



LVII. Some electrical experiments with crystalline selenium

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LVII. *Some Electrical Experiments with Crystalline Selenium.*
By ROBERT SABINE*.

THE following experiments were undertaken with the view of removing, if possible, some of the difficulties which I had found in the way of constructing constant resistances of crystalline selenium.

For convenience, I propose to retain the order in which the experiments suggested themselves and were made, and shall therefore divide the following account of them into (1) the experiments with crystalline selenium in darkness, and (2) its behaviour in light.

The experiments were made with several specimens of selenium, some of which were provided, when in the amorphous state, with platinum wires. The process of annealing was done in an iron pot contained in an oil-bath, the temperature of which could be kept steady at any required degree. The selenium was made in the form of plates about 0.1 centim. thick, 0.5 to 1 centim. broad, and 2 to 3 centims. long, wires (when employed) being inserted transversely at equal distances apart. In some specimens, the wires were laid upon a small piece of mica or platinum-foil, and the melted selenium dropped upon them; in others the platinum wires were heated to incandescence in a smokeless flame, and, while still hot, were imbedded in the amorphous selenium. The two methods appeared to be capable of giving equally firm contact, which was probably due chiefly to the contraction of the selenium round the platinum wire.

* Communicated by the Author.

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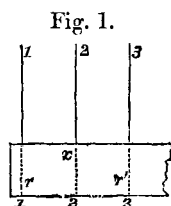
In preparing the selenium plates, care was taken to obtain as good a surface as possible. It was found that this might be effected by melting the amorphous selenium between edge strips of glass upon a piece of bright platinum foil, upon which it was annealed; the unequal contraction of the selenium and platinum prevented any adhesion after removal from the annealing-pot, whilst the selenium acquired a bright metallic surface.

Mercury Contacts.—It is necessary to discriminate between the resistance of the selenium and the resistance of the junctions. A plate of selenium was annealed at 200° C. with platinum end wires. Each end was then inserted in the side of a cup formed by a pill-box, where it was secured by means of shellac in such a way that mercury could be introduced into the cup to make connexion with the measuring-apparatus. Before the mercury was poured in, the resistance between the platinum wires was 124,300 ohms. After the cup at one end was filled with mercury, the resistance was found to be reduced to 82,300 ohms; and when the second cup was supplied with mercury, the resistance further diminished to 60,100 ohms.

In a subsequent experiment, a plate of selenium with platinum-wire connexions, having a resistance of 20 megohms, was found to have only 14 megohms resistance when the butt-ends were in contact with mercury. The resistances of some plates, however, were not greatly altered by this application of mercury connexions at the ends.

Resistance of Junctions, and want of homogeneity of the material.—The resistance of the junctions between the selenium and the platinum wires imbedded in it was found to be very various, but not to depend upon the manner in which the wires were imbedded in the selenium previous to its being crystallized. It was also found that the conducting-power of the selenium differed materially in different parts of the same plate.

Fig. 1 represents a plate of selenium with three platinum wires (1, 2, 3) imbedded transversely in it. The resistance of one of the wires was found as follows:—If x is the resistance of junction 2 under examination, r and r' the resistances of the neighbouring junctions plus whatever selenium may be between them and the wire 2, the measured resistances are:—



$$\left. \begin{array}{ll} \text{Between 1 and 2,} & R = r + x \\ \text{,, } 1 \text{ ,, } 3, & R_1 = r + r' \\ \text{,, } 2 \text{ ,, } 3, & R_2 = x + r' \end{array} \right\} x = \frac{R - R_1 + R_2}{2}.$$

The resistance of each of the wires (except the end ones) with which the plates of selenium were provided was approximately ascertained in this way; and, by deducting the resistances of the junctions, the resistance of the intervening selenium was also ascertained.

A plate of selenium was provided with four platinum wires 0·5 centim. apart, annealed at 170° C. The resistances were measured with + and - currents, and the means assumed to be sufficiently near for the purpose.

Between wires.	Measured resistances.
1 and 2	31 megohms.
2 „ 3	162 „
3 „ 4	11 „
1 „ 3	174 „
2 „ 4	172 „

From these measurements the separate calculated resistances are :—

Junction number.	Resistance of junction.	Resistance of selenium between junctions.
2	9·5 megohms	} 152 megohms.
3	0·5 megohm	

This is an instance of high selenium resistance in the middle and low resistance towards the ends in an otherwise apparently homogeneous plate, and of low junction resistances. The two junctions were made at the same time, in the same manner, by melting the selenium upon the wires; and yet one of them has nearly twenty times the resistance of the other.

