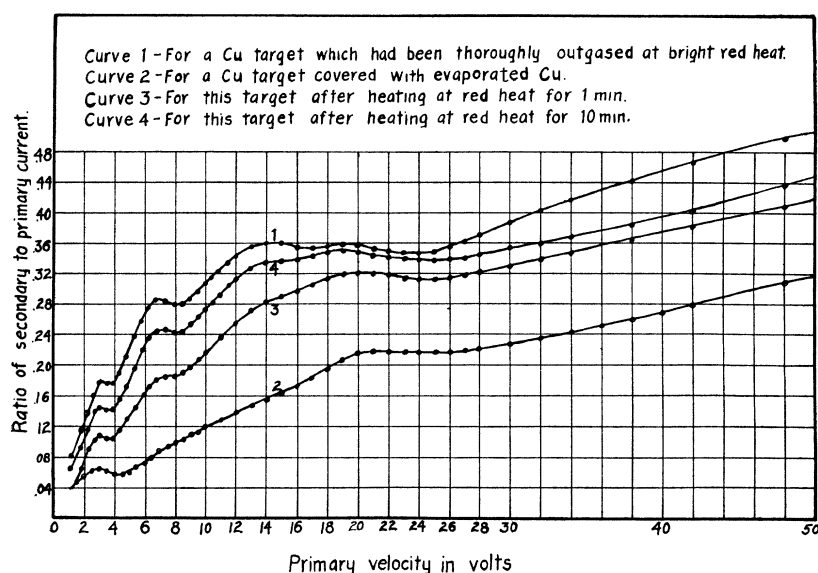


Fig. 4. Secondary electron curves for crystalline copper and evaporated copper films.

target for 45 min., a coat of copper being deposited that was practically opaque to visible light. After heating the target in this condition at dull red heat for one min., curve 3 was obtained and curve 4 after 10 min. of heating. The copper disk had been thoroughly outgassed before the target was exposed for deposit and during the deposition the pressure was probably less than 10^{-7} mm of Hg, as the McLeod gauge showed no reading. A curve similar to curve 2 was obtained during preliminary runs when the copper disk was not thoroughly outgassed before the depositing. This makes it probable that the difference between curves 1 and 2 is not due to gas brought down with the metal and this conclusion is further supported by the fact that gas should be more easily re-

moved by further heating than is indicated by curve 3. Also, the effect of outgassing in other experiments has been to decrease the secondary current, while exposing to gas again increases it. It appears more likely that the different results are due to difference in structure, the crystalline surface being covered by evaporation, with an amorphous layer which is subsequently removed or changed over into crystalline form with further heating.

This idea is further supported by some observations taken after heating another copper target at various temperatures and exposing to air at various pressures. Curve 1, Fig. 5, is for a copper target before the apparatus had been baked; curve 2 is for the same target after baking

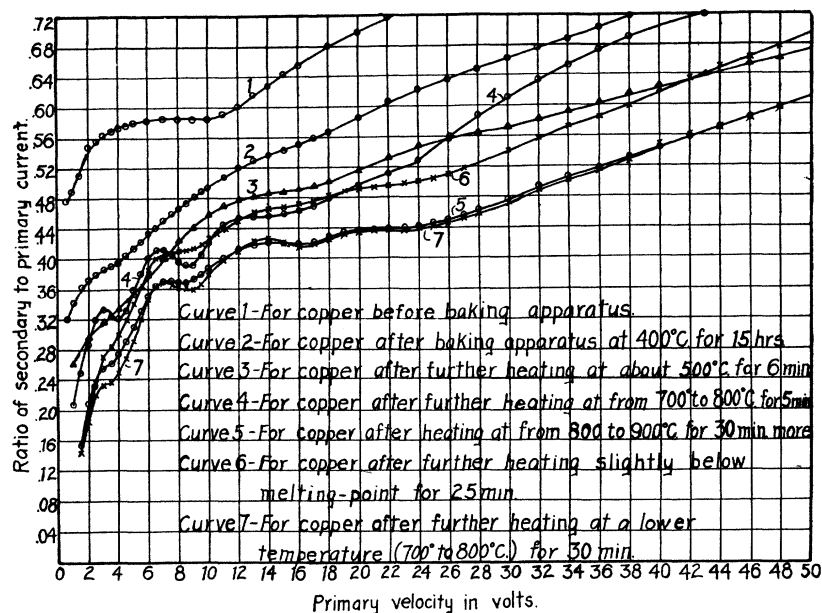


Fig. 5. Secondary electron curves for copper, showing effect of heat treatment.

the apparatus at 400°C for 15 hours; curve 3 for the target after it had been heated separately at a very dull red heat (just visible in a dark room) for 6 min.; curve 4 for the same target after heating at red heat (somewhat brighter than previously, probably between 700° and 800°C) for 5 min. more; curve 5 for the target after heating somewhat hotter (probably between 800° and 900°C) for 30 min. more; curve 6 for the target after heating at a higher temperature (edges of target melted) for 25 min. more; and curve 7 for the target after heating at a somewhat lower temperature for 30 min. more. After this last heating the target showed a decidedly crystalline appearance which was previously not as noticeable.

