IX. *The Action of Light on Selenium.*

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THIS paper contains an account of a series of experiments which have been carried on by the authors during the last year and a half, and which have had for their object the investigation of the electrical behaviour of selenium, especially as regards its sensitiveness to light.

Early in the year 1873 it was discovered by Mr. WILLOUGHBY SMITH that when an electrical current was passing through a bar of crystalline selenium, its resistance was less when the bar was exposed to the action of light than it was when the bar was kept in the dark.

Through the kindness of Mr. WILLOUGHBY SMITH we have been able to follow up his remarkable discovery with, among others, the same bar of selenium with which he made his original experiments.

The objects we have had especially in view have been:—

(1) To determine whether this change in the resistance of selenium is the direct result of radiations, and if so, whether the dark-heat rays, the luminous rays, or the chemically active rays produce the greatest changes.

(2) To compare the changes of resistance in the selenium due to exposure to light from different sources and also to light which has passed through various absorbing media.

(3) To determine whether the action is instantaneous or gradual, and to measure as far as possible the intensity of the action.

(4) To examine into the character of the electrical conductivity of selenium when kept in the dark.

(5) To determine whether light could actually generate an electrical current in the selenium.

Discussion of Results previously obtained by one of us, and communicated to the Royal Society (see Proc. Roy. Soc. nos. 163 & 166).

In all the earlier experiments we used the selenium plate belonging to Mr. WILLOUGHBY SMITH. It is a plate of the substance 5·4 centims. long, 1·2 centim. broad, and ·08 centim. thick. It has been very carefully annealed, so that it is in a very fair crystalline condition, and, for selenium, conducts electricity very well. Along each end of the plate are attached platinum wires forming electrodes, and those wires are connected with binding-screws fixed on a plate of ebonite. The whole is contained in an oblong wooden box 30 centims. long, which is furnished with a draw-lid. Through the end of this box, in which there are two small holes lined with ebonite, the binding-screws are connected by means of insulated copper wires with the set of resistance-coils which are used for measuring the resistance of the selenium.

A Wheatstone's-bridge arrangement was formed, in which the four sides were the selenium, a resistance-box from 1 to 10,000 ohms, a fixed resistance of 4 ohms, and a coil of 2000 ohms—the battery electrodes being connected to the junction of the selenium and resistance-box and to the junction of the two fixed resistances, and the galvanometer electrodes being connected to the other two junctions.

In the first series of experiments, the object of which was to determine the general character of the action, the method of procedure was as follows:—

The box containing the selenium was placed on its side, and, close in front of it, was placed a black screen with a rectangular aperture, $6 \times 3\frac{1}{2}$ centims., opposite the selenium. On the further side of this aperture was a ledge for supporting, when necessary, coloured glasses and other absorbing media. Beyond this was placed the light whose effect was to be examined. The resistance of the selenium was then balanced as nearly as possible, without, however, permitting the current to remain on for any length of time, since its prolonged passage rapidly increases the resistance; the lid of the box was then withdrawn, and the circuit was again completed, so that the exposure and the passage of the current went on simultaneously for, in general, about 15 seconds, after which the box was closed, and then the circuit interrupted.

The resistance of this plate of selenium increases with an increase of the atmospheric temperature; but in the dark, and at ordinary temperatures, its resistance is about $2\frac{1}{2}$ megohms.

When not exposed to the light the resistance of this bar of selenium begins to increase as soon as the electric circuit is completed, and continues to do so at a uniform rate, owing to the heating-effect of the current or to polarization. Although the heating-effect of the current must be small, yet the selenium is so sensitive to the slightest changes of temperature that this continuous increase of resistance may be due in part to the heating-effect of the current. On one occasion unintentionally the current from the battery was allowed to pass continuously for an hour and a half, and the resistance was found to increase continuously during the whole of that time. The rate of increase was the same as that observed when the current was allowed to pass only for a short time.

On exposure to light while the current is passing the resistance is diminished, but when the light is again eclipsed the resistance of the selenium returns in a very few minutes nearly to its previous value. This diminution of resistance is generally manifested by a strong "throw" of the galvanometer-needle towards the side of lessening resistance, followed by a more steady deflection in the same direction, which gradually attains a maximum. After this the heating and other effects of the current overbalance the action of the light, and the resistance henceforward increases steadily.

When first exposed, after being kept in the dark for some days or even hours, the selenium is much more sensitive to light than it is after repeated exposures, and hence the quantitative result obtained from the first of any series of experiments is generally not comparable with the others.

Exposure to the light of an ordinary wax taper at a distance of 20 centims. diminished the resistance of this plate of selenium by about one eighth part of the whole.

The light of an ordinary lucifer-match was found to have a powerful effect.

The diminution of resistance, when this plate of selenium was exposed to a powerful gas-light, was found in many cases to amount to from 10 to 25 per cent. of the whole resistance.

Effect of Moonlight on Selenium.

The effect of moonlight on the selenium was tried during the month of January 1875. An experiment was made first with the window open, so that the selenium was exposed to cold air as well as to moonlight, and the galvanometer-needle was deflected through 36 divisions of the scale in about two minutes, on the side indicating a diminution in the resistance of the selenium, amounting to about 18,000 ohms.

An experiment was afterwards made with the window shut, and a deflection of about 20 divisions of the scale was produced by the moonlight alone.

On another occasion when the moon was nearer full, but shining very obliquely through the window, exposure of the selenium to the moonlight produced a deflection of 150 divisions in three minutes, which was balanced by diminishing the variable resistance in the bridge by 120 ohms, showing that the resistance of the selenium was diminished by 60,000 ohms by the action of moonlight.

On another occasion, a plane mirror was placed inside a window, which was kept shut, and the moonlight was reflected upon the selenium or away from it at pleasure without approaching or in any way disturbing the selenium or its connexions. On reflecting the moonlight on to the selenium, the needle was deflected through 20 divisions of the scale very gradually; as soon as the mirror was turned away, the needle gradually fell back again. This experiment was repeated a great many times, and always with the same result. The moonlight was not bright enough to see the seconds-hand of a watch clearly. As the moonlight fell on the window at a very oblique angle, the mirror was now placed on a balcony outside the window so as to throw the reflected beam almost perpendicularly on the panes of glass (the window being kept shut during the exposures). The deflection of the needle now gradually rose to 40 divisions, and the resistance of the selenium was balanced and found to be diminished by 20,000 ohms.

On opening the window, the deflection rapidly rose on the same side to 110 divisions, and the resistance of the selenium bar was further diminished by about 57,500 ohms.

These experiments show that exposure to cold produces a change in the selenium in the same direction as exposure to moonlight or exposure to any other kind of light which has been as yet tried. They also show that the change produced in selenium by exposing it to rays of light is not due to the increase of temperature which would be caused in the selenium by those rays.

From these and a variety of other experiments which have been already described, and which point all in the same direction, we conclude that for a slight increase of temperature the resistance of the selenium is greatly increased, and for a slight lowering of temperature the resistance is greatly diminished.

The Use of a Selenium Bar as a Thermometer.

At the beginning of January 1875 there was severe frost and snow, which was followed by a sudden thaw on January 5th, when the temperature in the shade rose to 44° F. Previous to the thaw, in the room where the experiments were made, the resistance of the selenium was about 2·25 megohms; on the day of the thaw the resistance had increased to 2·7 megohms, the increase in the resistance of the selenium amounting to 450,000 ohms, or nearly one fifth of its total resistance. These results suggest that a piece of selenium kept in the dark and forming part of an electric circuit would form a very delicate thermometer, and that a very delicate differential thermometer may be formed with two similar pieces of selenium balanced against one another.

Exposure of Selenium to Radiations from the Bunsen Flame.

The effect of the ordinary non-luminous flame of a Bunsen burner was compared with that of the same flame rendered luminous by closing up the air-holes.

On exposing the selenium for several seconds to the non-luminous flame at a distance of 20 centims., only a very slight effect was observed, the deflection of the galvanometer-needle being represented by about 10 divisions of the scale; but on making the flame luminous, by closing the air-holes of the burner, the spot of light was deflected off the scale with great rapidity.

On testing for the amount of radiation from the Bunsen flame in its two states, by means of a thermopile and a galvanometer, it was found that the actual amount of heat radiated from the non-luminous flame was very nearly, but not quite, as great as that from the same flame when rendered luminous.

These experiments with the Bunsen burner were repeated in various ways, and it was always found that, while the hot non-luminous flame produced scarcely any perceptible effect, exposure to the same flame when rendered luminous produced a diminution of the resistance amounting in some cases to nearly one fourth of the whole resistance of the selenium.

In order to examine this point more fully, experiments were made with the electric light so as to determine what effect was produced by the obscure heat-rays. The selenium was placed at a distance of about 2 feet from the carbon points, and some medium which would absorb the luminous rays was placed in the path of the beam.

A plate of smoked rock-salt and a plate of alum were interposed together in the path of the beam, and, on exposing the selenium, no effect whatever was produced. This experiment was repeated several times with the same result.

The plate of smoked rock-salt was then used alone with the same result, namely, of depriving the beam of all power of affecting the selenium.

A solution of iodine in bisulphide of carbon, which appeared perfectly opaque to ordinary gaslight, was then placed in the track of the beam, and, after exposure for one minute, the diminution of resistance was represented by a deflection of 100 divisions on the galvanometer-scale. This appeared to contradict the results of the preceding experiments; but, on looking through the solution directly at the carbon points, some red light was seen.

The thickness of the solution was then increased, and it was noticed that the effect on the selenium was diminished in proportion as the solution became more and more opaque to the luminous rays.

Hence we may conclude that heat-rays do not act powerfully in reducing the electrical resistance of selenium.