A second plate of selenium, provided with six platinum wires and annealed at 150° C., was measured with + and - currents in the same way, mean values being taken. This gave the following results :—

Junction number.	Resistance of of junction.	Resistance of selenium between junctions.
2	429 megohms	} 22 megohms.
3	479 „	
4	498 „	} 13 „
5	428 „	

In this plate, therefore, nearly all the resistance was situated in the junctions, whilst the selenium offered a comparatively small resistance, its conducting-power being much greater at one end than at the other.

A third plate was provided with seven platinum wires 0·7 centim. apart, annealed at 205° C. It showed electrically more homogeneity of material and equality of junction resistances.

Junction number.	Resistance of junction.	Resistance of selenium between junctions.
2 . . .	·0333 megohm.	0·1914 megohm.
3 . . .	·0553 " }	0·1045 "
4 . . .	·0328 " }	0·1233 "
5 . . .	·0199 " }	0·1084 "
6 . . .	·0285 " }	

It is clear from these measurements that a large portion of the observed resistance of a so-called selenium resistance may, and frequently does, reside in the junctions and not in the selenium. Therefore the larger we make the surface of contact between the platinum and the selenium, the less likely are we to find an otherwise sensitive piece of selenium rendered comparatively insensitive by the introduction of high junction resistance. In this respect the form of selenium plate designed by Dr. Werner Siemens, in which the platinum wires form gratings or interlying spirals, is unquestionably the best form to employ when the object in view is to obtain a high sensitiveness to light.

Steady variations of Temperature.—The following experiment had for its object to ascertain whether the alteration of resistance accompanying a steady* variation of temperature is confined to the selenium or to the junctions, or is participated by both. The following data were obtained with a plate furnished with four platinum wires (Nos. 1 to 4), annealed at 200° C., measured in a Wheatstone-bridge with + current of 2 Daniell cells, after it had been at rest in the dark for several hours at each temperature.

Temp.	Measured resistance between wires.				
	1 and 2.	1 and 3.	2 and 3.	2 and 4.	3 and 4.
°	meg.	meg.	meg.	meg.	meg.
7·5 C.	·1641	·2691	·1446	·2429	·1521
15·5	·2168	·3565	·1905	·3201	·2003
21·0	·2343	·3865	·2068	·3473	·2225
32·2	·2739	·4549	·2429	·4092	·2577

The several resistances of junctions and selenium are therefore as follows :—

* Unsteady and sudden variations of temperature gave very anomalous results. One plate of selenium, the resistance of which *increased* with a steady increase of temperature, was found to *decrease* in resistance for a few seconds by a sudden application of heat.

Temp.	Resistance of		
	Junction 2.	Junction 3.	Selenium between 2 and 3.
°	megohm.	megohm.	megohm.
7.5 C.	·0198	·0269	·0979
15.5	·0254	·0354	·1298
21.0	·0273	·0410	·1385
32.2	·0309	·0457	·1663

It appears from this, that the resistances of junctions and selenium are both affected by variations of temperature in nearly an equal ratio.

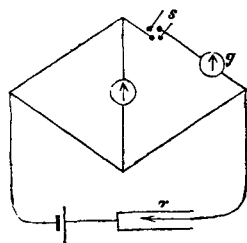
Resistance of Selenium altered by the inversion of the Current.

—The fact that the current strength in the circuit of a bar of selenium and a battery is subject to change when the direction of the current is reversed has been pointed out by Professor Adams and Mr. Day. I made an attempt to determine whether this change is due to electromotive force or to resistance, by carefully measuring the change on inversion while the current in the selenium was kept constant; but the total resistance of the circuit and the battery were increased in equal ratios. By this means the change, whatever it is, remains constant while all the other factors are different; and when the change is sufficient, there should be no difficulty in calculating it both as resistance and as electromotive force and discriminating between the two suppositions. Unfortunately, however, the majority of specimens of crystalline selenium did not alter sufficiently to afford definite evidence; and those recently prepared specimens which showed a considerable change, generally gave unsteady readings.

Seat of the Change.—The inquiry naturally occurs whether the seat of the change is in the selenium or at the junctions. To determine this, it is only necessary to ascertain the resistance of the junctions and of the selenium separately with two different battery powers to find which agrees best in the two measurements.