These results appear to support the following interpretation. The decrease in the secondary electron current from curve 1 to 3 without appreciable change in the form of the curve, is most likely due to removal of gas from the metal without disturbing the amorphous surface layer. (The target had been simply cleaned with fine emery cloth before assembling the apparatus.) Since the marked change in the form of the curve, as well as an increased secondary current, is produced by further heating at a slightly higher temperature for only a short time, it is obvious that some change has occurred at the metal surface. The time of heating required to effect this change is so short that little change in gas content would occur, and since it depends on temperature rather than on time of heating it appears natural to conclude that it is a structure effect such as the replacement of the amorphous surface layer by a crystalline surface layer. The amorphous layer may either be removed or changed over into the crystalline form by the heating, probably the latter, since no evaporation could be detected. The decrease of the secondary electron current to curve 5, with further heating, is then due to further removal of gas. The surface crystals are not visible until after several minutes of heating but the results do not seem to be affected by the size of the crystals. The increase in secondary current, as shown by curve 6, and the tendency toward disappearance of the various maxima would indicate that some further change of structure takes place with heating near the melting point, perhaps changing over into some other crystalline form or more likely to the amorphous form. P. H. Dowling, of this department, while working with copper in another investigation, found that the crystalline surface became less noticeable after prolonged heating near the melting point. Also, recent results of C. H. Desch⁴ show that at high temperatures the surface tension is sufficient to cause rounding of the sharp angles of a crystal of gold. It seems likely that a similar change took place in the above case of copper. Since further heating at lower temperature lowers the curve and brings back the maxima we may conclude that this treatment brings back the same structure as that present when curves 4 and 5 were obtained.

Results showing that gas has little effect on the form of the characteristic curve of copper were obtained after exposing the apparatus to dry air at various pressures. The general shape of the curve was not changed even after exposing the target to air at one atmosphere pressure for 15 hours, the only effect being to raise the curve, i.e., to increase the second-

⁴ Abstract of paper presented before the British Association for the Advancement of Science, Toronto, Aug., 1924.

ary electron current. It was found that the secondary current after exposing the target to 1 mm pressure of air for 15 hours was nearly as great as after exposing to one atmosphere pressure for the same length of time.

Our conclusions, then, are that the characteristic curve for copper is obtained only when the surface is crystalline⁵ and that this curve is little affected by gas content; that the metal brought down by evaporation forms an amorphous layer which persists on the copper surface until heated in a vacuum or removed by some means; that, in other words, the phenomenon observed is an atomic one, whose characteristics are not brought out until the atoms are arranged in definite order in the crystal structure.

It is also possible with the apparatus shown in Fig. 2 to expose the target to radiation from a quartz mercury arc while it is being bombarded with electrons. This was done to see if the atoms could be put into an excited state by the radiation and the electrons thus made more easily removable by bombardment. The radiation passes through a hole in the cylinder *C*, covered with gauze. The secondary electron curves thus obtained when simultaneously exposing the target to radiation and electronic bombardment, show that the constant photo-electric current was simply added to the secondary electron current, the photo-electric current being about 1 or 2 per cent of the other.

The form of the characteristic secondary electron curve for copper suggests the existence of several critical potentials at which inelastic collisions occur. It will now be shown that if we make a few simple assumptions we will obtain a curve very similar to the experimental one. Assume that the probability that an impacting electron will escape from the metal is a linear function of the energy with which it hits. Assume also that the primaries all have the same velocity and that *f* is the fraction that make inelastic collisions for velocities corresponding to *r* volts or above. At *r* volts this fraction loses all their energy and remains in the metal and the ratio of the secondary to the primary electron current drops suddenly from *cr* to $(1-f)cr$, where *c* is a constant. When the energy of the primary electrons is $r+\epsilon$, the electrons which make inelastic collisions will, however, possess an amount of energy after collision equal to ϵ . If all of these electrons escape from the metal the value of the ratio of