The next point to be examined was as to how much of the effect produced on the electrical resistance of the selenium was due to the action of the chemical rays coming from the light to which it was exposed.

For this purpose pieces of glass of various colours and of different thicknesses were interposed between the source of light and the selenium, and it was found, as a general result, that the amount of diminution of resistance on exposure depended on the intensity of the illuminating power of the light falling upon the selenium, and not on the presence or absence of the chemically active rays.

In one series of experiments, when the source of light was a paraffin-lamp, the light was allowed, in the first experiment, to fall directly on to the selenium, and in the two subsequent ones it was sent through a ruby and an orange glass respectively in order to absorb the chemical rays—the result being that, with air alone, the diminution of resistance was 3·86 per cent., while with the ruby and the orange glasses it was 2·96 and 2·63, and with a thick piece of green glass ·7 per cent., the lessened effect being clearly due to the absorption of light by its passage through the glass.

On another occasion the light was first sent through air, and then through a solution of terchloride of phosphorus, and the consequent diminution of resistance was 700 ohms in the case of air and 650 ohms with the terchloride of phosphorus. Where water was substituted for the terchloride of phosphorus, the effect was almost exactly the same.

These experiments were repeated on several occasions, and the results obtained were in all cases similar to those we have just described.

The effects of exposure to various parts of the solar spectrum, and also of the spectrum of the electric light, were examined, and it was found that the action on the selenium was greatest in the greenish-yellow and in the red portions of the spectrum, the violet and the ultra-red rays producing very little, if any, effect.

Numerous experiments were made in order to compare the effects of exposure to light emanating from various sources. For this purpose a platinum spiral or a piece of platinum gauze, with the substance upon it whose light was to be tested, was inserted in the flame of the Bunsen burner, care being taken not to expose the selenium to the light and heat coming from the Bunsen burner itself and the lower part of the flame. Selenium, barium, thallium, sodium, salts of strontium, and sal ammoniac were thus employed, and the general character of the results obtained showed clearly that the effect on the selenium depended much more on the illuminating power of the light than on the source whence it was derived.

From the experiments already described we may fairly conclude that the luminous rays are the cause of this peculiar behaviour of selenium, and that the dark-heat rays and the chemically active rays have very little, if any, share in producing it.

The Change in the Resistance is exactly as the Square Root of the Illuminating Power.

It then became a matter of interest to know in what way the amount of change in the resistance of selenium depended upon the illuminating power of the light.

It was found that, on exposing this bar of selenium to a constant source of light at different distances, the change in its resistance, on exposure for 10 seconds (as measured by the deflection of the galvanometer-needle), was almost exactly inversely as the distance from the source of light, that is to say, directly as the square root of the illuminating power. This law was found to hold whether the source of light was 1 candle or an Argand lamp of an illuminating power equal to 16 candles.

Taking the mean of a number of experiments, all of which agreed pretty well together, the deflections at the several distances were:—

	At $\frac{1}{4}$ metre.	At $\frac{1}{2}$ metre.	At 1 metre.	At 2 metres.
With Argand lamp	...	170	83	39
,, candle	...	41	18	8
,, ,, ...	82	39	18	8

Another set of experiments with the candle and the Argand lamp, which in this case had an illuminating power equal to that of 12 candles, both being at the distance of 1 metre from the selenium, gave the following results:—

With the candle the deflection was . . 19 divisions in 10 seconds.
,, ,, Argand lamp the deflection was 66 ,, ,, ,,

In another series of experiments the distance of the selenium bar from the Argand burner remained unaltered, but the illuminating power was altered and at the same time measured by a Bunsen photometer:—

With 1 candle the deflection was			. . . .	90 divisions.
„ 4 candles	„	„	. . . .	180 „
„ 8 „	„	„	. . . .	250 „
„ 9 „	„	„	. . . .	270 „
„ 16 „	„	„	. . . .	380 „

These experiments clearly show that the change in the resistance of this bar of selenium varies directly as the square root of the illuminating power.

Diminution of Resistance with Increase of Battery-power.

At an early stage of these experiments it was found that, with the same piece of selenium and at the same temperature, the resistance diminished as the battery-power was increased. As an illustration, we may take the following observations made with Mr. W. SMITH's plate of selenium:—

Number of Leclanché cells.	Resistance of the plate.
5	2·7 megohms.
35	2·2 „
5	2·7 „
30	2·3 „

And after some hours we had with

30	2·4 „

and almost immediately afterwards with

5	2·9 „

It was also found that the electrical resistance of this plate was different for currents going through it in opposite directions: that is to say, that when the selenium plate was in the dark, and the positive direction of the current was from the electrode A to the electrode B, and its resistance was balanced by the Wheatstone-bridge arrangement in the usual manner, on reversing the current so that the positive direction was B to A through the selenium, the numerical value of the balancing resistance was always found to be different from that previously obtained. If the electrical conductivity of selenium followed the ordinary law of metallic conduction, this difference would not exist; and as it seemed probable that a careful investigation of these phenomena might afford some clue to the causes of the peculiar behaviour of selenium under certain conditions, we have of late been devoting especial attention to this branch of the inquiry.

Description and Mode of Preparation of new Specimens.

In the experiments hitherto described the original plate of selenium belonging to Mr. WILLOUGHBY SMITH had been exclusively employed; but as it now seemed desirable to make the inquiry more general, and not to limit it to the examination of the behaviour of one specimen only, several pieces of selenium were fitted with electrodes, and otherwise prepared for use. Each piece had a number attached to it, by which it was afterwards always distinguished, and by which it will always be referred to in the following descriptions of the experiments.

The usual method of preparing these pieces of selenium has been as follows:—A small piece, varying from a quarter of an inch to an inch in length, was broken off a stick of amorphous selenium. A platinum wire was then taken, and one end bent round into a small ring, and then this ring was turned up so that its plane was at right angles to the rest of the wire. The rings of two such wires were then heated in the flame of a spirit-lamp, and pressed into the ends of the little cylinder of selenium, to act as electrodes. The whole was then annealed in the manner described below. After annealing, copper wires were soldered on to the electrodes, and the selenium was inclosed in a piece of glass tube, and the electrode passed through corks fixed in the ends of the tube by means of sealing-wax. A label with a number was then attached to one end of the tube, and the electrode nearest to this number was then always described as the "*marked*" electrode.

A few pieces were also prepared according to the method adopted by Dr. W. SIEMENS. They were formed of two spirals of platinum wire laid upon a plate of talc in such a manner that they ran parallel without touching. Upon the plate a few drops of molten selenium were let fall, and then, before solidification, another plate of talc was pressed down, and the whole heated gently, so that the wires became firmly imbedded in the mass. The protruding ends of the platinum wires served as electrodes. These were soldered to silk-covered copper wires, which were passed through a cork, and the whole was then inserted in a test-tube. A thermometer was then inserted through the cork, so that its bulb was opposite to, but not in contact with, the selenium plate.

The plates, made up according to Dr. SIEMENS'S method, were annealed by placing the test-tube in a water or a paraffin bath, which was then kept for some hours at a high temperature, after which the selenium was cooled down very gradually.

The pieces made up according to the other method, and which, for the particular purposes of our inquiry, we have found to be the most convenient, were either annealed in a sand bath or in a hot-air bath. The former has been found to give the best results. The method of annealing is very simple. A large iron ball is heated to a bright red-heat in the fire and then placed in a large iron bowl filled with sand, which is heaped up all over the ball, and then left for an hour. The ball is then taken out and the pieces of selenium, wrapped up in paper, are put into the hot sand, and left there for twenty-four hours. On removing the selenium from the sand, its appearance is a sure indication whether or not the annealing has been successful; for, in the former case, the bright and glossy appearance of the amorphous selenium will have changed to a dull slate-coloured one, and when this is the case the conductivity of the specimen will, in general, be found to be very good.

In the remainder of this Paper the pieces of selenium used in each experiment will be referred to by their numbers, and, as it would not be desirable to have to describe each one of them whenever it is mentioned, we shall give here a brief account of the nature of each of the specimens which will be referred to hereafter.

Mr. WILLOUGHBY SMITH's plate, which will be referred to as W. S., has been already described.

No. 2 is a plate of selenium made up according to Dr. SIEMENS's method. It was first heated in a water bath up to 100° C., kept at that temperature for some hours, and then cooled slowly. After this its resistance at ordinary temperatures was about 120 megohms. At a subsequent period it was heated in a paraffin bath up to 205° C., kept at that temperature for 3 hours, and then cooled gradually. The next morning its resistance at a temperature of 9°·5 C. was ·402 of a megohm.

No. 3 is a plate exactly similar to No. 2, and its history is almost identically the same.

No. 4 is a plate similar in construction to Nos. 2 and 3. Its resistance before annealing was so great that we could not measure it. It was then placed in a paraffin bath, its electrodes being all the while connected with the usual arrangement for measuring its resistance. As the temperature rose its resistance gradually diminished until at 100° C. it was about 216 megohms. It was kept at this temperature for $2\frac{1}{2}$ hours; but this did not seem to have permanently affected it, as, on cooling it slowly, its resistance gradually increased again, so that at 55° C. it was 11·6 megohms, and when thoroughly cool its resistance was 120 megohms. The next day it was heated up to 140° C., kept at that temperature for 3 hours, and then gradually cooled; this had a permanent effect in reducing its resistance, which at a temperature of 9° C. is now about ·193 megohm.

No. 7 is a small plate of selenium whose platinum electrodes pass through corks at the end of a piece of glass tube. A length of about three millims. at the end of a piece of platinum wire was turned round at right angles, then two such pieces were laid upon a plate of talc, a drop of molten selenium let fall upon them, and then pressed down by another plate of talc. This plate was heated for 4 hours in a hot-air bath up to 110° C., and then cooled gradually. Its resistance at ordinary temperatures is now about ·585 of a megohm.

