THE VARIATION OF THE PHOTOELECTRIC CURRENT WITH THICKNESS OF METAL.

BY OTTO STUHLMAN, JR.

SYNOPSIS.

Silver and platinum deposited in the form of transparent and semitransparent wedges were examined for variation of the photoelectric current as thickness of the metal was increased. The metal was deposited on quartz by the evaporation method and examined when monochromatic light fell on the metal side of the plate.

The results are found to be consistent with the view that the probability of an electron going a given distance without losing its ability to escape falls off exponentially with the distance, when this distance is less than about 40 $\mu\mu$. Up to this thickness there is a parallelism between optical absorption and photoelectric emission. For large wave-lengths this parallelism is more pronounced than for short wave-lengths. For greater wave-lengths optical absorption may increase, but photoelectric emission decreases terminating at the threshold value of photoelectric sensitivity.

The results seem to support the view that photoelectric emission is probably not caused by the absorption of energy from the incident light beam, the light only acting as the agent which sets the electron free from its parent atom.

TO test any theory of the photoelectric effect it is necessary to know how the photoelectric current varies with the thickness of the metal through which the electrons must pass and the depth to which the light energy penetrates in the metal. To obtain an adequate conception of the laws governing the penetration of both light and electrons it was thought of primary importance to investigate the change in photoelectric current as the metallic film was increased in thickness.

It was hoped, furthermore, that the results of such an investigation might afford a check on the simple assumption that the number of photoelectrons which escape falls off exponentially with the distance moved in reaching the surface of the metal.

The investigation of the behavior of photoelectrons in passing through metals is confined to a few articles[1–7] which in general agree amongst themselves only in the order of the magnitude of the constants involved. The literature[8] presenting the optical point of view is, however, extensive

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[1] "Density Law of Absorption," Lenard, Ann. d. Phys., 12, p. 730, 1903.

[2] Ladenburg, Ann. d. Phys., 12, p. 558, 1903.

[3] Crother, Phil. Mag., 12, p. 379, 1906.

[4] Rubens u. Ladenburg, Ber. d. D. Phys. Ges., 24, p. 749, 1907.

[5] Partzsh u. Hallwachs, Ann. d. Phys., 41, p. 247, 1913.

[6] Stuhlman, PHYS. REV., 13, p. 132, 1919.

[7] K. T. Compton and Ross, PHYS. REV., 13, p. 374, 1919.

[8] For a summary see Partzsh and Hallwachs, Ann. d. Phys., 41, p. 250, 1913.

though often very contradictory. Whether the light penetrates the metal to a depth of several wave-lengths or only a fraction of a wave-length is still an open question.

Method.—The results were obtained with the apparatus outlined in the writer's above-cited paper[6] and are a continuation of this work and an effort to extend and correlate similar problems investigated by K. T. Compton, Ross, Robinson, Partzsh and Hallwachs and by the writer.

The metals, platinum and silver, were deposited by the evaporation method[1] in the form of wedges, transparent at their thin ends and opaque, or nearly so, at their thick ends. These semitransparent wedges deposited in quartz were then examined for their photoelectric effect at successive millimeter intervals along their lengths, when light from a 110-volt Cooper-Hewitt quartz mercury vapor lamp was allowed to fall at normal incidence on the metal side. A quartz lens of about 20 cm. focal length was used with a slit, which appeared as an image one millimeter in width, when focussed on the metallic wedge under examination. When monochromatic light was used, a Hilger quartz monochromatic illuminator was interposed.

Results.—The curve ABC in Fig. 1 shows the characteristic photoelectric emission obtained from a metal as a function of the thickness of the metal, when exposed to the full radiation from the quartz mercury vapor lamp, at normal incidence. Somewhat similar results, though only qualitatively interpretable, were previously published by J. Robinson,[2] and the writer working with K. T. Compton.[3] One possible theoretical treatment of the problem was worked out by Partzsh and Hallwachs.[5] They suggested that if I_p is the intensity of the light which enters and penetrates the surface of the metal, then at a depth x this intensity drops to $I = I_p e^{-\alpha x}$, where α is the coefficient of absorption of the light. From any thickness dx located some distance x below the surface of the metal $nIdx$ electrons start. These are absorbed exponentially in passing back through the thickness x with coefficient of absorption β. The total number emerging is

$$N = nI_p \frac{1 - e^{-d(\alpha+\beta)}}{\alpha + \beta},$$

where d is the thickness of the metal under examination. Three tacit assumptions are involved, namely that the number of electrons which retain their ability to escape falls off exponentially with the distance moved *normally* to the surface, and that the coefficients of absorption of

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[1] Stuhlman, Jour. Optical Soc., 1, p. 78, 1917; PHYS. REV., 13, p. 112, 1919.