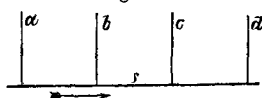
Fig. 2.

A plate of selenium was carefully measured between its four wires (marked *a*, *b*, *c*, and *d*) inserted in a Wheatstone bridge with an intervening commutator, so that the selenium could be inverted whilst the other members of the bridge remained unaltered. The side containing the selenium (*s*), fig. 2, was also furnished with a reflecting galvanometer



(g) of comparatively low resistance, by means of which the current moving in that side could, within a very small percentage of error, be observed. The battery-circuit was provided with a sliding resistance (r), by means of which, whichever section of the selenium plate was in circuit, the current in it, as indicated by galvanometer (g), could be kept at a constant value. In this way the following measurements were made:—In the first series the current-strength in the selenium was kept uniformly at 2·9 microwebers, and in the second at 0·42 microweber. The positions of the selenium are indicated as “direct” and “inverted”—“direct” when the current moved in the selenium as shown by the arrow (fig. 3), “inverted” when it moved the other way.

Fig. 3.



Resistance measured between	Current = 2·9 microw.		Current = 0·42 microw.	
	Direct. meg.	Inverted. meg.	Direct. meg.	Inverted. meg.
a and b	·3176	·3181	·3202	·3244
b „ c	·3864	·3858	·3936	·3893
c „ d	·2734	·2734	·2747	·2782
a „ c	·6095	·6097	·6116	·6116
b „ d	·4842	·4846	·4906	·4900

Call the resistance of the selenium between b and c $\left\{ \begin{smallmatrix} s \\ s' \end{smallmatrix} \right\}$ when the current is $\left\{ \begin{smallmatrix} \text{direct} \\ \text{inverted} \end{smallmatrix} \right\}$; the resistance of the junctions $\left\{ \begin{smallmatrix} b \text{ and } c \\ b' \text{ and } c' \end{smallmatrix} \right\}$ when the current is $\left\{ \begin{smallmatrix} \text{direct} \\ \text{inverted} \end{smallmatrix} \right\}$; the resistance from a up to the junction b $\left\{ \begin{smallmatrix} a \text{ direct} \\ a' \text{ inverted} \end{smallmatrix} \right\}$; and, lastly, the resistance from the junction c to the end d $\left\{ \begin{smallmatrix} d \text{ direct} \\ d' \text{ inverted} \end{smallmatrix} \right\}$.

It is evident that by measuring the resistance between each of the wires (a , b , c , and d), in turn, with two different current-strengths, we have data which enable us to calculate the mean resistances of the junctions as well as that of the selenium. If, with the two different current-strengths, the calculated values of the junctions agree, we may assume that the change resides in the selenium; on the other hand, if the selenium agrees in both calculations, the change must reside in the junctions.

The above tests furnish the following results:—

Resistance of	Measured.	Current = 2.9 microw. meg.	Current = 0.42 microw. meg.
$b + b'$	{ direct	·0945	·1022
	{ inverted	·0942	·1021
$c + c'$	{ direct	·1756	·1777
	{ inverted	·1746	·1775
$s + s'$	·5028	·5032

The agreement is in favour of the selenium, the mean resistance of which does not appear to change by decreasing the current-strength: the mean resistances of the junctions, however, increased, one of them considerably; and it is therefore probable that in them, and not in the selenium, lies the change in question.

Resistance altering with strength of Current.—Professor W. G. Adams has pointed out that when the battery-power is increased the apparent resistance of the selenium is diminished. In some of the specimens of selenium which I tested, I found that while the current was weak, up to a certain limit, the resistance *increased* in one direction and *decreased* in the other direction; but after passing the limit in question, the resistance *decreased* in both directions for any further increase of current.

One plate of selenium, annealed at 200° C., was kept at a constant temperature and measured in a Wheatstone bridge, the proportional resistances of which were respectively 1000 and 100,000 ohms. The selenium was inverted each time by a commutator, so that measurements were repeated in both directions, whilst the currents in the bridge-resistances always went in the same direction.

