THE SENSIBILITY CURVES FOR SELENIUM; A NEW SENSIBILITY-WAVE-LENGTH MAXIMUM AND A NEW PRINCIPLE.

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RECENTLY Pfund[1] found a maximum in selenium at wave-length 690 $\mu\mu$ which disappeared when the intensity of illumination became very faint. This disappearance calls attention to the complexity of the light action in selenium. The present authors were led to believe as a result of a mathematical analysis that the complex behavior might be simplified by using very short periods of exposure to the light, and even that the maxima might disappear for intense illumination also. We have been surprised to find in the Giltay cell a very pronounced maximum at 800 $\mu\mu$, which disappears with small intensity just as the maximum discovered by Pfund in the region of 690 $\mu\mu$ was observed to vanish. And further, not only does this maximum disappear with intense illumination when the selenium is exposed for a short interval of time, but all maxima disappear, such that the remarkable result is obtained that the change of resistance of the particular cell studied is independent of the wave-length of the incident light between 460 and 790 $\mu\mu$. The change of resistance for light in this region is solely a function of the intensity. This last conclusion is important in that it promises us an instrument for measuring energy in the visible spectrum more delicate than the thermopile or bolometer. In this article we propose to restate the conditions under which the maxima appear and to define a method of using the selenium cell for energy comparisons of the various wave-lengths in the visible spectrum.

THEORY.

First we wish to make clear that for intense illumination made up of all visible wave-lengths, we should obtain the simplest conditions by using short exposures. A mathematical analysis has revealed[2] that for the Giltay cell when exposed to approximately white light there are two direct and two reverse changes taking place and only one conducting

[1] PHYS. REV., XXXIV., p. 370, 1912.

[2] See paper by F. C. Brown, PHYS. REV., 33, p. 403, 1911.

element. On p. 408 of the article referred to are given the rates of change and the constituents of the cell under specified conditions. For a short exposure at 18° C. the changes in the conductivity are made up relatively as follows:

$$\begin{aligned} A \rightarrow B &= \alpha_1 A = 11{,}200 \times .054 = 604 \\ A \leftarrow B &= \alpha_2 B = .8 \times 12 = 9.6 \\ B \rightarrow C &= \beta_1 B = .8 \times .9 = 0.7 \\ B \leftarrow C &= \beta_2 C = 3.6 \times .004 = 0.0 \end{aligned}$$

Thus it appears that we obtain appreciable changes only between the A and B components, and of these the direct change constitutes about 98 per cent. of the total. But for long periods of exposure the amount of each of the four changes above noted approaches equality, as A becomes less, and B and C become greater. The analysis shows therefore that the short exposure gives simple and single changes, while any long exposure gives a most complex and varying summation, because the amounts of A, B and C are continually changing with time. Maxima obtained for long exposure really have very little meaning until we first establish what part of the maximum can be sorted out and attributed to the direct change from A to B.

But aside from what has just been said, short exposures should give a constant change, because for a short interval the amounts of the A, B, and C components are approximately fixed, and since the rates of change are unvarying under given conditions, the sum of $\alpha_1 A - \alpha_2 B - \beta_1 B + \beta_2 C$ should be constant. For any long interval the interchange of the components makes the process very complex.

We therefore decided to map out the sensibility of the selenium for equal energy throughout the spectrum, by exposing the selenium for only a fraction of a second, using sensibility curves for longer exposure merely for comparison.

There is nothing so far in the theory to indicate why short exposures should or should not give sharp maxima. Short exposures however should give simple conditions.

Arrangement of Apparatus and Method of Measurement.

To obtain the sensibility curves, the principle laid down by Pfund[1] was followed. The change of resistance for equal energy was measured throughout the visible spectrum. The arrangement of apparatus is shown in Fig. 1. Light from a Nernst filament, N, manufactured by Pye and Co. for their lamp and scale outfit, is focused by the lens L, on the collimating slit S_1 of a constant deviation monochromatic illuminator,

[1] Phil. Mag., Jan., 1904.

manufactured by Spindler and Hoyer. The Nernst glower was maintained at constant intensity by using storage battery for heating current. The bundle of quasi-homogeneous rays was then focused on the slit S_2, and from there was focused by means of the concave mirror M, upon either the thermopile slit or the selenium cell, as desired. The lenses of the monochromatic illuminator were 20 mm., or $f/12.7$ in diameter, and hence with this apparatus, much of the energy is lost. A new illuminator of greater light-gathering power has been obtained and will be used for future work. The slits S_1 and S_2 were kept of equal width, which varied from 0.2 to 1 mm. The length of the slits was one centimeter.