[2] Robinson, Phil. Mag., 25, p. 115, 1913; ibid., 32, p. 421, 1916.

[3] Stuhlman and Compton, PHYS. REV. (2), II., p. 208, 1913.

the light and of the electrons are independent of the thickness of the metal.

This simple theory leads one to expect the photoelectric current to increase exponentially from zero thickness, to a saturation value comparable to the current obtained from a thick sheet of metal under the usual circumstances. The thickness at which this occurs is then the maximum depth to which the light penetrates the metal.

The extensive curve shown in Fig. 1 was not obtained from a single metallic wedge. At first a wedge very rapidly increasing in thickness was examined. This information gave the general outline of the curve. Then a very thin wedge was examined. This gave the data for the points lying at the beginning of the curve. These detailed data usually covered about the first third of the graph as shown in Fig. 1. Then this wedge was replaced in the deposition apparatus and more metal was deposited, thus increasing the thickness uniformly over the whole surface. Upon examination this second wedge usually furnished the data for the second third of the graph. This was repeated until the saturation value of the photoelectric current curve was obtained. A check on the shape and location of the sink in the curve was obtained by placing two quartz plates end to end and depositing a metal wedge on both simultaneously. In this way the deposit on one plate gave the data for one part of the curve and the deposit on the other the data for the adjoining part.

The thickness of the metal at some point along the wedge was obtained as follows: A quartz plate was covered with a uniform deposit of the metal and matched in color with a similar point on the wedge, to identify its relative position. The photoelectric current from this plate, when exposed under the same conditions as the wedge, was compared with the photoelectric current from the wedge. The thickness of the uniformly deposited plate was determined by weighing, and this thickness identified the thickness of the metallic wedge which produced the same photoelectric current as the uniformly deposited plate.

Where no points of observation are shown on the graphs, it is understood that a combination of several of the above methods furnished the data. Where extrapolations or interpolations are resorted to, the curves are shown by broken lines.

The dotted line in Fig. 1 shows the results to be expected from the above theory on the assumption that the two coefficients are of the same order of magnitude and independent of the thickness of the metal. The experimental data do, in general, conform to this theory especially for large wave-lengths. For the data presented above, however, there exists a marked departure from the simple theory. While the experimental results usually fit the theory for very small and large thicknesses of metal, for intermediate thicknesses there is a marked departure as at *ABC*. Here the curve is seen to pass through a pronounced minimum, *B*, before reaching its saturation value.

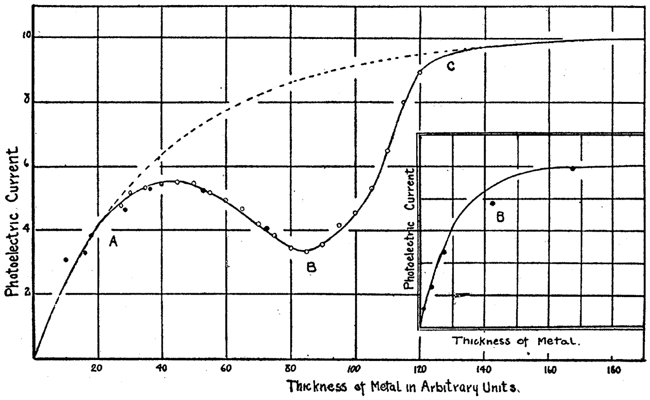

Fig. 1.