Current in selenium.	Measured resistance.	
	Current direct.	Current inverted.
microwebers.	megohm.	megohm.
2	·4107	·4093
4	·4119	·4080
6	·4128	·4072
8	·4131	·4063
10	·4133	·4056
12	·4133	·4050
14	·4133	·4047
20	·4130	·4038
30	·4126	·4023

A similar result was found with a second plate, the resist-

ance of which was smaller. The following are the observations:—

Current in selenium.	Measured resistance.	
	Current direct.	Current inverted.
microwebers.	ohms.	ohms.
0·6	40090	40130
3·0	40020	40300
6·0	39800	40400
9·0	39600	40440
14·4	39240	40450
21·6	38800	40370
50·4	37570	39790
72·0	36900	39350
108·0	36130	38720

In each case it was found that the resistance of the selenium had somewhat increased during the measurement, due probably to heat generated by the current.

The behaviour of the selenium in these experiments is open to one of two interpretations. If due to resistance, the alteration is possibly a consequence of the operation of the Peltier effect; if due to electromotive force, it is probably a simple consequence of electrolytic polarization.

When the current passes through the selenium, it encounters a compound conductor analogous to that in which Peltier observed the cooling and heating effects of the junctions between antimony and bismuth. The crystals round the point of contact which cools contract, and have a tendency therefore to recede and to make the contact with their neighbours still worse; the crystals about the heated contact expand and improve the conduction. The effects are opposite, but not necessarily equal, because one junction may be more susceptible than the other. It is of course questionable how far this heating and cooling of an uncertain number of points of bad contact between the crystals of a selenium plate near the electrode would be sufficient to produce a sensible effect. But it is necessary to bear in mind the nature of the doubtful contacts which we are probably dealing with, and which the smallest conceivable approach or recession may improve immensely or break entirely.

When the direction of the current in a compound conductor is reversed, the heat or cold produced at one of the junctions has to disappear, and the opposite effect to be developed, before the resulting change can be completely observed. It was found that when the bridge resistance was adjusted, in anti-

cipation of a changed (increased or decreased) resistance, before inverting the selenium, the galvanometer (introduced immediately after the inversion) showed a deflection always indicating that the resistance had not entirely changed but had still a value in the direction of that last measured; and it required two or three minutes to arrive at the settled value corresponding to the new conditions. This difference was small but distinct, and would be such as would correspond with change from heat to cold or *vice versa*.

On removing the battery and inserting a galvanometer, the discharge current which issues from the selenium is in the opposite direction to the battery current, and agrees with the thermoelectric current which would result from the Peltier effect.

On the other hand, the supposition that the behaviour is due to polarization is the more probable. The increase of the resistance with increasing current (when weak) in one direction, indicates the existence in the selenium of a small independent electromotive force, and leads to the suspicion that a portion of the material in contact with one of the platinum electrodes is in an electrolytic condition, or both perhaps, one being more so than the other. As the measuring current increases in strength, it appears to polarize the electrodes in the selenium, as in an ordinary electrolytic conductor, and the small independent current is overpowered and lost sight of. The apparent decrement of resistance by increasing the battery, is probably due to the fact that the polarization increases in a less ratio than the measuring current, so that when this current is weak the polarization is proportionally stronger, and the apparent resistance higher, than when the measuring current is strong. The discharge after removing the battery is such as would answer to the depolarization of an electrolyte.

Electromotive force of crystalline Selenium.—The action of light in modifying the conductivity of selenium is evidently a surface action, the effect of which penetrates very little, if at all, into the mass. It therefore occurred to me that the phenomenon could best be studied, particularly in relation to heat, by making up the selenium plate in the form of a galvanic element. By this means we can deal with the surface without reference to the interior, both as regards light and heat.

A plate of crystalline selenium was prepared at 200° C. with a platinum wire fused into it, by which it was suspended in a test-tube. The back of the plate and the platinum wire near it were covered with a black insulating varnish. The tube was then placed in a light-tight box, in which a shutter could

be opened to admit light to the uncovered face of the selenium. A pole of platinum foil was placed in the tube, and distilled water sufficient to nearly cover the selenium plate. This selenium (galvanic) element, when in the dark, gave an electromotive force of 0.112 volt, the selenium being positive to the platinum. On admitting diffused daylight, the direction of the current was changed, the selenium becoming negative to the platinum, with an electromotive force of 0.056 volt; so that by the admission of diffused daylight the selenium surface had become very much less electropositive than it was in the dark.

Two similar plates of selenium were prepared and placed side by side in a suitable cell, which was enclosed in a light-tight case with two shutters, by means of which light could be admitted to one or the other of the plates at pleasure. Distilled water being poured into the bottom of the cell, so as to reach about three fourths up each plate, the electromotive force between them was measured with an accumulator, discharge-key, and galvanometer.