⁵ An attempt was made to produce a crystalline surface in air by etching and then studying its secondary electron characteristics before it had been heated at red heat, to see if the curve thus far obtained only after red heat treatment could be reproduced. However, the surface appeared oxidized and the crystals contaminated after being kept in a vacuum for a short time so that the results are of no value.

secondary to primary electrons at $r+\epsilon$ primary volts will be the same as it would have been had there been no inelastic collisions, the only difference being that f of the electrons possess an amount of energy equal to ϵ volts. However, if we assume, as in the original case, that of the fraction f , only $cf\epsilon$ are able to escape, then the total number escaping at $r+\epsilon$ primary volts will be

$$c(1-f) \cdot (r+\epsilon) + cf\epsilon = c(r-fr+\epsilon). \quad (1)$$

If there had been no inelastic collisions the number of secondary electrons per primary at $r+\epsilon$ volts would have been

$$c(r+\epsilon). \quad (2)$$

Since the difference between (2) and (1) is $cf r$, which is constant, the slope of the curve above the potential at which inelastic collisions occur is the same as that of the portion of the curve below this potential, and the vertical distance between the two parts of the curve is given by $cf r$ (see Fig. 6). Also for a primary voltage of $r+\epsilon$ volts, we would expect

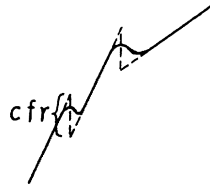


Fig. 6. Theoretical secondary electron curve for crystalline copper.

$c(r+\epsilon)(1-f)$ secondary electrons having an energy corresponding to $r+\epsilon$ volts and $cf\epsilon$ having an energy of ϵ volts.

Let $(r+\epsilon)$ increase to a value i (ionization potential) and let F be the fraction of the total number of primary electrons that make inelastic collisions at i volts and lose all of their energy. Let f' be the fraction of the total number of primary electrons that make inelastic collisions at i volts and lose only r volts energy. f' would be expected to be smaller than f because of the second type of inelastic collisions beginning at i volts. At i volts, then, the ratio of the secondary to the primary current will drop suddenly from $c(i-fr)$ to

$$\{1 - (F+f')\} ci + cf'(i-r), \quad (3)$$

assuming as before that the electrons which lose all of their energy stay in the metal. Since the energy of the ionized electrons is also zero they also will remain in the metal. As in the case of the secondary electrons at $(r+\epsilon)$ volts, the slope at $(i+\epsilon)$ will be the same as that at $(i-\epsilon)$ volts if we assume the same constant of proportionality c . If, however, we assume for the ionized electrons a constant of proportionality c' which is

less than c , then the slope of the curve at $(i+\epsilon)$ volts will be correspondingly less than that at $(i-\epsilon)$ volts. If f' is constant above i volts, it will have no effect on the slope of the curve and at most will displace it slightly in the vertical direction.

There is also the possibility of inelastic collisions at the voltages $2r$, $i+r$, $i+2r$, and $2i$ but the number of such impacts would, of course, be expected to be relatively small.

If, as in the actual case, the velocities of the primary electrons have a Maxwellian distribution, then instead of the discontinuities in the curve we would obtain a smoothed over continuous curve as shown in Fig. 6. By properly choosing the values of the constants c , f , c' and F it is seen that a curve is obtained which approximates closely to the experimental curve, at least in the region of the first two maxima. The remaining indistinct maxima of the experimental curve may possibly be accounted for by some of the combinations of successive inelastic impacts mentioned above. These maxima would then be expected to be very indistinct but it is not clear why the secondary current should remain so nearly constant in the region of 15 to 24 volts.

If the above hypothesis is correct, one would expect to obtain evidence of this from the form of the velocity distribution curves. Thus, for example, for a primary voltage somewhat above the first resonance potential one would expect some low-velocity electrons in addition to those having velocities nearly equal to that of the primary beam, the number depending upon the number of inelastic collisions. Since this number is a small fraction of the total number of impacts, as shown by the ratio of f to the ordinate of the curve at that point, one would not expect the evidence of these to be very prominent on the distribution curve. Then too, when one considers the possibilities of a "smoothing over" of any such distribution it is doubtful whether one would obtain experimental evidence of such low-velocity electrons even though inelastic collisions do occur.

