SOME EXPERIMENTS ON THE NATURE OF TRANSMITTED LIGHT-ACTION IN CRYSTALS OF METALLIC SELENIUM.

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RECENTLY we showed[1] that light falling on one part of a crystal of selenium would produce a change of conductivity throughout the crystal. In the acicular crystals this effect was observed practically undiminished in amount as far as 10 mm. away from the point of illumination. This effect was denoted by the authors as a new property in matter. The work described in this paper consists essentially of two investigations designed to give information concerning the nature of this light-action. The first was an experiment to determine the velocity of transmission of the light effect along the crystal, and the second was a study of certain interrelated phenomena between the pressure effect[2] and the transmitted light action. The one showed the action to be transmitted much too rapidly for a temperature effect. The other definitely proved that the increase of conductivity at a distance could not arise from transmitted free electrons. Incidently, the results call forth a new view as to the nature of electrical conduction as exhibited in crystals of metallic selenium.

THE RATE OF TRANSMISSION OF LIGHT-ACTION ALONG THE CRYSTALS.

To obtain information as to the rate of transmission of this new effect the method used was to determine the resistance after short intervals of time following illumination at a distant point. A lamellar crystal of the fifth system, of size about 4 × .6 × .3 mm., with striations perpendicular to the length of the crystal was mounted with opposite ends between separate sets of electrodes as shown conventionally in Fig. 1. Under crossed nicols the crystal would show parallel extinction. A constant source of illumination was obtained by focussing a Nernst glower on the crystal.

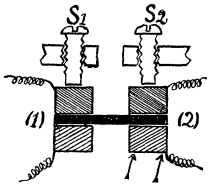

Fig. 1.

[1] Brown and Sieg, Phil. Mag., Ser. VI., Vol. 28, p. 497, 1914; Brown, PHYS. REV., N. S., Vol. IV., p. 85, 1914.

[2] For a description of this effect see paper by author in PHYS. REV., Ser. 2, Vol. 14, p. 85, 1914.

The procedure was to connect the resistance between electrodes at end (2) in one arm of a Wheatstone's bridge circuit. The resistance of this part of the crystal was measured in the dark and when it was illuminated, and then the same part was measured again when the opposite end (1) was in the dark and then in equilibrium under the same constant illumination as was previously on the conducting end. Next the above procedure was repeated several times, with the modification necessary to measure the change of resistance during the first 0.4 second of illumination. The object was to determine what part of the total change of resistance was transmitted two millimeters along the crystal in this short interval. Of course, even if the light falls directly on the part of the crystal whose resistance change is under determination all the effect does not take place at once.[1] Thus the opposite ends of the crystal were illuminated alternately in order to find the relative lag in the transmitted effect.

The method of measuring the change of resistance in these small intervals was that described by Brown and Clark.[2] A shutter was attached to a ballistic pendulum, which automatically put a galvanometer in circuit for a short interval at any desired time after the shutter moved out of the path of the beam of light directed on the crystal. Thus in Table I. the change of resistance was recorded as divisions throw of the galvanometer, which was afterward reduced to ohms.

In the first series of observations, where the conductivity of end (1) of the crystal was measured there is a rather wide variation of the readings, but this was brought about by a deliberate variation of the lighting arrangement, extra screens to cut off stray light, etc., being used. The purpose was to make observations under corresponding conditions when each end was illuminated.

The result of these experiments can be stated as follows:

Both the direct and the transmitted actions are very rapid, more than 50 per cent. of the equilibrium change taking place in 0.4 second. In searching for an explanation of the fact that the percentage change of conductivity in 0.4 second was quite different depending on which end of the crystal was tested, facts were discovered which indicate that the ratio of the area illuminated to the cross sectional area conducting is a factor in the rate of change in short intervals of time. Whatever may be the outcome of a study of this relation, it is not believed that the accompanying results will be at all vitiated. Second, that the total amount of the transmitted action is of the same order of magnitude as the direct action and yet distinctly less. Third, the difference between

[1] See PHYS. REV., Vol. 33, p. 403.