Both plates in the dark gave a very slight current. Then light was admitted by one of the shutters being opened. The plate on which the light fell instantly became electronegative. The consecutive readings were :—

—0.05 volt
—0.04 „
—0.03 „

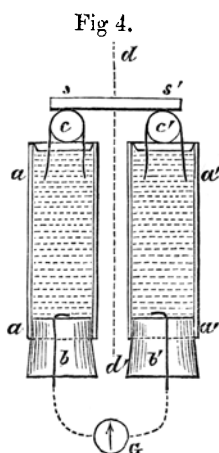
Then that shutter was closed and, after a few minutes, the other opened. The readings were now :—

+0.09 volt
+0.08 „
+0.07 „

On connecting a galvanometer direct between the poles and observing the deflection, it was found that the current immediately following each reversal was higher, and that it subsided to a lower reading in a short time. This is probably due to polarization of the plates, and is exactly what might be expected.

Action of Light and Heat the same.—The next experiment was to ascertain if the effect of light upon the surface is the same or the reverse of that of heat. Two short lengths of glass tube, $a\ a$ and $a'\ a'$, fig. 4, were stopped at the lower ends with corks, b and b' , through which strips of platinum foil were passed. Across the tops of the vertical tubes

(which were nearly filled with distilled water) two smaller horizontal glass tubes, c and c' , were fixed, over each of which a small saddle of white blotting-paper, intended to act as a conducting pad, was laid. The ends of the blotting-paper dipped into the water, and formed the connexion with a plate of crystalline selenium, $s s'$, which rested on the top. The circuit was completed by inserting a galvanometer (G) between the strips of platinum foil. The whole was mounted in a light-tight case with a diaphragm, $d d'$, so that light could be excluded from or admitted to either side at pleasure. When light was admitted to one side, it had of course to reach the contact surface of the selenium, after passing through the glass, the water, and the blotting-paper pad. It was therefore diffused and much weaker than had it fallen directly upon the face of the selenium as in the previous experiments. The indications were therefore less in amount, but nevertheless perfectly distinct.



Next, instead of admitting light to the selenium plate, both of the tubes were kept dark, and warm water was passed through either c or c' , so that the wet blotting-paper pad upon it, and therefore the contact face of the selenium and water, was slightly warmed. A current was immediately observed. When this current had subsided, warm water was passed through the other tube, and the new deflection noted.

Now in both these tests it is evident that we are dealing, in respect of light and heat, with the *surface* of the selenium only, and have therefore eliminated any effects due to the molecular condition of the interior.

Lastly, the plate of selenium was removed, and a small bar of copper and zinc, soldered together in the middle, was laid across the pads, for the purpose of determining the direction in which heat and light had acted in modifying the electro-positiveness of the selenium. The following are the results:—

	End c .	End c' .	Deflection.
(1)	illuminated	dark	— 200 div.
(2)	warmed	cold	— 160 „
(3)	copper	zinc	— off scale.
(4)	dark	illuminated	+ 50 div.
(5)	cold	warmed	+ 80 „
(6)	zinc	copper	+ off scale.

Therefore the effects of light and heat upon the surface of crystalline selenium are identical. Both heat and light render the contact-surface between crystalline selenium and water more electronegative; and therefore we may surmise (although the experiment does not amount to a proof) that the surface does not become more metallic, as has been assumed as accounting for the higher conductivity of selenium in the light.

It is worthy of remark, that the end which was the more sensitive to light was also more thermoelectric. The difference may be due to inequality in the selenium plate, one end being better annealed than the other; and it indicates still further the similar behaviour of heat and light in this experiment.

Effect of Light on Conductivity.—The object of the following experiments was to determine whether the effect of light upon a plate of selenium when in a galvanic circuit, in increasing the current, is due to a photo-electromotive force in the same direction as the battery current, or to a decrement of resistance.

Let the resistance between the wires of the selenium plate in the dark and of the galvanometer be r , the electromotive force of the measuring battery be E , and the observed current c . On admitting light the current increases to c' , and one of two things must have happened. Either (1) the increment of current is due to a decrement (x) of resistance, in which case

$$c = \frac{E}{r} \text{ has changed to } c' = \frac{E}{r-x},$$

$$x = E \frac{c' - c}{cc'}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (I.)$$

or (2) the increment of current is due to a photo-electromotive force (y) in the selenium, in which case

$$c = \frac{E}{r} \text{ has changed to } c' = \frac{E+y}{r},$$

$$y = E \frac{c' - c}{c}. \quad . \quad . \quad . \quad . \quad . \quad . \quad (II.)$$

With a single measurement it is, of course, impossible to discriminate between the two cases; but by a known augmentation of battery and of resistance, it is easy to find which supposition affords the better agreement.

