SECONDARY ELECTRONS FROM IRON

By H. E. Farnsworth

Abstract

Secondary electron emission from iron as a function of energy of primary electrons, 0 to 300 volts.—Curves showing ratio of secondary to primary electron current as a function of primary velocity were obtained with three forms of apparatus. Two have been previously described. The limiting curves obtained after red-heat treatment of samples of electrolytic Fe having very large crystals, and of chemically pure Fe obtained from Kahlbaum were similar to those obtained for a film of Fe deposited by evaporation. The curves all have sharp maxima at 1.2 and 7.0 volts with minima at 3.7 and 12.0 volts, and a less prominent maximum and minimum at 10.0 and 9.0 volts, respectively. Of several metals tried, Fe is the only one, in addition to Cu, for which such sharp maxima and minima have been obtained. Potentials corresponding to positions of the maxima are interpreted as critical potentials. A steady upward trend of the curve begins at 12.0 volts, which is interpreted as being due to ionized electrons. Slight changes in slope of the curve at higher potentials were observed but these varied with conditions, and hence are taken to have no real significance.

Evidence of structure of evaporated Fe film.—While previous results for Cu indicate that a layer deposited by evaporation is amorphous, the present results indicate that a similarly formed layer of Fe is crystalline.

I. Introduction

A STUDY of secondary electrons produced when various metals, namely Ni, Cu, Ag, W, Pt, Pd, Mg, and Al, are bombarded by electrons varying in velocity from 0 to 250 volts has previously been described.[1,2] The study consisted first, in obtaining the number of secondary electrons as a function (1) of the primary velocity, (2) of the previous heat treatment of the metal, and (3), in the case of Cu, of the surface structure of the metal; second, in obtaining the velocity distribution of the secondary electrons for any given primary velocity.

In the case of all the metals investigated, a marked change in the magnitude of the secondary electron current, as well as in the shape of the secondary electron curve (curve showing secondary current as a function of primary velocity), was produced by heating the metals at red heat. The secondary current decreased with heat treatment for all metals tried, except Al and Mg for which it increased. A limiting curve for each metal was obtained after heating at red heat for some minutes. The changes in shapes of the secondary electron curves con-

[1] H. E. Farnsworth, Phys. Rev. **20**, 358 (1922).
[2] H. E. Farnsworth, Phys. Rev. **25**, 41 (1925).

sisted in the appearance of various breaks in the region of low velocities, 0 to 30 volts, but for no metal were these changes found to be so noticeable as they were for Cu. For this metal, four distinct maxima and four minima appeared in the region 0 to 30 volts, subsequent to red-heat treatment of the target. Further experiments on Cu showed that heat treatment produces two separate results: (1) outgassing of the metal, the rate of which varies with temperature, (2) removal of an amorphous surface layer, thus exposing the crystalline structure beneath, or the transformation of this amorphous layer into crystalline form. The second result occurred at a very critical temperature (dull red heat) in less than one minute. This change was detected by the sudden appearance of the several maxima and minima in the secondary electron curve, while previous heating at a slightly lower temperature for some time was only effective in lowering the curve without changing its shape—a result of outgassing.

Since the other metals were studied previous to the above observation, the above two effects were not separated, although they undoubtedly exist. No direct reason could be found as to why Cu is the only one of the investigated metals upon which heat-treatment produced such a marked effect, except that visible surface crystals of Cu are the most easily produced. Hence, it might be expected that other substances upon which prominent surface crystals are formed would show effects similar to Cu. To investigate this point the secondary electrons from Fe were studied. Fe was chosen because some very crystalline electrolytic Fe was available from Professor Terry.

The existence of several critical potentials, in the region 0 to 200 volts, at which the secondary electron current from Fe suddenly increases has been reported by Stuhlman.[3] These have been attributed to the photoelectric action of soft x-rays that are caused by electronic bombardment of the metal surface. More recently Petry[4] has obtained many slight changes in slope of the secondary electron curves for Fe, Ni, and Mo in the region zero to several hundred volts which, in the case of the higher potentials, do not appear to be due to the above cause. In the present experiments on Fe, special effort was made to obtain evidence of the existence of such critical potentials by taking observations at smaller voltage intervals than previously in the higher velocity region.