[2] PHYS. REV., Vol. 33, p. 53, 1911.

TABLE I.

Change of Resistance of Crystal at End (1).

	Illuminated at Electrode (2), Ohms.	Illuminated at (1), Ohms.
Resistance in dark	880,000	880,000
Resistance in equilibrium with light	450,000	370,000
Change of resistance at equilibrium	430,000	510,000
Change of resistance in 0.4 sec	7.0	9.0
	7.5	9.0
	7.0	11.5
	9.0	12.0
	9.0	12.5
	8.0	12.0
	7.5	12.0
	9.0	15.0
	11.0	15.0
	11.0	18.0
Mean in div.	8.6	12.9
Mean ohms	183,000	234,000
Ratio, $\frac{\text{change in 0.4 sec.}}{\text{equilibrium change}}$	.426	.459

Change of Resistance Measured at End (2).

	Arranged to Illuminate end (1).	To Illuminate (2).
Resistance in dark	510,000	510,000
Resistance in equilibrium in light	340,000	260,000
Change of resistance at equilibrium	170,000	250,000
Change of resistance in 0.4 sec	11.0	18.0
	10.5	17.5
	11.0	16.5
	11.0	16.5
	10.0	14.5
Mean in div.	10.7	16.6
Mean in ohms	136,000	215,000
Ratio, $\frac{\text{change in 0.4 sec.}}{\text{equilibrium change}}$	.80	.86
Change of resistance in 0.2 sec	10. div.	16.
	10.5	15.5
Mean in ohms	133,000	201,000
Ratio, $\frac{\text{change of resistance in 0.2 sec.}}{\text{equilibrium change}}$	.78	.80
Change of resistance in 0.1 sec	7.0 div.	13.5
	7.5	12.5
	7.5	12.5
Mean	7.3	12.8
In ohms	95,000	162,000
Ratio, $\frac{\text{change in 0.1 sec.}}{\text{equilibrium change}}$	.56	.65

the fractional parts of the total change taking place in 0.4 second for the direct and the transmitted effects is very small. The proportional change in 0.2 second is also observed to be the same within the limits of accuracy of the measurement. Even for 0.1 second exposure there is almost as great a fraction of the effect transmitted to the opposite end of the crystal as at the illuminated end.

The conclusion is fairly safe that practically all of the transmitted action by light may travel a distance of 2 mm. in less than 0.1 second. How much faster than 2 centimeters per second it may travel, I was not prepared to determine. At any rate the effect travels so fast that we are warranted in saying that it can not be transmission of a temperature change along the crystal. This conclusion is quite in agreement with recent experiments by Sieg and Brown,[1] in which it was shown that for equal quantities of energy in different parts of the spectrum falling on the crystal, a maximum transmitted effect occured in the visible spectrum, not far from the position where the maximum occurred for direct action of the light. Likewise, if the transmission is too rapid to be a transmitted temperature disturbance, it must, according to the electron theory, be too rapid to be merely an equalization of electronic pressures throughout the crystal.

THE ACTION AT A DISTANCE IS PROPAGATED MECHANICALLY.

The fundamental fact is that light falls on a crystal of selenium at one spot and produces a change of conductivity at any other part of the crystal. It is inconceivable that the light itself could, on entering a crystal, diffuse almost without absorption to the most distant part of a crystal, and yet such may be the case. Therefore the nature of this transmitted effect was investigated along other lines. One view would suppose the light by virtue of its electromagnetic properties to be able to directly tear the electrons free from the atomic structure. In order that there might be almost undiminished action at a distance, either these electrons must disperse to all parts of the crystal structure or at the place where the light falls there must be an increased concentration of electrons which would quickly be felt throughout the crystal, the same as an increased quantity of gas in one part of a tank system would be felt everywhere in the enclosure. The velocity of such a disturbance would be largely a function of the elastic properties of the electrons in confined space. Another view is that the light acts upon a certain mechanism which produces automatically a certain instability throughout the crystal structure. This instability manifests itself by a greater electrical con-

[1] PHYS. REV., N. S., vol. 4, p. 507, 1914.

ductivity, which means either an increased number of free electrons or a greater instability of the fixed electrons. The first view involves the direct carrying over of the action without the aid of the crystal structure as such while the second view involves something analogous to an elastic medium propagation.