No. 8 is a plate made up at the same time and in the same way as No. 7. Its resistance at ordinary temperatures is about ·213 of a megohm. This plate had previously been raised to 210° C., but not cooled sufficiently slowly.

No. 10 is another plate prepared at the same time and in the same way as Nos. 7 & 8. The annealing was, however, not very successful in this case, its resistance at ordinary temperatures being about 3·2 megohms.

In making up the remaining 15 specimens no talc has been employed.

No. 11 is a small piece, about 4 millims. long, of a stick of selenium made up after the manner described on page 320. Its resistance at the ordinary temperature of the air is about ·0143 of a megohm.

No. 12 is a plate made up like Nos. 7, 8, & 10. It was annealed in hot sand. Its resistance at ordinary temperatures when measured with a battery of 20 Leclanché's cells is about ·375 of a megohm.

No. 14 is a piece similar to No. 11. Its resistance at ordinary temperatures is about ·390 of a megohm.

No. 15 is a piece very similar to No. 14, but it has evidently undergone the annealing process much better than No. 14, as its resistance at ordinary temperatures is about ·025 of a megohm.

No. 20 is a small piece of selenium stick, about 2 centims. long, made up like No. 11. It was annealed in hot sand, and its resistance at 14° C. is about 905 ohms.

No. 21 is a piece of the same wire, made of the same stick, and annealed with No. 20. That it did not take the annealing so effectually is clear from the fact that its resistance at 14° C. is about 120,000 ohms.

No. 22 was made up at the same time and in the same way as Nos. 20 & 21. The annealing was more successful than in the case of No. 21, its resistance at 14° C. being about 570 ohms.

No. 23 is a small piece of a selenium stick about 4 millims. long, fitted up like No. 11. It was annealed in hot sand, and its resistance at 14° C. is about 58 ohms.

No. 24 is a piece of the same wire, made up at the same time and in the same way as No. 23. Its resistance at 14° C. is about 55 ohms.

No. 25 is a piece just like Nos. 23 & 24. Its resistance at 14° C. is about 68 ohms.

The values of the resistances of the several pieces here given must only be taken as approximate ones, and are merely intended to show the general character of the resistance of each specimen. The resistance of any particular bar of selenium is so constantly altering, owing to the action of any currents that may be sent through it, that measurements of the resistance of the same piece, at the same temperature and with the same battery-power, made on two consecutive days, will hardly ever be found to give exactly the same results. As an example of this we will give the following Table of the resistances of most of the selenium plates mentioned in this paper, and which was compiled from observations made on the 8th and 9th of May. The battery-power was in all cases 2 Leclanché's cells, and the positive pole of the battery was always connected with the marked electrode of the tube.

TABLE OF RESISTANCES.

Number.	May 8.		May 9.			
	Temperature.	Resistance in ohms.	Temperature.	Resistance in ohms.	Temperature.	Resistance in ohms.
7	14° C.	1525000	0° C.	938750	15° C.	1700000
8	,,	612500	,,	405000	,,	670000
10	,,	7600000	,,	3225000	,,	5800000
11	,,	14900	,,	16570	,,	16500
14	,,	460000	,,	398000	,,	475000
15	,,	30600	,,	28270	,,	31300
20	,,	905	,,	1025	,,	1140
21	,,	120000	,,	115000	,,	123500
22	,,	570	,,	472	,,	411
23	,,	58	,,	63	,,	58
24	,,	55	,,	53	,,	77
25	,,	68	,,	55	,,	68

Definition of Direct or Positive Current as regards the Selenium.

When it was found that the resistance of the selenium varied with the direction of the current, it became very important to know what was the direction of the current in any particular case. We shall in future call those currents direct in which the positive electrode of the battery is connected with the marked electrode of the piece of selenium under examination. Such currents will be designated as positive or + currents, and those currents which go through the selenium in the opposite direction will be designated as negative or — currents.

Resistance altered by changing the Intensity or Direction of the Current.

The two phenomena of diminution of resistance with increased battery-power and change of resistance on reversing the direction of the current are closely connected and are both illustrated in the following experiments.

In order to be able to reverse the current with respect to the selenium without affecting any other portion of the circuit, the ends of the wire electrodes of the selenium were made to dip into two mercury-cups fixed on to a piece of ebonite, and these cups were connected with the binding-screws of the Wheatstone-bridge arrangement. Thus, by reversing the position of the electrodes, the direction of the current in the selenium was reversed. The positive direction of the current was always determined by means of a delicately suspended magnetic needle.

A few preliminary experiments were made in order to determine whether the change of resistance of the selenium with a change in the direction of the current depended in any way on the position of the selenium, or on the direction of the current, with respect to the magnetic meridian. No such connexion was found to exist.

Mr. WILLOUGHBY SMITH'S plate was then placed in a copper air bath, and its resistance was measured with direct and reverse currents, the temperature of the inclosure being observed each time. The battery-power was kept the same, being that of 10 Leclanché's cells in series.

Direction of current.	Resistance in megohms.	Temperature.
		° C.
+	4·650	11
−	3·600	11
−	3·800	16·5
+	4·825	17
−	4·275	20
+	5·314	20
−	4·620	21
+	5·533	21

In the next series of observations the battery-power was again kept constant, being that of 20 Leclanché's cells in series, and the temperature of the inclosure was varied.

Direction of current.	Resistance in megohms.	Temperature.
		° C.
+	4·61	10·3
−	3·66	"
+	8·05	30
−	7·90	"
−	7·58	25·8
+	7·72	"
+	7·54	23·5
−	7·20	"

In the next series the temperature was kept nearly constant, while the number of cells in the Leclanché's battery was varied.

Direction of current.	Resistance in megohms.	Temperature.	Number of cells.
		° C.	
+	4·105	10·5	20
−	3·280	"	
+	4·190	10·6	15
−	3·335	"	
+	4·330	10·8	10
−	3·410	"	
−	3·670	10·9	5
+	4·450	"	

In the next series the temperature of the enclosure was kept constant at 13° C., while the battery-power was varied. It was also thought advisable to take two pairs of observations for each change of battery-power, and to note the interval of time between every two observations.

Time in minutes.	Direction of current.	Resistance in megohms.	Number of cells.
0	+	4·15	2
4	—	3·40	
2	+	4·15	
2	—	3·40	
7	—	3·34	4
2	+	4·03	
2	—	3·34	
1	+	4·03	
5	+	3·99	6
4	—	3·29	
4	+	3·98	
3	—	3·29	
8	—	3·27	8
3	+	3·94	
4	—	3·27	
4	+	3·94	
7	+	3·90	10
5	—	3·24	
5	+	3·89	
6	—	3·24	
6	—	3·22	12
4	+	3·87	
2	—	3·22	
1	+	3·87	

A set of observations made with tube No. 10, the temperature being kept constant, while the battery-power was varied, gave the following results:—

Interval in minutes.	Direction of current.	Resistance in megohms.	Number of cells.
0	+	5·65	2
1	—	6·05	
6	—	5·87	4
2	+	5·25	
1^h 9	+	5·07	10
7	—	5·40	
2^h 0	—	4·92	18
4	+	4·43	
4	+	4·41	20
2	—	4·77	

Another and more complete set of observations made with No. 10, the temperature being constant, while the battery-power was varied, gave the following results:—

Interval in minutes.	Direction of current.	Resistance in megohms.	Number of cells.
0	−	5·50	4
2	+	5·00	
1	−	5·40	
2	+	4·90	
5	−	5·20	6
1	+	4·70	
1	−	5·15	
3	+	4·70	
6	+	4·80	8
2	−	5·13	
3	+	4·72	
2	−	5·13	
3	−	5·13	10
2	+	4·69	
1	−	5·03	
2	+	4·50	
3	+	4·62	12
1	−	4·95	
2	+	4·55	
1	−	4·91	
4	−	4·96	14
3	+	4·53	
2	−	4·93	
1	+	4·49	
4	+	4·53	16
1	−	4·90	
2	+	4·43	
3	−	4·77	
5	−	4·92	18
4	+	4·43	
1	−	4·81	
1	+	4·35	
2	+	4·41	20
2	−	4·77	
1	+	4·31	
1	−	4·74	

Another set of observations, No. 15 being the tube used, gave the following results:—

Interval between observations.	Direction of current.	Resistance in megohms.	Number of cells.
minutes.			
0	+	·03175	2
7	–	·03155	
5	+	·03191	
6	–	·03182	
8	+	·03080	3
5	–	·03035	
6	+	·03080	
8	–	·03036	
35	–	·02952	4
10	+	·03005	
9	–	·02954	
8	+	·03007	
8	+	·02932	5
7	–	·02885	
8	+	·02945	
9	–	·02900	
10	–	·02840	6
7	+	·02892	
6	–	·02852	
6	+	·02887	
9	+	·02832	7
6	–	·02809	
8	+	·02842	
7	–	·02805	
4	–	·03155	2
2	+	·03175	

A similar set of observations made with tube No. 14, but only taking two observations for each change of battery-power, gave the following results:—

Interval of the observations.	Direction of current.	Resistance in megohms.	Number of cells.
minutes.			
0	+	·5000	2
7	–	·4820	
6	–	·4770	4
7	+	·4795	
8	+	·4620	6
5	–	·4697	
5	–	·4630	8
3	+	·4560	
17	+	·4440	10
6	–	·4589	

In the second experiment with the battery of 6 cells the current was kept on for more than a minute, producing a considerable increase in the resistance; and the consequence of this was that afterwards all the resistances taken with the negative exceeded the corresponding ones taken with the positive current.