As reported in a previous article,[2] attempts were made to obtain velocity distribution curves of secondary electrons from Cu which would indicate the existence of inelastic collisions at critical voltages corre-

[3] Stuhlman, Science **56**, 344 (1922); Phys. Rev. **25**, 234 (1925).
[4] Petry, Phys. Rev. **26**, 346 (1925).

sponding to the position of the maxima in the secondary electron curves. Although some indication of such inelastic collisions was found, the results were not entirely satisfactory, so further investigation is described in the present paper.

II. Apparatus and Procedure

As formerly described, two different forms of apparatus were used for study of Cu. The first, which was suitable for measuring only the ratio of the secondary to the primary current as a function of the primary velocity, consisted of a series of insulated molybdenum cylinders and diaphrams. The target to be studied was alternately interposed and withdrawn in front of a Faraday cylinder (Fig. 2, loc. cit.[2]). The second, which was designed for the purpose of obtaining an accurate measure of the velocity distribution of secondary electrons for any given primary velocity, consisted essentially of a conducting sphere at whose center the small target to be studied could be placed (Fig. 3, loc. cit.[2]). A nearly radial retarding field for secondary electrons could be applied between sphere and target so as to effect an accurate measure of the velocity distribution of secondary electrons. Although this apparatus was intended only for observations on velocity distribution of secondary electrons, it was found that results on the ratio of secondary to primary current for Cu agreed with those of a previously used apparatus, so that this apparatus was used to extend the investigation to Fe. As previously mentioned, it was necessary to keep the potential of the cylinder C (Fig. 3 loc. cit.[2]), which limits the primary beam, about 3 volts positive with respect to the sphere in order to keep the primary beam from spreading before reaching the target. While studying an Fe target it was found impossible to give C a potential for low primary velocities, which would prevent spreading of the primary beam. From the nature of the measurements, a spreading of the primary beam, so that some of it misses the target and strikes the sphere, results in an effective increase in the secondary current which cannot be separated from the true secondary current. Hence, the curve obtained was much higher than the correct one in the region of low velocities, the height varying with the potential of C. This effect was negligible for primary velocities higher than about 10 volts. In order to obtain the correct curve in the region below 10 volts, the apparatus shown in Fig. 2 (loc. cit.[2]) was used. By means of this apparatus the effect of scattering could be eliminated. It was at first thought that this scattering was due to the magnetic property of the iron target, but investigation indicated that it was independent of the position of the target and occurred very near the opening in the sphere

where the primary electrons enter, and that all of those electrons which are scattered suffer a very great change in direction, there being no electrons which are scattered through only a few degrees. These scattered electrons are probably the ones which pass close to the edges of the diaphram.

Since this scattering would change with the retarding potential of the sphere, it is obvious that it would seriously affect the results on velocity distribution of secondary electrons. In an attempt to eliminate this difficulty, the apparatus was modified as shown in Fig. 1 of the present paper. It is the same as that described on p. 46–47 of the above reference,[2] except for the addition of a Faraday cylinder E surrounded by a co-axial cylindrical metallic shield G, both constructed of copper. The position of the cylinders is as shown, with the forward ends at the center of the

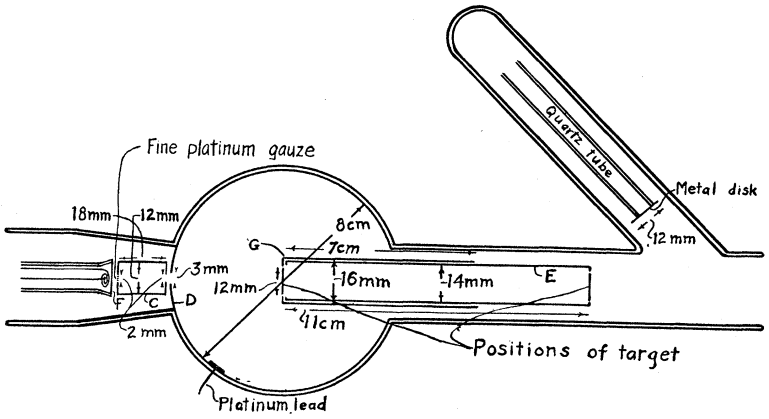

Fig. 1. Apparatus.