The thermopile was of the Rubens type, but it was of bismuth-silver wires of the improved design of Dr. W. W. Coblentz. It was remarkably

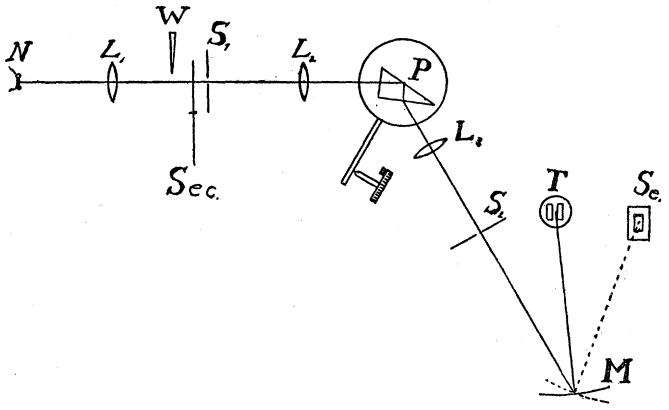

Fig. 1.

free from drift and altogether very satisfactory, as used with a Thomson galvanometer made by Siemens & Halske. The galvanometer had a resistance of 5.4 ohms, and the thermopile had a resistance of 7.4 ohms. This combination when a glass cover was in front of the thermopile junctions gave a deflection of 300 divisions with a candle at a meter. The period was about 5 seconds for this sensibility. By increasing the period the sensibility could have been increased several times, easily to more than 1,000 divisions per candle per meter.[1]

[1] Since the above test was made we have received a standard carbon incandescent lamp from the Bureau of Standards, calibrated for total radiation in a given direction. By means of this standard lamp we found the sensibility of the thermopile to be 9.3×10^{-8} watts/mm. deflection on our scale. It must be remembered that this sensibility was obtained with a glass cover over the thermopile. Had this cover been removed, the sensibility would have been much greater.

A Giltay cell, the one previously studied by one of the authors, was used.[1] It had a resistance of 299,000 ohms in the dark with 4 volts in the circuit, or 270,000 ohms with 20 volts. It was connected in a Wheatstone bridge. For the long exposures a potential of 4 volts was left in the circuit continuously, but for the exposures of a fraction of a second duration the potential was changed to 20 volts. During the experiments the temperature did not vary from 24° by as much as one degree. For the long exposures a Leeds & Northrup high sensibility galvanometer of about 1,000 ohms was used. For the short exposures the method outlined by Brown and Clark[2] was adopted. With this a ballistic galvanometer of 22 seconds period was substituted for the above galvanometer.

We deviated from the procedure outlined by Dr. Pfund in two essentials. An exposure of a fraction of a second was used, and secondly we did not give the cell a special treatment of the nature of preliminary exposure before making each observation. Aside from the advantage of simplifying the conditions, the short exposure has the advantage in that a shorter time is necessary for recovery. We do not believe in the special treatment immediately before making an observation, because such only exaggerates the complexity, and makes it more difficult to define the characteristics of a given sample of selenium. Each distinct preliminary treatment should give a corresponding distinct sensibility curve, providing only that the special treatment varies either in duration or nature of action on the slow rates of change in the selenium.

The intensity of illumination was varied by a rotating sector disc, *Sec*, and an optical wedge, *W*, (Fig. 1) either singly or in combination. It was very easy by this combination to verify the applicability of Talbot's law. However we did not make as extensive a verification as was made by Pfund.

The total area of the selenium exposed was about 4 mm^2, which was only a little more than a thousandth part of the entire sensitive surface. The fact that only such a small portion of the selenium was exposed was marked only by an apparent decrease of the sensibility of the selenium by a constant value.