Conclusions.—From these experiments, made with different pieces of selenium, we may draw the following inferences:—

(1) That, on the whole, there is a general diminution of resistance as the battery-power is increased.

(2) That the first current sent through the selenium causes a more or less permanent "set" of the molecules, in consequence of which the passage of the current, during the remainder of the experiments, is more resisted in that direction than it is in the opposite one.

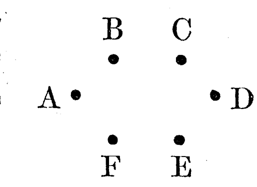
(3) That the passage of the current in any direction, at any period of the series of observations, produces a slight "set" of the molecules, which tends to facilitate the subsequent passage of a current in the opposite, but obstructs one in the same direction. Hence, when the current is sent through the selenium twice successively in the same direction, the resistance observed in the second case, even with the higher battery-power, is often equal to, or greater than, what it was in the first.

In some cases (for example, in the first of the series of observations with No. 10, see page 325) the first value of the resistance was less than one taken immediately afterwards with the current in the opposite direction. In these cases, however, it was always found, on referring to the laboratory notes, that a strong current, opposite in direction to that of the first one used, had been sent through the selenium, either a short time or sometimes as much as a day, previous to these experiments.

Polarization produced in the Selenium by the Current.

The experiments described above, and others of a similar character, seemed to indicate that the electrical conductivity of selenium is electrolytic. It was therefore important to discover whether, after the passage of an electrical current through a piece of selenium, any distinct characteristic of polarization could be detected. The existence of polarization may be considered to be established if, after the current from a voltaic battery has been passed for some time through the selenium, and then the electrodes have been disengaged from the battery and connected with a galvanometer, a current in the opposite direction to that of the battery is found to pass through the galvanometer.

In the following experiments a modification of the ordinary commutator was employed, which has answered exceedingly well and is very simple. It consists of six boxwood mercury-cups screwed into a plate of ebonite at the angles of a regular hexagon, A, B, C, D, E, F. Into the cups A and D are dipped the electrodes of the selenium bar to be tested. F and E contain the battery-electrodes, B and C the galvanometer-wires. These cups can then be connected in any way that is desirable by means of short pieces of thick copper wire. Various pieces were made and amalga-



mated at the ends, so that the change of connexions could be rapidly and easily effected.

On joining A F and D E, a simple circuit is formed through the battery and selenium; the wires A F and D E are then removed, A B and C D are joined, forming a simple circuit through the selenium and galvanometer.

The first experiment for polarization was performed with tube No. 14. The current from 20 Leclanché cells, in series, was sent through it for about a minute. The battery was then thrown out of circuit, and the selenium circuit completed through the galvanometer, when a deflection of 27 scale-divisions was obtained, indicating a current from the selenium in the opposite direction to that of the original one. On short-circuiting the selenium by means of a bit of thick copper wire across B C, the deflection of the needle at once came back to zero.

The battery-current was then sent through the selenium for about two minutes in the opposite direction to its previous one. On throwing the battery out of circuit and completing the galvanometer-circuit, a deflection of 15 scale-divisions on the other side of zero was obtained.

The next piece used was the W.S. plate. The current from 20 Leclanché cells was sent through it for two minutes, and this gave a polarization-current indicated by a galvanometric deflection of 47 scale-divisions to the right of zero. The selenium was then short-circuited, and in a few minutes all evidence of the polarization-current had disappeared. The battery-current was then put on for four minutes in the opposite direction, and this gave rise to a polarization-current represented by a deflection of 160 scale-divisions to the left of zero.

Another selenium plate, viz. that in tube No. 2, was then tried, and the same battery-current as before was sent through it for a short time. This gave rise to a distinct polarization-current, indicated by a deflection of 15 divisions to the left of zero. The same current was then sent for a considerable time through this plate in the opposite direction, and produced a polarization-current indicated by a deflection of 45 divisions to the right of zero.

That this is not due to a current arising from thermoelectric action in consequence of the junctions where the current enters and leaves the selenium being unequally heated is evident, since a current may be obtained from the selenium a considerable time after the battery-current has been interrupted, so long as the selenium electrodes have not been connected in the interval.

Here, then, we had distinct evidence of the existence of polarization when an electrical current was sent through the selenium; and it became an interesting matter to know what was the actual intensity of the currents which we were thus observing. This would be at once known if we knew the value of the current in absolute measure which, with a known electromotive force and through a known resistance, produced the unit deflection on the galvanometer-scale.

For this purpose a Daniell's cell was taken, and the porous cell was filled with a mixture of 1 part of sulphuric acid and 12 of water, the outer cell containing a saturated solution of sulphate of copper. This would give an electromotive force of ·978 volt. The resistance of this cell was very small, and that of the galvanometer with the 10th shunt about 650 ohms. The current from this cell was sent through the shunted galvanometer, and an additional interpolar resistance of 8·68 megohms, and produced a deflection of 57 scale-divisions. Hence, neglecting the resistance of the cell and of the shunted galvanometer as compared with the rest of the interpolar resistance, we have for the strength of the current in B. A. measure which, with the unshunted galvanometer, would produce the unit deflection

$$C=\frac{\cdot 978\times 10^{-1}}{57\times 8.68\times 10^{6}}=1\cdot 9767\times 10^{-10} \text{ of a B. A. unit of current.}$$

In future all currents will be expressed in scale-divisions of the unshunted galvanometer, and then, whenever it is necessary to find the value of any particular current in B. A. measure, all we have to do is to multiply the number of scale-divisions in the deflection produced by the current by the factor $1\cdot 9767\times 10^{-10}$.

A series of experiments on polarization were then undertaken with the W. S. plate.

A current of 37×10^{3} having passed through it for 10 minutes, gave a polarization-current of 45 in the opposite direction. After short-circuiting the selenium for a few minutes, no evidence of this polarization-current remained. It does not, however, follow that the original polarization was then dissipated, but that, owing to the great resistance of the circuit, the electromotive force due to the polarization, having become weakened, could no longer send any sensible current through the galvanometer. About a quarter of an hour afterwards a current of 33×10^{3} was sent for 10 minutes through the plate in the same direction as before, and the consequent polarization-current was 94 in the opposite direction.

Another series of experiments with the same plate gave the following results:—

Time.	Duration of passage.	Strength of current.	Polarization-current.
11.15 A.M.	5 minutes.	33×10^{3}	− 5
11.25 „	10 „	„	−12
11.43 „	15 „	„	−29

About an hour afterwards the current was sent through the same plate in the opposite direction, with the following results:—

Time.	Duration of passage.	Strength of current.	Polarization-current.
12.50 P.M.	5 minutes.	$24\cdot 5\times 10^{3}$	− 5·5
12.58 „	10 „	„	−13·5
1.11 „	15 „	„	−18

After the last of these experiments the electrodes of the plate were disconnected from the commutator and joined by a binding-screw, so as to allow the polarization-current gradually to subside.

On a subsequent occasion, when the current from 20 Leclanché cells had been sent through this same plate in the same direction for two successive intervals of 5 minutes, the consequent polarization-currents were —27 and —51 respectively.

A plate of selenium was next used which in outward appearance exactly resembles the last one, but which has evidently not been so well annealed, as its resistance is about 13·1 megohms. The current from the 20 Leclanché cells was sent through it for a short and also for a considerable interval of time, but no signs of a polarization-current could in either case be detected by the galvanometer.

The tubes numbered 3, 4, 8, and 12 were then tested in the same manner, with currents both of short and long duration from the battery of 20 Leclanché cells. They all showed polarization-currents, but only of feeble intensity, the deflection of the galvanometer-needle varying from 2 to 7 divisions on the scale. Though small, these currents were, however, quite distinct.

That all these currents were real polarization-currents was also evident from the fact that, on lifting any tube out of the commutator and replacing it with its electrodes reversed in the mercury-cups, the deflection was always on the opposite side of zero to what it had been previously.

The next piece used was that in tube No. 15, whose resistance is comparatively small, being about ·0247 of a megohm. The positive pole of the above battery having been connected with the marked end of the tube, the current was sent through it for five minutes, and gave rise to a polarization-current of —25. The same current was then sent through it in the same direction as before for 15 minutes, but at the end of that time the resulting polarization-current was only —11.

The next day the same tube was tried again, with the following results:—

Positive current from 20 cells for

5	minutes	in at the	marked end	gave	polarization-current of . . .	—12·5
10	,,	,,	,,	,,	,, . . .	—13·5
5	,,	,,	,,	,,	,, . . .	—10
10	,,	,,	unmarked end	,,	,, . . .	—15
10	,,	,,	,,	,,	,, . . .	—19

Tube No. 14 was then used, and the current from the above battery was sent through three times for 10 minutes at intervals of 15 minutes. The following observations were made:—

Strength of current.	Polarization-current.
250×10^3	—30
235×10^3	—25
236×10^3	—26

In the next set of experiments tube No. 11 was used. The resistance of this piece of selenium is small, being only ·0143 of a megohm. The current from 2 Leclanché cells was sent through it each time for a period of 5 minutes, and then the resulting polarization-current was measured:—

Interval between the experiments.	Polarization-current.
0	— 25
8 minutes	— 49
8 ,,	— 76
11 ,,	—112

This piece was then examined with a stronger battery-power, namely, that of 20 cells. The time during which the battery-current was kept on is indicated in the second column:—

Time when current was put on.	Duration.	Polarization-current.
1.32 P.M.	5 minutes	—550
2.5 ,,	3 ,,	—560
2.38 ,,	5 ,,	—450
2.49 ,,	10 ,,	—480

In these experiments the 10th shunt had to be used with the galvanometer, so as to keep the spot of light on the scale.