sphere. The shield was held in place and also insulated from the Faraday cylinder by three quartz rods of 1 mm diameter and 7 cm length. The rods were placed symmetrically and parallel to the axes of the cylinders and were held in place by small projections on the inner cylinder. The difference in diameters of the cylinders was just sufficient to insure a snug fit after inserting the quartz rods. The Faraday cylinder was fastened to and held in position by two glass rods (not shown in Fig. 1) upon which the target-mounting slid, so that the target could be moved along the axis of the cylinders, the plane of the target being perpendicular to the axis. Circular openings in the ends of the cylinders were just large enough to permit the free passage of the target. The target could thus be placed in the forward position, flush with the end of the cylindrical shield, or withdrawn (by means of a magnetic control) into the side-tube

where it could be heated at red heat by high-frequency induction. The Faraday cylinder and target were kept connected at all times. The presence of the shield prevented any electrons from reaching the Faraday cylinder by multiple reflection from the sphere or by scattering.

The procedure was then to measure (1) the current to the target when in the forward position, (2) the total or primary current to the Faraday cylinder and target with the latter at the back end of the cylinder, this being a measure of the total current striking the target since no electrons could escape from the cylinder.[5] Subtracting the first current from the second then gives the secondary current. The ratio of this secondary current to the primary current, as a function of the retarding potential on the sphere, should then give a measure of the velocity distribution of secondary electrons for any given primary velocity. The secondary electron curve can also be obtained by taking the ratio of secondary to primary current as a function of primary velocity, the potential of the sphere being constant and equal to that of the target. This procedure differs from that used with apparatus shown in Fig. 3 of above reference,[2] in the method of measuring the total current. Any scattering of the primary electrons on entering the sphere S will not influence the measurement of the ratio of secondary to primary current provided that this scattering remains the same for these two observations at any particular primary velocity. Thus the results should not be affected by this change even if the scattering changes with the primary velocity or with the potential of the sphere.

Conditions previously described regarding vacuum were obtained in the present experiments. In addition a charcoal tube was attached to the present apparatus and immersed in liquid air. This, however, did not change the results. Helmholtz coils were used to compensate the earth's magnetic field.

III. Results

A. Results on ratio of secondary to primary current, as a function of primary velocity, for Fe are shown in Fig. 2. Curve 1 is the limiting curve for an Fe target obtained after red-heat treatment. The form of the curve in the lower region, below about 13 volts, was found to be the same for two specimens of Fe—a very crystalline electrolytic Fe and a chemically pure Fe obtaiued from Kahlbaum—after red-heat treatment. It was also obtained with three different forms of apparatus: that shown in Fig. 1 of the present paper, and those of

[5] Measurements of current to the cylinder and target for various positions of the target showed that the cylinder was longer than necessary to be completely absorbing.

Figs. 2 and 3 of above reference.[2] The agreement was in all cases very close except in the one referred to above which was affected by scattering.