Satisfactory results were not secured with the apparatus shown in Fig. 2, but with the apparatus of Fig. 3, specially constructed for the study of velocity distribution, the following results were obtained. The curves shown in Fig. 7 are for copper after it had been heated at red heat for some time. Curves 1, 2, 3, 4 and 5 were obtained with primary velocities of 102, 80, 62, 41 and 21 volts, respectively; curves 6, 7, 8 and 9 with primary velocities of 15, 10.5, 6, and 5 volts, respectively. It will be noted that as the primary voltage is increased above 20 the number of low velocity electrons increases and the number of highest velocity electrons decreases. However, when the primary velocity is as great as 100 volts, 10 per cent of the secondary electrons have

velocities only slightly less than that of the primaries. For the curves 7, 8 and 9, corresponding to the lower primary velocities, it will be noted that there is a distribution similar to that described in the previous discussion. For a primary velocity of 10.5 volts there is a group of secondary electrons present having velocities up to 4 volts indicating a loss of 6.5 volts, which is in good agreement with the second maxima of the secondary electron curve. For a primary velocity of 6 volts, curves 8 and 9 indicate a loss of 2.5 and 3.25 volts, respectively, while the first maxima of the secondary electron curve is at 3 volts. The curves shown

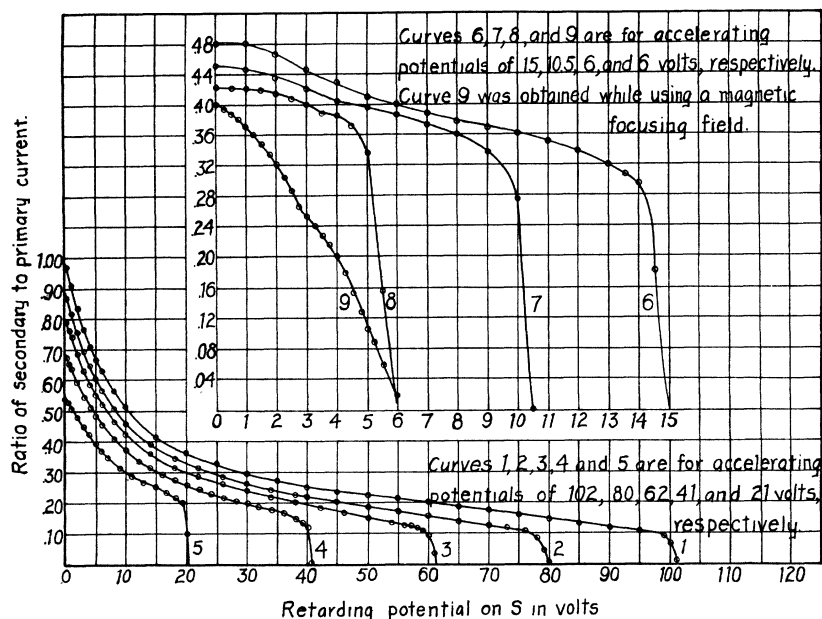


Fig. 7. Curves showing velocity distribution of secondary electrons from crystalline copper.

were selected from a large number and are ones which show this distribution most prominently. These curves could not be reproduced at all times under apparently the same conditions. A great many curves were taken for primary voltages in this region, and several different copper targets of chemically pure copper as well as commercial copper were used. A survey of the results indicates that curves similar to curves 8 and 9 were obtained about 50 per cent of the time, while the others are smooth curves with no visible breaks. Curve 7 is more easily reproducible. This might be expected since the second maxima of the secondary electron curve is much more prominent than the first.

Various attempts were made to determine the reason why the above curves could not always be reproduced, but without success. Curve 9 was obtained with a magnetic field in the direction of the primary stream of electrons and indicates a smaller percentage of higher velocity electrons than without the field. This may be due to a change in the direction of the secondary electrons resulting in the measurement of only one component of velocity. The other curves were obtained with no magnetic field present. It was found necessary to apply the retarding potential to both the sphere *S* and the cylinder *C* (see Fig. 3) so as to keep the potential between *S* and *C* constant. Actually *C* was kept 3 volts positive with respect to *S* at all times. This was necessary to keep the primary electron stream from spreading.

If the various maxima in the secondary electron curve and the breaks in the velocity distribution curves of the secondary electrons are due to the same cause, one would expect, of course, that they should be reproducible with equal accuracy. The only explanation seems to be that the secondary electron curve is obtained under conditions of constant potential difference between the target and sphere while this potential difference is continually being varied during the observations on velocity distribution. It may be that this procedure, necessary for measurements on velocity distribution, is effective in producing a condition which is very critical for velocity measurement of secondary electrons. The results do not appear characteristic of the apparatus since they were observed with two different types (see Figs. 2 and 3).