We first obtained a family of sensibility curves with varying energy intensity on the selenium using long periods of exposure, 30 sec. In general the energy on the thermopile was adjusted to constant deflection of the galvanometer (20 div.) or to within five per cent. of this value. Then the selenium was exposed to this same bundle of energy. The slit width was 0.2 mm. This width gave a very sharp maximum (see

[1] PHYS. REV., 33, p. 403.
[2] PHYS. REV., 33, p. 53, 1911.

Fig. 2) at 800 $\mu\mu$, a maximum less sharp and much less pronounced at 690 $\mu\mu$, and a broad maximum extending from 540 $\mu\mu$ to 600 $\mu\mu$ (Fig. 2). In obtaining Curve *C* a different practice was resorted to. First the energy from a Nernst glower was measured throughout the spectrum. And then to obtain equal energy on the selenium the calibrated sector disc openings were adjusted in inverse ratio to the energy in the different parts of the spectrum. This method had the advantage of picking out the characteristics of the curve quickly and with a small number of observations, but it required supplementary readings by the other method in some instances in order to obtain higher precision in the relative values of adjacent points. The energy intensity which gave curve *A* was

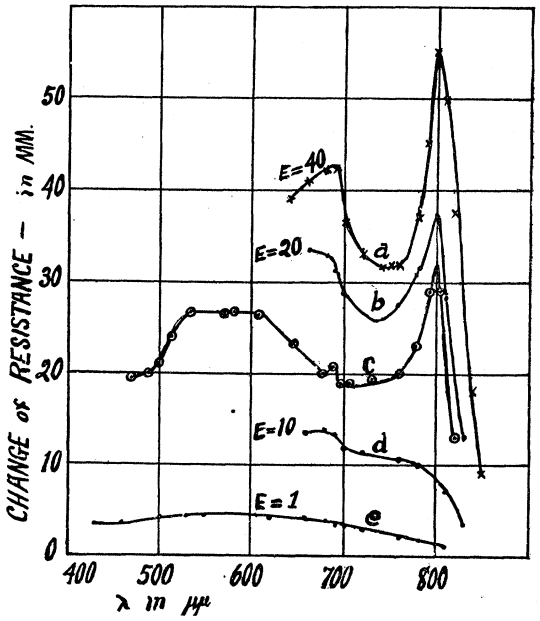

Fig. 2.

about that of a candle at four meters. The intensity of exposure on the selenium was decreased by use of the sector disc by steps, until it was diminished to one fortieth of the above value. The curves are shown in Fig. 2.

The points of interest are first that there is a sharp maximum at 800 $\mu\mu$ which has not hitherto been observed in selenium, and second that faint energy will not bring out this maximum. This last point is very similar to Pfund's observation. The vanishing of the maxima with faint illumination may be explained in terms of the rates of change

existent in selenium. For faint illumination all the rates of change are small, particularly are α_1 and α_2 small in comparison with their values for intense illumination. This simply means that in a 30-second interval with faint illumination there is only time for the A component to be transformed into the B component and of the original B component to be transformed into the C component, and that of the B component for example the excess formed by the light is so small in this time that only the original amount need be considered in the formation of the C component. A long exposure to faint illumination tends to approach the same simplicity that a short exposure to intense illumination accomplishes.

We next tested the effect of varying the time of exposure to intense light referred to in the theory to see if the maximum would tend to vanish. The new duration of exposure was .4 sec. and the slit width was one millimeter. The energy beam was focused on the selenium, so that we obtained a somewhat greater energy intensity than any which gave the curves in Fig. 2. The observations were found to agree with each other very well indeed; five observations were taken for each setting of the illuminator except one. One division on the scale was usually the maximum variation obtained. For the selenium the error was not as great as one per cent. However it was not easy to assure the individual thermopile readings to a greater accuracy than five per cent.

The Curve A (Fig. 3) shows the average of the deflections of the ballistic galvanometer, *i. e.*, the change of resistance, between 500 $\mu\mu$ and 810 $\mu\mu$. It is altogether probable that the single point that is off the curve was off as a result of error due to insufficient number of thermopile readings. By the method that we used it was necessary to diminish the energy in order to make observations beyond 500 $\mu\mu$. By diminishing the energy to 1/20 of the original value the Curve A_2 was obtained. The average of a large number of observations indicated that the independent relationship between wave-length and deflection extended back as far as 460 $\mu\mu$.