The earlier work by the writer and K. T. Compton[11] and J. Robinson[10] also showed an unusual change in the photoelectric current for metallic thicknesses comparable to 10^{-7} cm., apparently out of all proportion to the amount of light absorbed by the metal. Robinson's data stops just short of the point *B* in Fig. 1, hence he interpreted his results as showing an abnormal emission of current for thicknesses comparable to the point *A*. That is, his results are interpreted as showing a maximum in the curve at *A* while the above curve and subsequent data show that the photoelectric current proceeds normally as far as the point *A* and then departs from the theoretically expected current by an apparent subnormal development between *A* and *C*. Beyond *A* the photoelectric current seems to be no longer proportional to the thickness of the metal penetrated by the incident light energy.

In support of this interpretation are quoted some results from an earlier paper by the writer and K. T. Compton[11] shown as an insert in Fig. 1. This curve represents the photoelectric current emitted by a platinum film, cathodically deposited in successively thicker layers on a platinum plate. As in the above curve the current rises exponentially from zero thickness to its maximum, or saturation, value with a small but appreciable variation at the point *B*. This point of observation, at that time attributed to experimental error, lies below the exponential curve drawn through the other points. Here, as before, we meet with a subnormal current, not an abnormal rise in current, for thickness of metal comparable to 10^{-7} cm. Hence with the completed curve before us we must conclude that the photoelectric current is proportional to the thickness of the metal for all values of thickness except such critical values as give an apparent subnormal current.

Results With Monochromatic Illumination.—The work was next extended to determine the change in the photoelectric current with change in frequency of the incident light. Some characteristic results as obtained from silver are shown in Fig. 2. The upper curve shows the photoelectric current from silver as a function of metallic thickness when unresolved light from the quartz mercury vapor lamp fell on the metallic side of the wedge at normal incidence. It shows the approximate average location of the subnormal part of the curve referred to as B in Fig. 1. A cover-glass one millimeter thick was next introduced into the path of the incident beam. Previous examination with a Hilger monochromatic illuminator had shown that this plate absorbed all wavelengths below λ 3131. The results thus obtained are given by the lower curve of Fig. 2. A Hilger monochromatic illuminator was next introduced into the incident beam and set for λ 2536. These results are shown by the middle curve.

Increasing the wave-length of the incident light-energy shifts the subnormal part of the curve to regions of greater thicknesses.

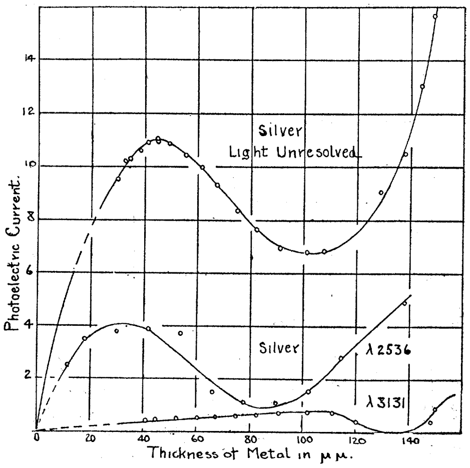

Fig. 2.

A similar comparison with platinum as given in Fig. 3 shows the same effect only to a less degree. If we compare platinum with silver, for wave-length λ 253.6 for wedges deposited under identical conditions, we find that the subnormal position of the curve for silver lies at thickness 90 μμ while platinum has its minimum at about 45 μμ thickness.

Results Due to Fatigue.—It was thought that the slight shift in the minimum of the curve as the wave-length of the incident light-energy decreased was due to aging because of occlusion of gases. Shrinkage in thickness due to aging might account for it, but this possibility was eliminated when the thickness of the metal was determined immediately after the photoelectric current measurements. To test for any change caused by aging due to absorption of gases, a silver wedge was examined directly after deposition (curve No. 1, Fig. 4), then twenty-four hours

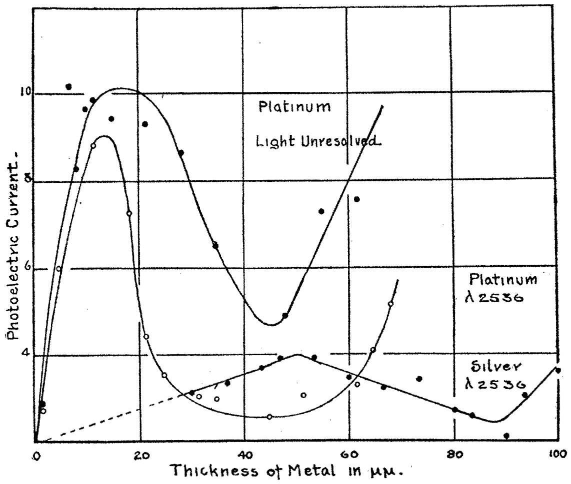

Fig. 3.