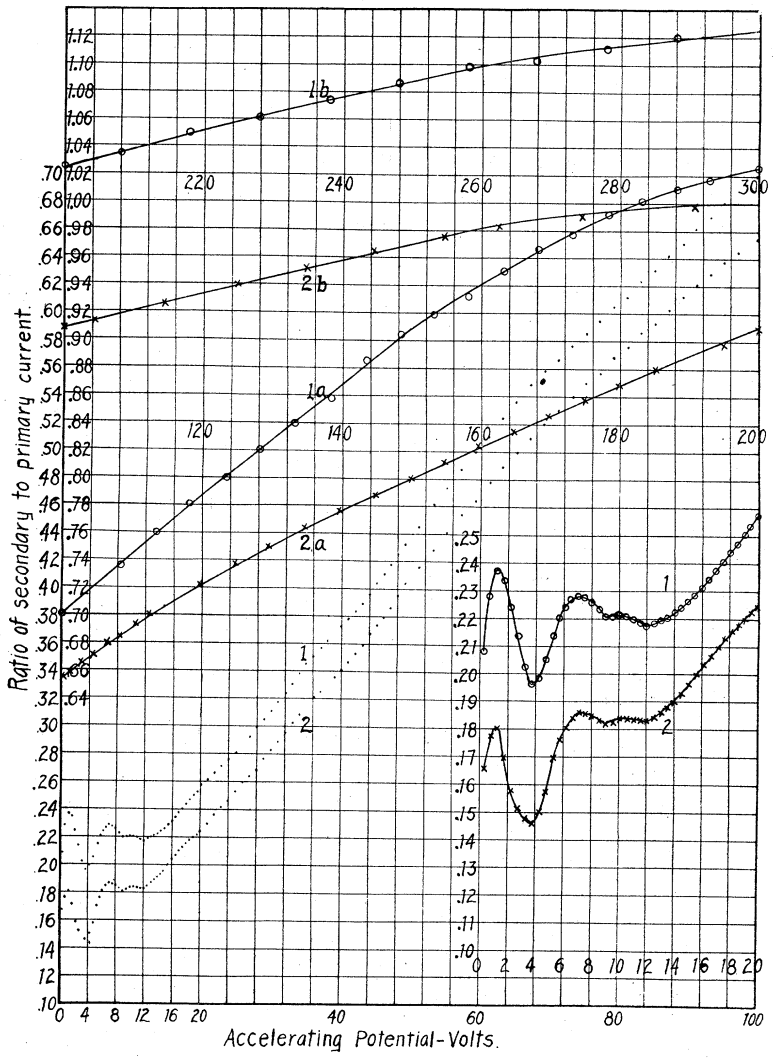

Fig. 2. Secondary electron curves. 1 is for Fe after red-heat treatment. 2 is for a film of Fe deposited by evaporation. 1a and 2a are extensions of 1 and 2, respectively, from 100 to 200 volts and are plotted to the upper scale of ordinates. 1b and 2b are extensions of 1a and 2a, respectively, from 200 to 300 volts. The inset is a magnified portion of curves 1 and 2.

It is seen that there are sharp maxima at 1.2 and 7.0 volts with minima at 3.7 and 12.0 volts and a less prominent maximum and minimum at

10.0 and 9.0 volts,[6] respectively, with a steady upward trend beginning at 12 volts. In the region above about 13 volts there are several slight changes in slope noticeable. Although the general trend of the curve in this region was similar in all of the above mentioned cases, the positions of the slight changes in slope were found to vary with uncontrollable conditions as well as with the form of apparatus and the particular target used. It may be mentioned, however, that of the curves obtained, it is possible to select a large number which agree fairly well with curve 1 in the positions of these slight changes in slope but this procedure has no justification. The disagreement in the position of these slight breaks does not appear to be due to errors in observation since it was possible to accurately repeat a set of observations within a short time after they were taken.

The effect of outgassing was to decrease the secondary current as in the case of most of the other metals previously investigated. The curve obtained subsequent to baking at 400°C but previous to red-heat treatment was a smooth curve without maxima and minima and higher than curve 1.

Curve 2 is for a film of Fe deposited by evaporation and is seen to be lower than curve 1 but agrees with it in the position of the maxima and minima.

Correction has been made in these curves for contact potential between source and target and for change in potential of target due to heating, as described in a previous paper (loc. cit.[2]).

B. *Velocity distribution of secondary electrons from Fe.* Although the apparatus shown in Fig. 1 was designed to give a more accurate measure of velocity distribution than that previously obtained, an unanticipated difficulty was encountered when attempting to effect these measurements. The number of electrons entering the Faraday cylinder, with the target withdrawn to the far end, was found to be equal to the number which struck the target when in the forward position, only when the potential of the sphere was equal to that of the cylinder and target. As the potential of the sphere was made negative with respect to the target and cylinder, the number of electrons which entered the Faraday cylinder, with the target back, became less than the number striking the target when in the forward position, the difference going to the shield instead of to the Faraday cylinder. This spreading of the primary beam at the opening of the Faraday cylinder was obviously caused by the distorted

[6] The maximum at 10 volts was in many cases not as noticeable as in the curve shown. In some curves there was no actual maximum but a region of the curve separated from the rest by changes in slope at 9.0 and 12.0 volts.

field which resulted when the target was withdrawn. This distortion increased as the retarding potential on the sphere was increased so that the condition necessary for the measurement of velocity distribution of secondary electrons effected circumstances which made this measurement impossible. Preliminary measurements with the apparatus before the Faraday cylinder was inserted were sufficient to show that, in general, the velocity distribution of secondary electrons from Fe is similar to that of other metals, i.e. the number of low-velocity secondary electrons increases as the primary velocity increases but these results are not accurate enough to decide the existence or non-existence of the effect in question.