As previously mentioned, the ratio of secondary to primary current could also be obtained with the apparatus shown in Fig. 3. This was always done before making measurements on velocity distribution of secondary electrons to make sure that the characteristic curve was obtained. In one instance a copper target was mounted at an angle of 45° with the primary electron stream. The magnitude of the secondary current for primary velocities below about 50 volts was found to be about the same as for perpendicular incidence. For higher primary velocities the secondary current is greater than for perpendicular incidence. At 250 volts primary velocity, the ratio of secondary to primary current was found to be 1.35 for 45° incidence and 1.14 for perpendicular incidence. The shape of the secondary electron curve for 45° incidence is similar to the one previously obtained for perpendicular incidence except that the first two maxima are much less prominent.

V. RESULTS FOR MAGNESIUM AND ALUMINUM

Since the inelastic potentials for magnesium in the vapor state have been experimentally determined, it was thought worth while to see if any indications of such could be obtained in the solid state. Fig. 8 shows the secondary electron curve for magnesium after it had been heated somewhat below the melting point by high frequency induction so that the surface had evaporated. The surface appeared very rough but there were no visible crystals present. It will be noted that there are no prominent maxima such as were observed for copper. The curve

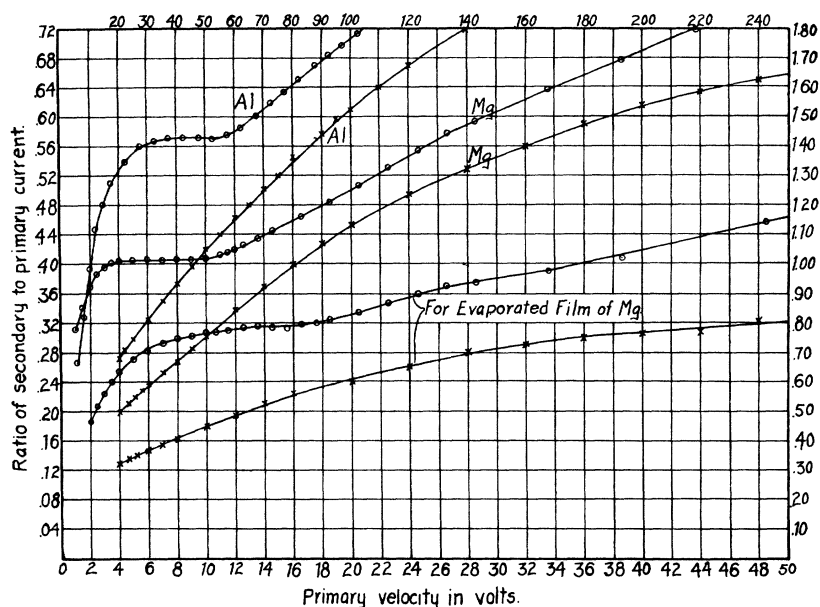


Fig. 8. Secondary electron curves for Al and Mg.

resembles more closely the one originally obtained for nickel, with the sudden increase coming at 11 volts instead of 9 volts. Measurements of velocity distribution of secondary electrons indicate that there are a few low velocity electrons present for primary velocities as low as 11 volts. A curve is also shown which was obtained after magnesium had been evaporated onto the target. Here, as also with copper, the effect of an evaporated film is to decrease the secondary current very much.

A curve for aluminum is also shown in Fig. 8, which was obtained after heating the target somewhat below the melting point by high frequency induction. The velocity distribution of secondary electrons from aluminum was found to be similar to that of magnesium. The unique feature

of the curves for Al and Mg is the extraordinarily large secondary current in comparison with that for the other metals studied. The secondary current was increased somewhat by the heating. The curves marked with crosses are plotted to the scale at the right and top of Fig. 8.

VI. CONCLUDING REMARKS

The reason why the characteristic secondary electron curve for copper should possess such prominent maxima when the curves for the other metals do not, is not at all clear. The fact that copper is the only one of the metals investigated which became visibly crystalline may be the determining factor. Since copper apparently has a rather limited temperature range at which crystals are formed, this would also be expected to be true for the other metals. Hence it may be that the temperature at which the other metals were heated does not lie within this range. This indicates the desirability of a more detailed study of the effect of heat treatment on other metals in the attempt to find a temperature at which surface crystalline characteristics will be developed.

The values of the accelerating potentials of 3.0 and 6.5 volts, at which evidence of inelastic collisions for crystalline copper was obtained, are lower than the values 3.8 and 7.69 volts, respectively, given by Foote and Mohler for the inelastic potentials of copper in the vapor state. However, it appears reasonable that the inelastic potentials of atoms when arranged in a crystal lattice should be different from those of the same atoms when separated from one another.

NATIONAL RESEARCH FELLOWSHIP,
THE UNIVERSITY OF WISCONSIN,
MADISON, WISCONSIN.
August 30, 1924.