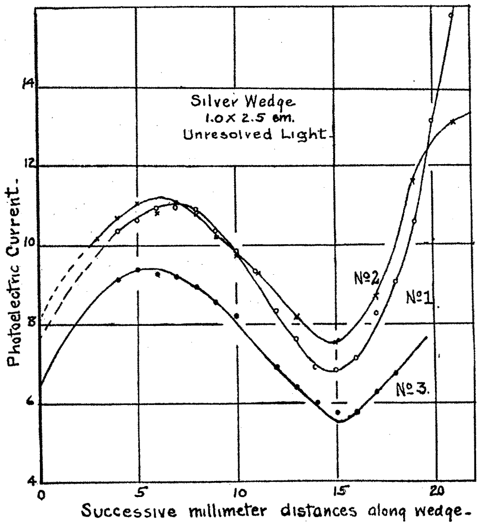

Fig. 4.

later. These latter results are shown by curve No. 2. Then the metal was examined eight days later with the results shown in curve No. 3. These curves show no measurable shift in the location of the minimum, although there is an indication of a slight shift in the position of the peak of the curve, towards the thin end of the wedge. The relative changes in magnitude of the current follow the usual course of changes which accompany "photoelectric fatigue." On the other hand a more detailed examination, of this possible change, with platinum and wave-length 253 $\mu\mu$, with a nine-day idle period between tests, showed a slight shift of the peak in the curve towards the region of greater thickness. No measurable change in the position of the minimum point, except that which could be accounted for by experimental error, was detected.

We might conclude therefore that for any given metal there is a real departure from the simple saturation curve showing that the thickness of the metal and photoelectric effect are proportional and that this departure appears as an apparent subnormal photoelectric current. The subnormal part of the curve or point of minimum photoelectric emission in the curve shifts to regions of greater thickness as the wave-length of the exciting light increases.

Discussion.—All the curves at the origin have one thing in common, they are either linear or possess a slight curvature concave downward. Robinson's results[10] show his curves as possessing a point of inflexion near the origin, as if the photoelectric current increased at first slowly and then more rapidly with thickness of metal. Theoretically the photoelectric emission and thickness are proportional, as there is a proportionality between absorption of light and thickness of metal.[7, 2]

If the amount of light absorbed is proportional to the resulting photoelectric current then this proportionality is only true for the first 10 $\mu\mu$ thickness of the metal penetrated by the light in case of very short waves, but may reach a thickness of 300 $\mu\mu$ or more for wave-lengths comparable to λ 3130. This initial depth in which exponential absorption takes place, as manifested by the emission of photoelectrons, increases as the wave-length of the incident light-energy increases. It cannot however increase as rapidly as the wave-length increases due to the decrease in kinetic energy of emission of the electrons as the wave-length approaches its photoelectric threshold value.

If the coefficient of absorption for silver as determined by Fritze[1] and later by W. Planck[2] are examined, for wave-lengths lying between 400 and 500 $\mu\mu$, we find in general an exponential increase in these

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[1] Fritze, Ann. d. Phys., 47, p. 763, 1915.

[2] W. Planck, Phys. Zeit., p. 563, 1914.

coefficients with increase in thickness of the metal through which the light penetrates. Their results show a depression in the coefficient of absorption-thickness curve in the vicinity of 50 $\mu\mu$ thickness for λ 546 and what appears to be a shift in this depression to smaller thicknesses as the wave-length decreases to λ 526.