IV. Discussion

The fact that the same type of secondary electron curve was obtained for two different specimens of Fe and with three different forms of apparatus is sufficient evidence of the validity of this curve. The occurrence of sharp maxima and minima at certain critical potentials in the low-velocity region of the above curve for Fe shows the existence of a phenomenon which has an effect on the secondary electron curve as noticeable as that observed in the case of Cu.

In the previous report on Cu it was shown that if one makes certain simple assumptions regarding inelastic collisions a curve containing maxima and minima is obtained which approximates closely to the experimental curve, at least in the region of lower velocities. The maxima occur at certain critical potentials followed by minima. If the work function of the metal is taken into account, as noted by Petry,[4] all primary electrons strike with energy due to the accelerating potential plus that acquired in falling through the surface and all secondary electrons with energy less than that corresponding to the work function will be unable to escape.[8] Hence an interval equal to at least the work function in volts might be expected to separate a maximum from the minimum following it. This interval, however, would depend on the type of critical potential. For an ionization potential it would depend on the distribution of the residual energy between the two colliding electrons after impact. If the energies of the two electrons are equal, the interval referred to above should be twice the work function. If either of the electrons has all of the residual energy after impact, the interval should be equal to the work function. In the case of a resonance posential it would also be equal to

[8] From this point of view it is evident that the effect of critical potentials of solids having a value smaller than the work function cannot be observed at primary velocities corresponding to the critical potential, since the slowest primary electron has an energy equal to the work function.

the work function. Referring to the present results on Fe, the difference between the maximum at 7.0 volts and the minimum at 12.0 volts is the same as the work function ascribed to Fe by Thomas.[7] There is, however, a slight minimum and maximum between these two values. The difference between the first sharp maximum at 1.2 and minimum at 3.7 volts is seen to be only one-half of the above work function of Fe. It therefore seems necessary to conclude either that the work function of Fe is less than 5 volts or that some such condition as the following exists: that the energy loss at the first inelastic collision is only equivalent to 3.7 volts but the probability of its occurrence is negligible until an actual accelerating potential of 1.2+5.0 volts is reached. (Eldridge[9] has shown that a similar idea is necessary to explain the 6.7 resonance potential of Hg vapor.) The residual energy of 2.5 volts is not sufficient to allow the election to escape through the surface so that the secondary current begins to decrease at this point. When the primary electron has energy of 3.7+5.0 volts, after falling through the surface layer, it loses 3.7 volts on collision and has 5.0 volts left which will just allow it to emerge through the surface. Thus the secondary current begins to increase at this point. A knowledge of the velocity distribution of secondary electrons should throw light on this question. At any rate, the gradual rise in the curve beginning at 12.0 volts is undoubtedly due to electrons resulting from ionization. It may be noted that Petry's[4] curve for Fe shows a maximum at about 7 volts with a minimum at about 10 volts.

In the study of Cu it was found that excessive heating of the target near the melting-point resulted in a smoothing out of the various maxima and minima, which was attributed to a change in crystal structure. No such effect was observed for Fe, which would indicate that the crystal structure of Fe is more stable than that of Cu.

The curve for evaporated Fe (curve 2, Fig. 2) is seen to be similar in form to curve 1, at least in the region of low velocities. Previous results show that depositing an evaporated Cu film onto a Cu target causes the disappearance of the sharp maxima and minima—a result which suggests that evaporated Cu is amorphous. The similarity of curves 1 and 2 for Fe then indicates that evaporated Fe is not amorphous but crystalline, the difference in absolute values indicating that evaporated Fe is more gas-free than the other.

Although the present results prove the existence of critical potentials for Fe in the region below about 13 volts accelerating potential, there appears to be no true critical potentials for higher accelerating potentials.

[7] C. H. Thomas, Phys. Rev. **25**, 331 (1925).
[9] J. A. Eldridge, Phys. Rev. **20**, 459 (1922).

Since this article was first written, two papers by A. Becker[10] have appeared on velocity of secondary electrons from Pt covered with lampblack and from pure platinum. They, however, contain nothing immediately related to the present results.

These experiments were performed at the University of Wisconsin during the past summer and the writer expresses his appreciation to Professor C. E. Mendenhall for the privilege of continuing the investigation in that laboratory.

UNIVERSITY OF MAINE,
ORONO, MAINE.
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[10] A. Becker, Ann. d. Physik **78,** 228 (Nov. 1925); **78,** 253 (Nov. 1925).