The merits of the above views were investigated largely with the use of the arrangement shown in Fig. 1. In my previous paper it was pointed out that the resistance of a crystal varies with the mechanical pressure under which it exists and also that the resistance varies with the potential differences producing the current. With this apparatus were studied the interaction of various agents, viz. light, pressure and electrical potentials, that alter the resistance of the crystal.

It was found, no matter how much the resistance might change at end (1) as a result of large differences of potential there, that the resistance at the opposite end (2) did not vary. Similarly pressure on end (1) of the crystal by the screw S_1 changed the resistance at (1) by a factor of ten but the resistance at the opposite end was thereby changed only by a zero or negligible amount. Thus we have the clear cut result that *light-action is transmitted along the crystal, but the pressure effects and the electrical potential effect*, as I have designated them, *are not transmitted.*

A most important part of the experiment was in the superposition of the pressure and the light effects. In this experiment only end (1) of the crystal was illuminated in all the observations. The conductivity was measured at both ends simultaneously, both when end (1) was in the dark and when it was illuminated. The observations are shown in Table II. The pressures were deduced from the conductivity values according to the relation found in an earlier paper.[1] The illumination was practically constant throughout. A brief study of the table will verify the following generalization: *the increase of pressure increases the light sensibility (i. e., the change of conductivity due to constant illumination) only when the pressure is applied to the part of the crystal where the conductivity is being measured.*

From the results stated we are warranted in making the following deductions: If electrical conduction in these crystals is due to *free electrons that exist in equilibrium according to the Maxwell-Boltzman law, it can not be possible that the mechanical pressure in increasing the conductivity increases the number of free electrons.* This follows because the pressure effect is not transmitted from one part of the crystal to another and because the light-sensitiveness with varying pressure remains constant everywhere except at the points where the pressure is applied. There might, of course,

[1] PHYS. REV., Ser. 2, Vol. 4, p. 85, 1914.

TABLE II.

Conductivity of Lamellar Crystal, $\times 10^7$.

	Between Electrodes at (1).	Between Electrodes at (2).
In dark.....	4.0, 4.0, 4.0	4.8, 4.5, 5.0
End (1) illuminated.	7,8, 8.0, 8.0	6.9, 7.4, 7.7
Increase of conductivity.....	3.8, 4.0, 4.0 mean 3.9 div.	2.1, 2.9, 2.7 mean 2.6 div.
Pressure on (1) 3, kgm./cm². on (2) 2 kgm.		
Pressure increased by S_1.		
In dark.....	8.0, 8.8, 8.8	5.2, 5.3, 5.3
End (1) illuminated.	16.0, 16.6, 16.4	7.8, 7.8, 7.8
Increase.....	8.0, 7.8, 7.6 mean 7.8	2.6, 2.5, 2.5 mean 2.6
Pressure on (1) 6, on (2) 2 kgm./cm².		
Pressure increased by S_1.		
In dark.....	28.0, 31.6, 31.6	5.3, 5.3, 5.4
End (1) illuminated.	52.8, 52.6, 52.2	7.3, 7.5, 7.2
Increase.....	24.8, 21.0, 20.6 mean 22.1	2.0, 2.2, 1.8 mean 2.0
Pressure on (1) 18 kgm./cm²., on (2) kgm./cm².		
Pressure increased by S_2.		
In dark.....	20.0, 24.0, 26.0, 25.6	20.0, 20.0, 25.0, 25.0
End (1) illuminated.	40.0, 42.0, 48.0, 47.0	23.2, 30.3, 33.0, 34.5
Increase.....	20.0, 18.0, 22.0, 21.0 mean 20.2	3.2, 7.3, 8.0, 9.5 mean 7.0
Pressure on (1) 18 kgm./cm²., on (2) 6 kgm./cm².		
Pressure increased by S_2.		
In dark.....	25.4, 26.0, 26.4	68.9, 71.4, 74.0
End (1) illuminated.	48.8, 48.6, 47.0	81.3, 86.9, 88.5
Increase.....	23.4, 22.0, 20.6 mean 22.0	12.4, 15.5, 14.5 mean 14.5
Pressure on (1) 18 kgm./cm²., on (2) 13 kgm./cm².		