Exposure to Light alters the Strength of the Polarization-current.

All the results given by the above experiments were obtained while the selenium was kept in the dark.

In a few experiments of a similar character made with Nos. 11 and 2 an attempt was made to discover whether, on exposing the selenium to light during the passage of the *polarization-current*, any change in the intensity of that current would be produced.

In the case of No. 11, there appeared to be a slight increase in the intensity of the polarization-current during exposure, and a decrease in the intensity on shutting off the light.

An experiment with tube No. 2 showed this action rather more conclusively. A current represented by a deflection of 146×10^3 having been sent for 15 minutes through No. 2, gave a steady polarization-current of 9 divisions of the scale. On exposing the selenium to the light of the galvanometer-lamp, the deflection was at once increased to 14, and on screening off the light the deflection came back at once to 11.

The current from the 20-cell Leclanché's battery having been sent through No. 15 in the positive direction for about half a minute, gave a polarization-current indicated by a steady deflection of 25 scale-divisions to the left of zero. On exposing the selenium to the light of a candle at a distance of 6 inches, the spot of light came gradually down to zero and then moved up to the 150th division to the right of zero. On screening off the light the needle came back at once to zero, and on removing the screen it at once returned to the 150th division. The light was then held on either side of the plate, but this made no difference in the character of the action.

On screening off the light the deflection was at once reduced to its original value, and similarly the effect on exposing the selenium to light was almost instantaneous.

Here, then, seemed to be a case in which light actually produced an electromotive force within the selenium which was, in this case, opposed to and could overbalance the electromotive force due to the polarization.

Currents produced in Selenium by the action of Light.

The question of course at once presented itself as to whether it would be possible to start a current in the selenium merely by the action of light.

Accordingly, the next morning the same tube, No. 15, was placed on the commutator, and its electrodes were connected through the galvanometer. While unexposed there was no action whatever. On exposing the selenium to the light of a candle at a distance of about an inch from it, there was at once a deflection of 150 scale-divisions. On screening off the light the deflection came back at once to zero.

Hence it was clear that a current could be started in the selenium by the action of light alone.

We next made use of the original W.S. plate. The box containing it was closed, and the electrodes were placed in the cups A and D of the commutator. On completing the galvanometer-circuit there was no motion whatever of the needle. A lighted candle was then placed opposite the centre of the box, and on opening the lid the needle at once swung up and settled, so that the deflection was equal to 17 divisions of the scale. On closing the box the deflection was at once reduced to zero.

A small battery-current indicated by a reduced deflection of 35×10^2 was then sent through this plate for about half a minute, and produced a distinct polarization-current represented by a deflection of 2 divisions to the left of zero. The lid of the box was then opened, and the selenium exposed to the light of the candle. The deflection began immediately to diminish, went down to zero, and then moved up to and remained at the 10th division on the other side. On closing the box the deflection was at once reduced to zero.

The effect, on this plate, of exposure to the light of the candle at different distances was then tried, with the following results:—

I.		II.	
Distance of candle in inches.	Steady deflection.	Distance of candle in inches.	Steady deflection.
3	10	6	3·5
4	6	5	4·5
5	4	4	6
6	2	3	8

In all these experiments we found that on closing the box the deflection was almost instantly reduced to zero.

On another occasion, when the electrodes of the same piece were connected with the galvanometer, exposure to the light of burning magnesium ribbon produced a deflection of 90 divisions. The needle came back to zero as the light died away.

Tube No. 11 was then put in circuit with the galvanometer, and a gas-burner was placed at different distances from it. The selenium was then exposed, the deflection when steady of the galvanometer-needle noted, and then the light was screened off, when in all cases the deflection came back at once to zero. The results were as follows:—

Distance of burner.	Deflection.
9 inches	1
3 „	6
$1\frac{1}{2}$ „	14

These deflections were in the same direction whichever side or end of the selenium was exposed to the light.

On another occasion, with the same tube, exposure to the gas-flame at 8 inches distance produced a current of 4, while exposure to the light of burning magnesium ribbon at the same distance produced a current of 27.

No. 15 was then tried in the same manner with the light from a gas-burner placed at different distances.

Distance of light.	Deflection.
18 inches	11
13 „	20
7 „	64
3 „	225

The light from the burner was very variable, so that in the case of the higher deflections the needle oscillated a good deal. The above values were the mean deflections.

On another occasion, when No. 15 had its electrodes connected immediately with the galvanometer, exposure to the light of the gas-flame at a distance of 8 inches produced a deflection of 90 divisions, while exposure to the light of burning magnesium ribbon at the same distance produced a deflection of 85 with the 10th shunt in the galvanometer in the same direction as before. On again exposing to the gas-flame at the same distance, the deflection was equal to 72 divisions in the same direction. In each case the deflection came back at once to zero on screening off the light.

Action of Light on Selenium through which no Electric Current has passed.

All the pieces of selenium hitherto used had repeatedly been subjected to the action of currents passing through them, and it therefore seemed desirable to examine the effects of exposure on pieces through which no electrical current had previously been sent.

For this purpose six pieces of selenium (Nos. 20–25) inclusive (see page 322) were prepared, and carefully annealed in hot sand.

No. 20 was first connected with the galvanometer, and when screened from all light there was no deflection whatever of the needle. On exposing the selenium to the light of a candle no effect could be observed; but exposure to the light of burning magnesium ribbon produced a deflection of 3 divisions as long as the light lasted. Hence this piece is slightly sensitive to the action of light.

No. 21 was then examined in the same way, and, to cut off all the obscure heat-rays, a glass cell of water was interposed in the track of the light. Exposure to the light of a candle produced a sensible effect. The light of a gas-flame at a distance of 8 inches produced a steady deflection of 9 divisions, and the same light at $3\frac{1}{2}$ inches distance a deflection of 14. In all cases the deflection came back at once to zero on screening off the light.

In another experiment with No. 21, exposure to the gas-flame at a distance of $6\frac{1}{2}$ inches produced a current indicated by a deflection of 6 divisions to the right of zero. Exposure to the burning magnesium ribbon produced a strong "throw" of 40 divisions on the same side, the motion of the needle stopping at once on the light dying out.

The electrodes were then reversed in the mercury-cups, and exposure to the gas-flame produced a deflection of 5 to the left of zero, while the magnesium light produced a deflection of 56 to the left of zero. Hence it appears that, in the case of No. 21, on whichever side of the selenium the light falls, it causes a current in the same direction through the selenium.

No. 22 was then examined in a similar manner, but it seemed to be quite insensitive to the action of light.

Hence it appears that three pieces of the same length, which were made from the same rod of selenium, and which were annealed together, may, owing to some slight difference in their molecular condition, be very different as to their relative sensitiveness to the action of light.

Effect of illuminating one end only of a piece of Selenium.

In the preceding experiments the piece of selenium under examination was always exposed as a whole to the influence of the light, so that it was not possible to tell whether any one part of a piece was more sensitive than any other.

In order to examine into this point, the lime-light was used, and, by means of a lens, the light was brought to a focus on the particular portion of the selenium to be examined. A plate of glass an inch thick was interposed in the path of the beam, so as to assist in absorbing any obscure heat-rays.

Mr. W. SMITH'S plate was the first examined in this way. The light was brought to bear upon the end near the marked electrode. This gave a steady deflection of 40 divisions to the right of zero, indicating a current from the marked towards the unmarked end of the selenium. On screening off the light the galvanometer-needle came back at once to zero. This was repeated several times with the same result.

The light was then brought to bear upon the centre of the plate, and then upon the end remote from the marked electrode. In neither case could any current be detected. Hence this plate appears to have one sensitive end.

No. 10 was then examined in a similar manner, but without our being able to detect any perceptible current.

No. 11, when under examination in this way, gave the following results:—

The light was brought to bear upon the marked end, and gave a current of 6 to the left of zero, *i. e.* in a direction from the selenium to the platinum at the illuminated end. Now, if platinum stands above selenium in the thermoelectric scale, the current due to heating of the junction in this case would have been from platinum to selenium, or in the opposite direction to the observed one.

When the light was brought to bear on the centre we obtained a deflection of 25 divisions to the left of zero, and then a current in the opposite direction seemed to commence, which gradually sent the deflection down to zero and away to the right. On screening off the light there was always a *throw* of the needle to the right.

The poles were then reversed in the mercury-cups of the commutator, so as to enable us to bring the light to bear upon the other side of this piece of selenium.

The light was first directed on the end remote from the mark, and gave a current of 15 to the right, *i. e.* in a direction from the platinum to the selenium.

No. 7 was then examined in the same way. When the lime-light was directed on to one end of it we obtained a steady deflection of 7 to the right of zero, and when brought to bear upon the other end a steady deflection of 4 to the left. On screening off the light, the deflection in each case came back at once to zero.

Hence in the case of No. 7 the currents produced by light falling on the two ends are in opposite directions through the selenium, and pass from platinum to selenium at the illuminated end.

No. 25 comes next. This piece had been only recently annealed, and had never previously had a current through it.

The lime-light was brought to bear upon the marked end, and produced a current of 6 from the selenium towards the platinum. The electrodes were then reversed, and the light was directed on to the end remote from the mark, and produced a current of 11 from the selenium towards the platinum at the illuminated end. In both cases we found that on screening off the light the deflection came back at once to zero.

In another experiment when the light was rather more brilliant, the currents produced by directing on to the two ends were 25 to the left and 30 to the right respectively. The direction of the current in each case was from the selenium to platinum.

Another piece, No. 23, also a new one, and through which no current had ever been sent from a battery, was next examined, with the following results:—

The lime-light falling on the marked end gave a current of 9 from the selenium to the platinum at the illuminated end.