I increased E to $2E$, and inserted a known resistance (r_1) as nearly equal to r as I could make it. The resulting current, when the selenium was in the dark, was c_1 ; and it increased to c_2 when subjected to the same source of light as

It appears from the above, that the agreement between the calculated values representing the change, on the supposition that it is due to a decrement of resistance, is much greater than that between the values calculated on the supposition that it is due to an electromotive force set up in the selenium in the same direction as the battery current.

There is much experimental work to be done yet with selenium before any theory of its behaviour can be advanced with confidence. So far, the experiments seem to suggest the suspicion that light causes a modification of the surface tension of selenium, possibly an expansion of the crystalline surface. The superficial crystals expanding and pushing against each other, so as to improve the doubtful points of contact previously existing between them, may account for the observed increase of conductivity in the light. Such a superficial expansion would probably be occasioned by heat; and this heat on the extreme surface might account for the alteration, by light, of the potential of the selenium plate, when made up in the form of a galvanic cell, being in the same direction as the alteration of potential produced by the direct application of heat when the selenium is in the dark. It might also account for the decreasing sensibility of the selenium by continued exposure to light, the superficial heat penetrating into the interior and relieving the state of tension of the surface.

I apprehend that the superficial atoms of any body, which are bounded on one side only by similar atoms, and on the other side by the medium in which the body is immersed, may be capable of assuming vibrations of different periods to those which the atoms underneath the surface can assume. It may also be that the luminous rays striking upon the superficial molecules of selenium, impart a vibration to them of a slower period than those of the exciting waves, and which corresponds nearer to the period of the heat rays.

To return, however, to the object with which this inquiry was undertaken, viz. the production of constant resistances for measuring-purposes, it is evident that selenium is, from its peculiar nature, a very unsuitable material. In its amorphous state it is dielectric; and in its imperfectly crystalline state its character seems to be that of a dielectric more or less charged with conducting crystals.

This character it probably never entirely loses, even when crystallized as far as it can be; and to this fact is probably due, in a great measure, its peculiar behaviour.

In the light it would of course be utterly useless for measuring-purposes, whilst in the dark the apparent resistance of its junctions with the conducting wires changes, not

only with the direction of the current, but likewise with its strength, and to some extent also with its duration. To construct a selenium resistance for exact measuring-purposes, coefficients for all these changes would have to be determined, at very considerable trouble; and when determined, the inconstancy of the material is such that they would probably soon be altogether inapplicable.

In preparing the apparatus and making the experiments, I have been greatly indebted to the efficient aid rendered me by Mr. McEniry.

Grosmont House, Hampton Wick,
May 1, 1878.

LVIII. *On the Edge-angle and Spread of Liquids on Solid Bodies.* By G. QUINCKE.

[Concluded from p. 339.]

10. **SPREAD** of Liquids upon the Surface of Solid Bodies.

—It is possible to form an opinion in another manner than by direct measurements, about the magnitude of the surface-tension at the boundary of a fluid and of a solid body, from the magnitude of the edge-angle which a fluid-surface forms with a solid body.

From equation (5) follows at once

$$\alpha_{21} > \alpha_{13},$$

if the edge-angle θ of the common bounding-surface of the fluids 2 and 3 with the solid body 1 is an acute angle for fluid 3.

For glass as the solid body, and water as fluid 3, and for bisulphide of carbon, chloroform, olive-oil, turpentine, petroleum, or mercury as fluid 2, this condition is fulfilled with the slight allowances already explained* for impurity of the solid surface of glass.

The water will therefore have a greater adhesion to glass than the fluids named.

Whenever free fluid-surfaces bounded by air are absent, none of the fluids 2 investigated drives the water away from the glass surface, however different in magnitude may be their capillary constants. The edge-angle was only in rare cases 0° ; consequently the water also usually did not drive the other fluids from the glass surface.

* Compare the researches upon flat drops and bubbles, Pogg. *Ann.* cxxxix. pp. 18-20, 22 (1870); upon submerged capillary tubes, *ibid.* pp. 42-44; upon the ascent in capillary tubes of several superposed fluids, *ibid.* pp. 50-52. And in Phil. Mag. April, May, and June, 1871.