be a transmission of the pressure effect of secondary magnitude and importance which would not be detected except in more highly refined work. Then at least that part of the conduction that is brought about by increased pressures can not result from an increase in number of dynamically free electrons, and likewise that part of the increased conductivity that comes from a constant illumination as a result of increased pressure can not arise from free electrons at constant pressure everywhere within the crystal. Of course this argument requires that the increased pressure reacts against the fixed crystal structure and not against the free electrons. Now if the increased conductivity resulting from pressure on the crystal is not due to free electrons, it is difficult to justify conduc-

tion by free electrons at atmospheric pressure. The conclusion then seems unavoidable *that electrical conduction in crystals of metallic selenium can not be due to the traditional free electron.*

This conclusion need not be inconsistent with the result of Richardson and Brown[1] that the electrons inside a metal are free in the sense of the kinetic theory of gases, for our result was based upon work with highly conducting metals. Perhaps conduction in all non metals is like that in selenium crystals and dissimilar to that in the good conductors. It might be urged that the conductivity of selenium crystals is a function both of the number of free electrons and of a resisting medium through which they must pass. But this particular motion is inconsistent with the rapid transmission of the light-action along the crystal as was found.

The most satisfying unification of the experiments related that I have been able to conceive rests upon the hypothesis of conduction by electrons in semi-stable equilibrium. Scattered throughout the crystal structure are centers, perhaps atomic center, in which are associated charges of electricity in almost unstable equilibrium. Electrons free to move about in the structure as gas molecules move in enclosure do not exist. True these electrons are fixed in number and in position in the crystal structure, but the degree of their stability will vary with the agencies acting on the crystal. Electrical conduction consists essentially of a pulling out of these electrons from their moorings in the direction of the electrical stress. While out of position an electron might behave temporarily as a free electron in equilibrium with the heat and electrical forces about it. This process of conduction bears a little resemblance to the transfer of electricity in electrolytes.

The fact that Ohm's law does not hold for these crystals or metallic selenium generally is against the free electron hypothesis. The conductivity increases very greatly as the electrical forces in the line of conduction increase, until a saturation value of the conductivity is reached.

On this view increased pressure or tension on the selenium reduces the electrons to an average lower degree of stability. Thus a given fall of potential across the crystal will be able to dislocate a larger number of electrons from their fixed positions, or will be able to use them on an average a longer time before they recombine.

Similarly, light by some mechanism yet undiscovered lowers the degree of stability of the electrons throughout the crystal or further the mechanism controlled by light frees the most unstable electrons throughout the selenium. Thus as found if pressure is applied to any part of the crystal and any other part of the crystal is illuminated, that part of the

[1] Phil. Mag. (6), Vol. 16, p. 353, 1908, and Phil. Mag. (6), Vol. 18, p. 649, 1909.

crystal under pressure, and only that part, has its absolute light-sensitiveness increased. This merely means that at the place of great pressure the mechanism of light finds a greater number of electrons in such a low degree of stability that more of them can be kept in the free state.

It is still to be investigated how the light-action may be transmitted to a distance. It has occurred to the writer that it may be a change of crystalline structure, or an elastic vibration, or merely light diffusion.