The light falling upon the other end gave a current of 16 from the selenium to the platinum at the illuminated end.

Light falling on the central portion gave a current of 22 from the unmarked towards the marked end; but as the incidence of the light was in this case oblique, we may further mention that it was from the less towards the more illuminated portion.

No. 24, also a new piece, gave the following results:—When the lime-light was directed upon the marked end, we obtained a current of 12 from selenium to platinum at the illuminated end.

When the light was made to fall upon the central part, it gave rise to a current of 6 in a direction from the unmarked towards the marked end.

The electrodes were then reversed in the mercury-cups so as to bring the other side of the metal under the action of the lime-light.

When the light was directed on the end remote from the mark, it produced a current of 42 towards the illuminated end.

In all these experiments we found that on interposing a screen in the track of the beam the deflection of the galvanometer-needle was at once reduced to zero.

In examining No. 21 with the lime-light the following results were obtained:—

When the light was directed into the marked end it produced a current of 75 from the selenium to the platinum at the illuminated end; and when the poles were reversed in the mercury-cups, and the light was directed on to the unmarked end, it produced a steady current of 21 from the selenium to the platinum at the illuminated end. When the light was directed on the central portion there was no perceptible current.

No. 14, which has been used both for *direction* and also for *polarization* experiments, was examined in the same way with the lime-light.

When the light was brought to bear upon one face, there was a current of 30 to the left of zero, and when, by means of a reflector and a lens, the light was directed on to the rear face of the selenium, there was a current of 100 in the same direction as before.

On examining No. 15, which is a piece of selenium which shows the phenomena of polarization very well, some powerful currents were developed by the action of the lime-light. Having noticed in some previous experiments (p. 334) that this piece was very sensitive to light, the 10th shunt was put into the galvanometer-circuit.

When the light was directed on to the unmarked end, a steady deflection of 60 was obtained with the shunted galvanometer, indicating a current from selenium to platinum at the illuminated end.

The light was then directed on to the central part, and the resulting current was 9 in the same direction as before. The poles were then reversed in the mercury-cups so as to enable the light to be thrown on to the other end of this piece of selenium.

When the light was thrown on the *central part* there was a current of 50 (with the shunt) in the same direction with respect to the selenium as in the previous experiments with this piece. When the light was thrown quite on the end the resulting current was much weaker, being only 10, but in the same direction as before, through the selenium. In all these experiments we found that on shutting off the light the deflection of the galvanometer-needle came back at once to zero.

Hence the exposure of any part of this piece to light causes a current in it from the marked to the unmarked end.

To these currents, which are due to the action of light, and which seem to differ in character from thermoelectric currents, it will be convenient to give the name of *photo-electric* currents.

Is it possible to balance a weak battery-current by the action of Light?

Knowing now that light can produce an electric current in a piece of selenium when no other current is passing or has ever passed through it, and that the apparent resistance of a plate of selenium is diminished when the selenium is exposed to the action of light, it is an interesting matter to examine what will be the effect on the apparent strength of a current which was passing through a piece of selenium in the dark when a beam of light was allowed to fall upon it.

Mr. W. SMITH's plate, enclosed in its box, was therefore put in circuit with the galvanometer, and the light of burning magnesium ribbon was found, on opening the box, to produce a deflection of 90, without any shunt. The lid of the box was then closed, and the current from one Leclanché's cell was sent through the plate, and while the current was passing, the lid of the box was opened and the selenium was exposed to the light of a gas-burner at a distance of $6\frac{1}{2}$ inches. The 10th shunt being in the galvanometer, the following were the observed results:—

Deflection due to current of 1 Leclanché's cell	156 to right.
ditto ditto and gas-flame	208 „

The poles of the selenium plate were then reversed in the mercury-cups without altering the actual position of the plate, and we then found that

Deflection due to current of 1 Leclanché's cell entering at the opposite end....	188 to right.
ditto ditto and gas-light	240 „

The battery-current was then turned off, and the light of the gas-flame at the same distance as before produced a deflection of 12 divisions to the left (without any shunt). These experiments were important, inasmuch as they lead us to notice the following points:—

(1) That the same light at the same distance produced in both cases the same increment of current, viz. 52 with the 10th shunt to the galvanometer.

(2) That in both cases the action of the light increased the strength of the current flowing through the selenium.

These experiments with the gas-flame and the current from one Leclanché's cell were repeated several times, and gave substantially the same results as before.

With the magnesium-light in the place of the gas-flame we obtained the following results, the 10th shunt being in the galvanometer:—

Deflection due to current of 1 Leclanché's cell			180 to right.
ditto	ditto	and magnesium-light	280 „
Current cut off and only magnesium-light on			11 to left.

In order to examine into this point more fully we made use of the lime-light. The current from one Leclanché's cell was sent through the selenium, from the marked end, and produced a deflection (with the 10th shunt) of 137. The lime-light was then focused on the end furthest from the marked end, and this sent the deflection up to 155. On screening off the light, the deflection was at once reduced to 150. Hence we see that though at this end (see p. 336) light produces by itself no sensible current, yet, when the battery-current is passing, it facilitates its passage.

The lime-light was then focused on the marked end, and the following results were obtained:—

Deflection due to the current of 1 Leclanché's cell			160 with 10th shunt.
ditto	ditto	and lime-light	185

When the light was focused on the central part, we obtained the following results:—

Deflection due to the current of 1 Leclanché's cell			171 with 10th shunt.
ditto	ditto	and lime-light	176 „ „

When the light falls on the central part, and there is no battery-current passing, there is no deflection.

Hence it appears that the action of the lime-light on any portion of this selenium plate tends to facilitate the passage of a battery-current through the plate, whatever be its direction, but that, when no battery-current is passing, the lime-light falling upon certain portions produces a small current of its own in one particular direction, viz. from the marked to the unmarked end of the selenium.

In order that the action of the photo-electric current might be comparable with the original current, it was evident that the original (or battery) current should be one of weak intensity, and also that the resistance of the circuit should be as small as possible. The tubes numbered 23, 24, and 25 were accordingly used, and a small thermopile was made use of to send a current through them.

In the first series of these experiments tube No. 25 was used.

The positive current entering the selenium at the marked end, gave a deflection on the unshunted galvanometer of 65 to the left. While this current was passing, the lime-light was focused on the marked end, and the deflection was at once reduced to 38 to the left of zero. On screening off the light the needle took a swing up to 72, and then remained steadily at 70.

The position of the battery-poles was then reversed in the mercury-cups so that the positive current should enter the selenium at the unmarked end. Before exposure, the deflection, due to the passage of the battery-current alone, was 50 to the right of zero. The lime-light was then focused on the marked end, *i. e.* the end where the current was leaving the selenium, and the resulting deflection due to the light and the current combined was 70 to the right.

In another experiment, with the electrodes in the same positions, the deflection when the selenium was not exposed, and when the battery-current alone was passing, was 35 to the right, and on focusing the light on the end where the current was leaving the selenium, the deflection was 52 to the right.

In all these cases, the action due to the light was almost instantaneous, and the deflection came back at once to its original value when the light was screened off.

In another experiment, when the positive current entered the selenium at the unmarked end, the deflection before exposure was 40 to the left of zero; and when the lime-light was focused on the same end, *i. e.* the end where the current was entering the selenium, the deflection was 20 to the left.

The battery-current was then cut off, and the same end being exposed to the action of the lime-light, a deflection of 20 to the right indicated a current of that intensity from the selenium to the platinum at the illuminated end, just as if there had been no original current.

The electrodes of No. 25 were then again reversed in the mercury-cups, so that the positive current from the battery should enter at the marked end. The deflection before exposure was 40 to the left. The light was then focused on the unmarked end, and the deflection was at once increased to 65 to the left, and back again to 42 on screening off the light. Repeating this experiment we had, before exposure, a deflection of 43 to the left, and on exposure a deflection of 70 to the left of zero.

The positive current was then sent in at the unmarked end, and produced a deflection of 30 to the right. The light being focused on the unmarked end, the deflection was reduced to 8 to the right of zero.

Tube No. 24 was next examined in the same way, with the following results:—

			Deflections.
(1) + Current entering at the marked end			50 to the left.
ditto	ditto	light on the marked end	45 „ „
(2) + Current entering at the unmarked end			40 to the right.
ditto	ditto	light on marked end	47 „ „
(3) + Current entering at the marked end			50 to the right.
ditto	ditto	light on unmarked end	60 „ „
(4) + Current in at the unmarked end			52 to the left.
ditto	ditto	light on unmarked end	44 „ „

These experiments were repeated several times with similar results, and point to the same conclusions as those made with No. 25.

Tube No. 23 was then examined in the same way, with the following results:—

	Deflections.
(1) + Current in at the marked end	55 to the left.
ditto ditto light on marked end	47 „ „
(2) + Current in at the unmarked end	56 to the right.
ditto ditto light on marked end	66 „ „
(3) + Current in at the marked end	62 to the right.
ditto ditto light on unmarked end	72 „ „
(4) + Current in at the unmarked end	56 to the left.
ditto ditto light on unmarked end	48 „ „

Hence the experiments with all three pieces point to the same conclusions, viz.:—

(1) That when light falls on the end of the selenium at which the positive current from the thermoelectric pile is entering, it *opposes* the passage of the current.

(2) That when light falls on the end of the selenium at which the positive current from the thermoelectric pile is leaving the selenium, it *assists* the passage of the current.

(3) That when no battery-current is passing, the action of light is to cause a flow of electricity from the selenium to the platinum at the illuminated junction.