The Curves B and C represent the observations for long periods of exposure to the same intensity as above mentioned. The ordinates for Curves B and C are arbitrary and do not correspond to those for Curve A. It is observed that a 60-second exposure (Curve C) makes the maxima and minima slightly more pronounced than a 30-second exposure (Curve B). Perhaps a difference curve between an exposure curve for a very long time and one for a very short time would give a sensibility curve arising solely from the slow changes in the selenium. However this has not been carefully thought out yet. Observations taken after quickly repeated exposures, particularly to longer wave-lengths, tend to smooth

out the maxima. Dr. Pfund has had the kindness to communicate some very interesting and as yet unpublished results by Mr. P. J. Nicholson which are directly in agreement with our result, viz., that the slow rates of change arise from light of the longer wave-lengths. His results show that the form of sensibility curves is markedly altered by varying the wave-length of the preliminary exposure, and that under the continued influence of infra-red radiations (800 $\mu\mu$), the usual fatigue

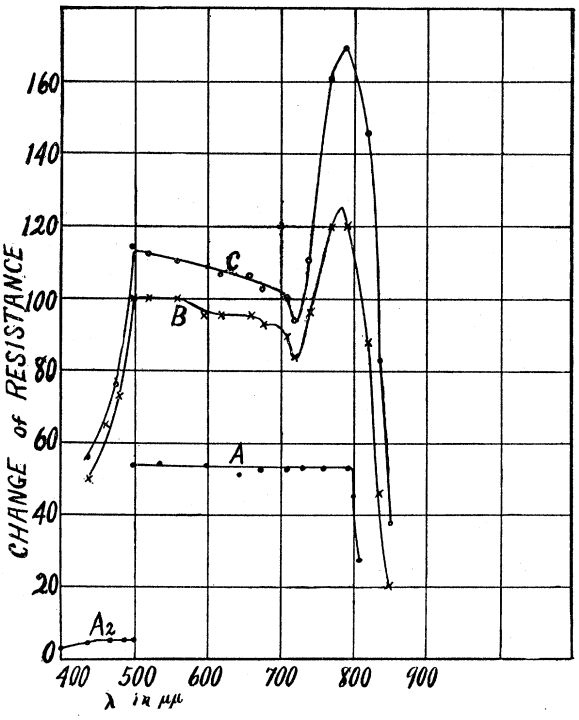

Fig. 3.

A is for 0.4 second exposure; *B* is for 30 seconds exposure; *C* is for 60 seconds exposure.

and lag almost disappear. The fatigue and lag seem to us merely evidences of the slow changes in conductivity.

Having received a more powerful illuminator we are extending our work, to find out the limits in which the change of resistance is independent of the wave-length for short exposure, to establish the law of change of resistance with intensity, and to compare other varieties of selenium and light-sensitive materials.

It is interesting to note how rapidly the curve falls off beyond 800 $\mu\mu$. We are unable to account for a mechanism that would produce a sudden jump of this kind.

The minima as well as the maxima arise from the longer periods of exposure. It may be that minima indicate the normal states for short exposure for particular wave-lengths, which means that spurious maxima arise from slow changes.

SUMMARY.

1. The sensibility curve for a Giltay cell has been determined under varying conditions.

2. In accordance with theory it has been shown that long periods of exposure give varying degrees of complexity, and are responsible for the regions of maximum sensibility.

3. By long periods of exposure a new maximum is obtained at 800 $\mu\mu$.

4. By exposures of a fraction of a second the maxima and minima vanish and between about 460 $\mu\mu$ and 790 $\mu\mu$ the change of resistance is independent of the wave-length.

5. The work thus far accomplished emphasizes the importance of defining simple conditions for obtaining the maxima of such a complex acting agent as selenium.

6. The maxima and also the minima in the Giltay cell studied arise from the slow rates of change.

7. A selenium cell of this type by virtue of the independence of wave-length for short periods of exposure promises to be the most delicate instrument constructed for measuring energy within the range noted.

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