If we examine the absorbing power of these two metals or their transparency, with increasing thickness, we at once notice several interesting analogies. Silver and platinum as examined by Hagen and Rubens for their relative transmission, for a given wave-length as a function of the thickness of the metal, found that a silver surface 80 $\mu\mu$ thick became more and more transparent as the wave-length of the incident energy decreased from λ 7000 to λ 3210. At the latter wave-length the silver transmitted 32 per cent. of the incident energy. From this wave-length down to λ 2210 the surface rapidly became less transparent, reaching a minimum of 1.5 per cent. for wave-length 2210.

Upon comparing equal thicknesses of metal, say 80 $\mu\mu$, we find as shown in Fig. 2, that with decreasing wave-length, the photoelectric results show an increase in the transmission of light by silver. This transmission reaches a maximum at λ 3210. Here the absorption is a minimum but not quite zero. Photoelectrically the light absorption ceases at λ 3250, the threshold value for silver. Beyond this wave-length photoelectric action does not set in again although optical absorption increases very rapidly. If absorption of light and emission of photoelectrons go hand in hand, why does not the photoelectric effect follow the increase in optical absorption? It seems as if the two phenomena at this point were only remotely related or have nothing in common. It appears probable that there are really two phenomena superimposed; the optical absorption which removes energy from the light-wave, and the photoelectric effect which removes no energy from the light-wave. The light appears to act only as the agent reaching into the atom to release a particular electron.

Hagen and Rubens' optical results showed that silver possesses marked regions of selective transmission; a given thickness becoming more and more transparent as the light decreased in wave-length from λ 3160 to λ 2510. This is also verified by the above photoelectric measurements. Where the photoelectric current passes through a minimum the metal must allow most of the incident energy to pass through it without producing a photoelectric effect, so that the light transmitted by this layer is the same as the amount transmitted by a much thinner layer of metal. Under these circumstances it would be impossible to use the transmitted energy as a measure of film thickness as has been done by Compton and Ross.[7]

If we compare the results from silver with those from platinum, say for wave-length λ 2536, we at once notice that the photoelectric current for platinum is very much larger than that for silver, when equal thicknesses of metal are compared. This is also in agreement with the optical absorption of these metals. Hagen and Rubens[1] found that for λ 3210 silver was about one thousand times more transparent than platinum when equal thicknesses of metal (80 $\mu\mu$) were compared. Judging from the photoelectric results and using the assumption that the photoelectric current is proportional to the amount of light absorbed, this magnitude seems very much too large. At most the photoelectric results show platinum only ten times more absorbing than silver. This variation might be accounted for by the great difference in the absorption of the electrons as they pass through the metals. Unfortunately the coefficient of absorption of the electron for platinum is not more than twice as large as that for silver.[2] Again we are confronted with the same difficulty, in that the optical absorption does not allow us to arrive at a conclusion as to the magnitude of the photoelectric current that may be liberated by a metal.

Finally an examination of the photoelectric current for a change in the intensity of the light showed a corresponding change in the magnitude of the current but no measurable shift in the curve along the thickness axis.

Conclusions.

The amount of light absorbed by a metal and the photoelectric current generated as the result of the penetration of the light into the metal are not in general proportional to each other.

If the light penetrating a metal is absorbed according to the known simple exponential law then the photoelectric current is only proportional to the amount absorbed in a depth of metal comparable to less than one tenth a wave-length of the incident energy.

The greater the wave-length of the energy producing photoelectric activity the greater the depth to which absorption of light and emission of current are proportional.

In the case of silver the variation in optical transmission runs parallel to the variation in the photoelectric current as the thickness of metal changes.

Optical absorption of the light may take place without photoelectric emission.

Photoelectric emission is not caused by the absorption of the light

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[1] "Durchlässigkeit" as used by Hagen and Rubens, Ann. d. Phys., 8, p. 449, 1902.

[2] Stuhlman, Phys. Rev., 15, p. 549, 1920.

energy, but the light acts only as an agent in setting the electrons free from their parent atoms.

The number of photoelectrons retaining ability to escape falls off exponentially with the distance moved in reaching the surface of the metal. The data presented could not however be used to distinguish between this conclusion and one in which the ability to escape falls off exponentially with the distance moved normally to the surface.

THE UNIVERSITY OF NORTH CAROLINA,
CHAPEL HILL.