We have been led to infer, from the experiments with those pieces of selenium through which no battery-current had ever been passed, that the currents thus produced in the selenium by the action of light are not thermoelectric currents due to the heating of the junctions between the platinum electrodes and the selenium, from the following considerations:—

(1) Assuming that platinum stands above selenium in the thermoelectric scale, the positive direction of the current, due to heating a junction of platinum and selenium, would be across the heated junction from the platinum to the selenium. Hence in all the above experiments the current, supposing it to have been a thermoelectric one, would always have been away from the illuminated end—that is to say, from the platinum to the selenium. In the above experiments, however, we find that, in general, the current is from the selenium to the platinum at the illuminated end, and, in those cases where this is not found to be the case, we have the current almost always in one direction with respect to the selenium, whichever end is illuminated.

(2) A thermoelectric current does not usually attain its maximum strength immediately, nor does it cease altogether immediately after the withdrawal of the source of heat. In these experiments we have invariably found that, on interposing a screen in the path of the beam of light, the current immediately ceased, and on withdrawing the screen, the current was at once renewed in its original strength. The phenomena noticed are exactly similar to those observed when a tangent-galvanometer and a galvanic cell are joined up by a key in simple circuit. On closing the circuit, the needle swings at once up to, and then oscillates about its ultimate position of rest, and stays there while the current is passing. On breaking the circuit, the needle at once returns, oscillates on either side of, and then stops at zero.

During these experiments we were frequently struck by the analogy of the two cases, and impressed with the idea that cutting off the light was, in point of fact, removing the electromotor of the current.

In these investigations we have seen:—

(1) That a slight increase of temperature of a piece of annealed selenium is accompanied by a large increase of electrical resistance.

(2) That on increasing the strength of the current through the selenium, there was a diminution in its resistance, which seems to be due to a kind of polarization which is similar in its effects to electrolytic polarization. This polarization seems to be a permanent effect, or at least to last for a long time, so long as the ends of the selenium are not short-circuited.

(3) On exposure to light while a battery-current is passing through it, the electrical resistance of a piece of annealed selenium is apparently diminished.

The experiments with the Bunsen flame, with weak sources of light, and with moonlight, seem to show that this effect is due to the illuminating-power rather than to the heating effect of the source.

(4) The apparent change in the electrical resistance is directly proportional to the square root of the illuminating-power of the light.

(5) After the battery-current is disconnected from the selenium, the strength of the current due to polarization is increased in most cases by exposure to light.

(6) Pieces of annealed selenium are, in general, sensitive to light; that is to say, that under the action of light a kind of electromotive force is developed among the molecules, which, under certain conditions, can produce an electric current through the selenium.

(7) This sensitiveness is different at different parts of the same piece of selenium.

(8) In most of the pieces which we have tested, the action of light, when there is no battery-current passing, causes a flow of electricity from the selenium to the platinum at the illuminated junction. To distinguish these currents from currents arising from any other cause, we have called them *photoelectric* currents.

APPENDIX.

Received May 17, 1877.

The place of Selenium in the Thermoelectric Scale.

In the above paper it has been assumed as a fact established by the researches of the late Dr. MATTHIESSEN (Proc. R. S. vol. ix. p. 99, 1857, and Phil. Trans. 1858) that platinum stands above selenium in the thermoelectric scale, and therefore that the direction of a thermoelectric current would be from platinum to selenium at the heated joint. It has been suggested that, considering the changes produced in selenium by the process of annealing, it would be well to try the thermoelectric properties of the several pieces used in the above experiments.

As many of these pieces are only 3 or 4 millims. in length, and as the ends of the platinum wires were melted into and buried in them, it is somewhat difficult on applying the heat to the junctions to know on which junction the heat is concentrated.

We have investigated the thermoelectric properties of sixteen of the twenty-five pieces of selenium on which we have hitherto experimented.

Effect of Exposure to Sunlight.

Mr. W. SMITH's plate of selenium, enclosed in its box, was joined up as part of a Wheatstone's bridge as in the first experiments in the paper, the battery being 10 Leclanché's cells, and was placed in such a position that, on withdrawing the lid of the box, the sunlight was brought to a focus by a powerful lens on one of the junctions of selenium and platinum (the marked end of the selenium). By altering the position of the box, the sunlight could be brought to a focus on any other point of the selenium plate.

First Experiment.—The current entered the selenium plate at the marked end, the resistance being balanced by the bridge; when the sunlight was brought to a focus on the marked end, a deflection was produced to the left, showing that the resistance of the selenium was diminished, *i. e.* that the light *assists* the passage of the battery-current from the platinum to the selenium at the marked end.

Second Experiment.—The current entering the selenium as before at the marked end, and therefore passing from selenium to platinum at the unmarked end; when the sunlight was brought to a focus on the unmarked end, a deflection was produced to the left, showing that the light *assists* the passage of the battery-current from selenium to platinum at the unmarked end.

Third Experiment.—The battery-current was reversed, so that it passed from platinum to selenium at the unmarked end; when the sunlight was brought to a focus on the unmarked end, a deflection was produced to the right, showing that the light *assists* the passage of the battery-current from platinum to selenium at the unmarked end.

Fourth Experiment.—With the same arrangement as in the third experiment, when the sunlight was brought to a focus on the marked end, a deflection was produced to the right, showing that the light *assists* the passage of the battery-current from selenium to platinum at the marked end.

In all four experiments, the light *assists* the passage of the battery-current whether it is passing from platinum to selenium or from selenium to platinum at the illuminated junction.

Next, to determine the effect produced by sunlight when there is no battery-current:—

Fifth Experiment.—The plate of selenium was joined up in simple circuit with a galvanometer only. When the sunlight was brought to a focus on the marked end, there was a deflection of 30 divisions to the left, showing that the light gave rise to a current of its own from platinum to selenium at the marked end. This current ceased when the light was removed.

Sixth Experiment.—When the sunlight was brought to a focus on the unmarked end, there was a deflection of 7 divisions to the right, showing that the light gave rise to a current from platinum to selenium at the unmarked end. Hence in this plate of selenium sunlight produces a current from platinum to selenium at the illuminated end, but the marked is much more sensitive than the unmarked end.

This agrees with previous experiments described in the paper, with the exception that the lime-light was not sufficiently powerful to give rise to a current when it was brought to a focus on the unmarked end.

It will be seen from the first four experiments just described, the results of which entirely agree with our previous investigations, that the action of sunlight on the selenium produces a very singular effect when a current from a battery is passing through it; in all cases it seems to assist the battery-current in whatever direction it is passing, so that the resistance of the selenium appears to be diminished; and yet, when there is no battery-current, sunlight causes a current from platinum to selenium at the junction on which it falls.

To Mr. WILLOUGHBY SMITH's plate, which is $1\frac{1}{2}$ inch in length, heat was applied by holding each of the junctions in turn between the finger and thumb, the connecting wires being attached to a galvanometer. When the marked end was heated, a current was produced from the platinum to the selenium at the heated junction. When the unmarked end was heated, less effect was produced, but the current was from the platinum to selenium at the heated junction.

The results of the experiments just described agree with the results of the investigations of Dr. MATTHIESSEN on the thermoelectric properties of selenium, which led him to place platinum above selenium in the thermoelectric scale.

For the smaller pieces the following method of heating the junctions was adopted. A glass tube about 1 centim. in diameter was drawn out to a very fine point, and a source of heat, usually one or more Bunsen burners, placed underneath it, the fine point being placed opposite to and directed towards the junction to be heated; a blast of air was then sent into the large end of the tube, which became heated by the tube, and issued as a hot blast at the fine point where it fell upon the junction of selenium and platinum or upon any required point. On applying this method of heating to Mr. WILLOUGHBY SMITH's plate at the marked end a current was produced from platinum to selenium, and on heating the unmarked end a current was produced from platinum to selenium at the unmarked end. Hence platinum stands above this piece of selenium in the thermoelectric scale.

Other specimens of selenium were then tried in the same way, and, where it was possible, heat was also applied by holding the junction of platinum and selenium between the finger and thumb.

In nearly all those pieces of selenium with which the investigations described in the early part of this paper were carried on, a current was found to be produced at the heated junction from platinum to selenium, showing that the changes through which they had passed in the process of annealing had not raised these pieces of selenium above platinum in the thermoelectric scale. Some of these pieces which gave no current or very little current when their junctions were exposed to the lime-light, gave stronger thermoelectric currents when their junctions were held between the finger and thumb. The pieces which stand below platinum in the thermoelectric scale are Mr. W. SMITH's plate, and Nos. 4, 7, 8, 10, & 14.

On examining No. 11, the current produced on warming the marked end by the finger gave a deflection of 15 divisions in the direction from selenium to platinum at the heated end. On warming the unmarked end by the finger there was a deflection of 110 divisions, indicating a current from selenium to platinum at the heated end.

On heating the marked end by the hot blast, there was a deflection of 55 divisions, indicating a current from selenium to platinum at the heated end; and on heating the unmarked end, there was a deflection of 115 divisions, indicating a current from selenium to platinum at the heated end.

The unmarked end of this piece is much more sensitive than the marked end.

On referring to the experiments with lime-light, it appears that the unmarked end was more sensitive to lime-light than the marked end, but that when the light was brought to a focus on the unmarked end, there was a current produced in a direction from platinum to selenium at the illuminated junction. Thus there seems in this case to be a difference in character between the action of the heat of the hand, or of the blast, and the action of the lime-light.

This is the first instance in which we have found that the process of annealing has placed selenium above platinum in the thermoelectric scale.

On referring to the paper, we see that after sending a current from a battery through this piece of selenium very strong polarization-currents were obtained from it, and that on exposure to light there was a slight increase in the intensity of the polarization-current.

No. 15 was the first piece from which a current was obtained by the action of light alone. It shows polarization-currents very well, and in it we first found that exposure to the light of a candle produced a current which was opposed to and greatly over-balanced the polarization-current. This piece is very singular in its action when its junctions are heated.

It will be convenient to call a current giving a deflection of 50 divisions of the scale a current of 50, and to denote platinum and selenium by P and S respectively.

On applying heat to one of the junctions by touching it with the hand, a current was produced from platinum to selenium at the heated junction. On warming the other junction in the same way, the current was reversed, so that, in both cases, at the heated junction the current passed from the platinum to selenium.

On repeating the experiment, with the marked end heated by the hand, there was at first a current giving a deflection of 120, or a current of 120, from P to S at the heated junction; this diminished to 50. When the hand was removed there was a deflection of 50 on the other side of zero, and the needle rested for some time at 10, showing a current from S to P at the end which had been heated. With the unmarked end heated by the hand there was at first a current of 90 from S to P, which was replaced by a current of 90 from P to S, while the finger was kept on the junction. On removing the finger the current diminished to 30 from P to S, and then very slowly back to zero.

Experiments were also made on this piece with the hot-air blast.

On heating the marked end there was a current of 100 from P to S; on continuing the blast the current diminished to 20 in the same direction, and then increased again.

On heating the unmarked end there was at first a current of 150 from S to P at the heated end, which diminished to zero, and then increased again on the same side to 50 while the blast lasted. On stopping the blast there was a current of 60 in the opposite direction, which rapidly fell to zero.

These experiments were repeated.

On heating the unmarked end there was, first, a current of 75 from S to P at the heated junction, and then a current of 60 from P to S while the hot blast lasted. The current rapidly fell to zero when the blast was removed. Figure 1 is intended to represent these changes, currents being measured by deflections to right and left, and time downwards.

Fig. 1.

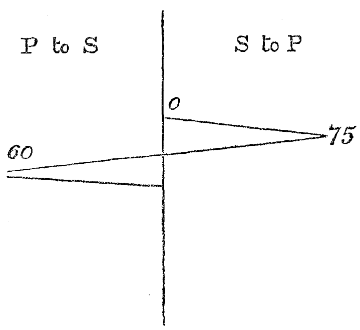
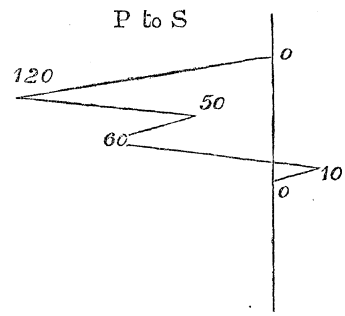


Fig. 2.



On heating the marked end we have the changes represented in fig. 2, the break denoting the stopping of the blast—a current of 120, which fell to 50 and then rose to 60 while the blast lasted. When the blast was removed there was a current of 10 in the opposite direction.

Fig. 3.

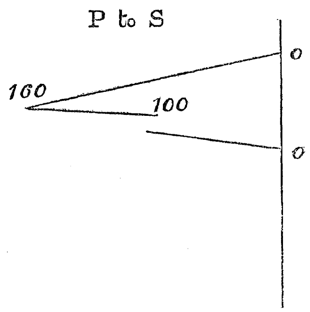


Fig. 4.

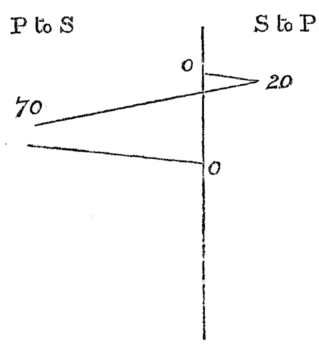


Fig. 3 represents another experiment, with the marked end heated; and fig. 4 an experiment with the unmarked end heated.

It appears from most of these experiments that on heating the marked end there is a current from P to S at that junction, and on heating the unmarked end there is a current from S to P at the heated junction. Hence, on heating the whole piece, it would appear that a continuous current is produced. The whole piece may be used as a thermoelectric pile, and would form a very delicate thermometer, since the exposure of either end of this piece to heat causes a current in it from the marked to the unmarked end. This agrees with the results of exposure to the lime-light, as recorded in the paper.

On referring to the experiments with lime-light (p. 337), we see that, when the light was brought to a focus on any part of this piece, there was a current in it from the marked to the unmarked end.

In one or two other pieces of selenium we have found that heat applied at one end produced a current from platinum to selenium, and heat applied at the other end produced a current from selenium to platinum; so that, on the whole being heated, there was a current from the first to the second end through the selenium.

The other pieces of selenium whose thermoelectric properties have been tested are Nos. 18, 20, 21, 22, 23, 24, and 25. At each junction of each of these pieces it was found that the application of heat gave rise to a current from selenium to platinum, so that the process of annealing had in these cases raised selenium from the bottom and placed it above platinum in the thermoelectric scale.

In most instances the currents due to heating the two ends did not differ much from one another. No. 21 is exceptional.

On warming with the hand the unmarked end there was a current of 10 only, whereas on applying the same source of heat to the marked end there was a current of 150. With the hot blast the values were 15 at the unmarked end and 65 at the marked end.

It seems to be pretty well established by these experiments that the more complete the process of annealing, the higher selenium is raised in the thermoelectric scale; and on referring to the Table of Resistances (p. 323), we see that the more the resistance of a piece of selenium is diminished the higher is it raised in the thermoelectric scale.

Thus all the earlier pieces, except Nos. 11 and 15, were of high resistance.

Nos. 11 and 15 are of smaller resistance, but appear to have been unequally annealed at the two ends, so that one end is above, or near, platinum, whilst the other is below platinum in the scale.

All the later specimens appear to have been well annealed at both ends, and are of very small resistance, except No. 21, which was of high resistance, and which appears to have been only partially annealed at one end at the time of the experiment.

It would seem from these experiments that the process of annealing raises selenium in the thermoelectric scale at the same time that it diminishes its electrical resistance.

Selenium changed in Character by the action of time.

Since these investigations were made in December last, the pieces of selenium have been placed in a box and laid aside, and no experiment was made with them until May 1877. On determining their resistances afresh, and repeating some of the experiments, we find that some of the pieces have changed very greatly, both in resistance and even in their position in the thermoelectric scale, through the action of time.

Those pieces which were at first not so completely annealed, and which were still of high resistance, appear to have become more completely annealed, and their resistance is very greatly diminished. This change seems to be accompanied by a rise of selenium in the thermoelectric scale.

In the following Table the resistances of several pieces, as determined in May 1876 and May 1877, are compared:—

Table of Resistances.

Number.	Resistance in ohms. May 1876.	Resistance in ohms. May 1877.
No. 7.	1525000	3950
„ 8.	612500	5000
„ 10.	7600000	745
„ 11.	14900	19000
„ 14.	460000	207000
„ 21.	120000	1123
„ 22.	570	272
„ 24.	55	60
„ 25.	68	28·5

Immediately after sending currents through these pieces, even from a single Leclanché cell, their resistances are usually increased and change very rapidly.

Those pieces (Nos. 7, 8, 10, and 14) which in December last were below platinum in the thermoelectric scale have risen higher in the scale.

No. 7.—On heating the marked end by contact with the finger there is a current of 240 from platinum to selenium at the marked or heated junction; but on heating the unmarked end there is a current of 200 from selenium to platinum at the unmarked or heated junction.

On heating the whole there was a current of 190 from the marked to the unmarked end.

No. 8.—On heating the unmarked end there is a strong current from platinum to selenium at the heated junction (the needle was deflected beyond the scale); on heating the marked end there was a current of 70 from selenium to platinum at the heated end. Repeating the two experiments with a shunt to the galvanometer, the deflections were 70 and 9 respectively.

No. 14.—This ranks with Nos. 7 and 8. On heating the marked end there is a current of 50 from platinum to selenium at heated end; and on heating unmarked end there is a current of 70 from selenium to platinum at the heated end. On heating the whole of the piece there was a current of 50 from the marked to the unmarked end. This piece has a resistance of 207,000 ohms for a direct current, and 195,000 ohms for a reverse current.

No. 10.—The resistance of this piece is now only one ten-thousandth part of its value a year ago, and its place in the thermoelectric scale is completely altered. Whether the heat be applied at the marked or at the unmarked end, there is a current of 90 from the selenium to platinum at the heated end. On heating the whole piece there is no effect.

Experiments have been made with Nos. 21, 22, and 24 to determine whether their resistance is diminished on exposure to light while a battery-current is being sent through them.

In all these pieces it was found that on exposing either end, or on exposing the whole to light the resistance was diminished; but in the case of No. 24 the resistance was diminished from 60 to 50 ohms, and then increased to 54 before the light was shut off; and on shutting off the light the resistance increased to 67 ohms.

No. 8.—After the last experiments with this piece, which have been described above, its resistance was found to be 5290 ohms.

The two balancing-resistances in the Wheatstone's bridge were equal, and each 100 ohms. On connecting the marked end to the positive pole of the battery, and exposing the marked end to the lime-light, the resistance was increased, the needle being deflected beyond the scale. On exposing the unmarked end the resistance was also increased, the needle being again deflected off the scale in the same direction. On exposing the whole piece to the lime-light, the resistance was also increased, and was found to be 6290 ohms on balancing with the bridge. On shutting off the light, the resistance at once began to diminish; it had diminished to 5790 ohms in about 1 minute, and remained for some time at about 5650 ohms.

On allowing the piece time to recover its former state, and then reversing the battery-current, the resistance was again increased by about 1000 ohms on exposing the whole piece to the action of the lime-light, and the resistance was also increased on exposing either end. On shutting off the light the resistance again rapidly diminished.

This piece in its present state is different in character from every other piece with which we have experimented, in that its electrical resistance is increased when it is exposed to the action of light during the passage of an electric current through it.