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XXXVIII. *Notes on the Construction of the Photophone.*

By Professor SILVANUS P. THOMPSON*.

(1) **I**N the selenium photophone, light of varying intensity is received upon a prepared surface of sensitive crystalline selenium, the electric resistance of which it thereby changes. In the construction of the receiving "cell" it is obvious that certain relations must hold between the dimensions of the sensitive surface and the degree in which a given quantity of light will change the electric resistance—relations which ought to be observed in the construction of the instrument, and which are certainly worthy of investigation.

Professor Bell's typical selenium-cell consists of a small cylinder about 2 inches in diameter and $2\frac{1}{2}$ inches in length (giving at most a superficial area of 15·8 square inches available), built up of alternate disks of brass and mica, filled between the edges of the brass disks with selenium, and having alternate brass disks connected up in multiple arc. This cell, in his usual apparatus, is placed at the bottom of a parabolic mirror.

Certain experimental observations made in attempting to repeat Prof. Bell's experiments led the writer to query whether this arrangement was the best possible one, and suggested an investigation, of which the following paragraphs are the chief points.

(2) **THEOREM I.**—*With a given maximum of incident light distributed uniformly over the surface, the change of electric resistance in a selenium-cell will vary proportionally with its linear dimensions, provided its parts be arranged so that on whatever scale constructed the normal resistance shall remain the same.*

Suppose there to be a cell of a certain size, having a certain normal resistance (*i. e.* a certain resistance in the dark as measured under a standard electromotive force), and presenting a certain area of surface; then, if a perfectly similar cell be made on a scale n times as great (in linear measure each way), the same total amount of light falling upon its surface will produce n times as great a variation in the electric resistance.

The proof of this theorem depends upon the law discovered by Professor W. G. Adams †—namely, that *the change in the resistance of selenium is directly as the square root of the illuminating-power.*

* Communicated by the Physical Society, having been read at the Meeting on January 22.

† Proc. Roy. Soc. vol. xxv. 1876, p. 113.

For let it be supposed (as in the proviso of the theorem, introduced so as not to complicate the electrical conditions) that the enlargement should be to the scale $n : 1$ in all respects, save only in the depth of the selenium film, the brass conductors being the same in number as before, but of n times their former size, touching selenium along edges n times as long as before, the intervening selenium films being n times as broad as before. Such an enlargement will leave the normal electric resistance where it was before, provided the depth of the selenium films be not increased—though, as the photo-electric action is almost entirely a surface action, a slight increase in the depth of the film would probably produce no great change in its electric sensitiveness.

Suppose the light to be caused, by appropriate optic means, to fall upon the whole enlarged surface uniformly. The linear dimensions being increased in the ratio $n : 1$, the area will be increased as $n^2 : 1$. The average intensity of the illumination will now be $\frac{1}{n^2}$ of what it was. Each portion of surface equal to the original surface will receive but $\frac{1}{n^2}$ part of the whole light.

But by Adams's law the change of electric resistance is proportional to the square root of the illumination. Hence the electric effect over each portion of surface equal to the original surface will be $\frac{1}{n}$ of the original electric effect; and, since the effect is proportional also to the amount of surface which is under illumination, this quantity $\frac{1}{n}$ multiplied into the ratio of the enlarged surface to the former surface ($n^2 : 1$), gives for the total electric sensitiveness of the enlarged cell a value n times as great as that of the original cell. Thus the proposition is proved.

(3) THEOREM II.—*With a given maximum of incident light the change of electric resistance will vary in proportion to the third power of the linear dimensions of the cell, if, while its linear dimensions are increased, the absolute thicknesses of the brass conductors and of the selenium films remain the same as before, and their number be proportionately increased.*

It was supposed above that the surface was increased n times by an enlargement in length and breadth, which left the total normal resistance where it was before. But since the breadth of the films is dictated solely by practical considerations of construction, the increase of linear width to n times will en-

able n times as many conductors to be employed; and the thickness of the selenium film may be reduced to $\frac{1}{n}$ of what it was reckoned above. This will reduce the total normal resistance of the cell to $\frac{1}{n^2}$ of what it was reckoned above, and would therefore make it n^2 times as sensitive were its resistance the only one in the circuit.

Combining this result with the former, we obtain the result that the change of electric resistance exhibited by the cell of linear dimensions n , under the influence of a given quantity of light distributed uniformly over its surface, will be n^3 times as great as that exhibited by a cell of linear dimensions 1, provided that the absolute thickness of the films and conductors remain the same (the resistance of the brass conductors themselves being reckoned small).

(4) The practical inference from this is, that the selenium-cells should be made as large as possible, and that the beam of light received by the mirror from the distant station should be so constructed as not to concentrate the light on one point of the selenium, but to distribute it uniformly over the sensitive surface.

Now the supposed advantage of the parabolic mirrors hitherto employed is that they collect parallel rays to one focus. If this be no longer necessary or advisable, then some other form of mirror than that of the paraboloid of revolution ought to be employed.

(5) A short cone, polished on the interior surface, appears therefore to offer certain advantages over the paraboloid in respect of its distribution of light, besides being far cheaper to construct. It only remains to calculate the appropriate angle of aperture that shall, with a cylindrical selenium-cell of given length, give the greatest available linear aperture and reflect into the cell the greatest number of effective rays.

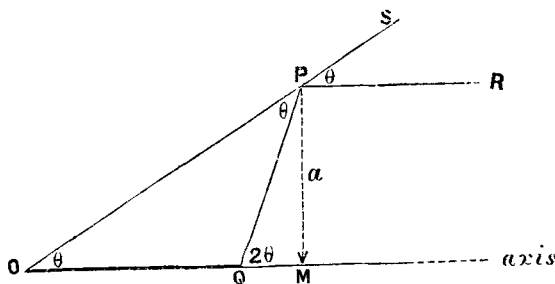
(6) THEOREM III. *A hollow cone along whose axis lies a cylindrical selenium-cell of given length will reflect onto that cylindrical surface the greatest number of rays (that traverse space parallel to the axis) if its angular semi-aperture be 45° .*

The calculation amounts to finding the angle that will, with a given length of cell, give the greatest possible linear aperture.

In the figure 1, let POM represent the angle of half-aperture, which we will call θ . Let OQ ($=l$) be the length of cylinder, which may be supposed to be thin. Let the ray

R P, P Q, be drawn making equal angles of incidence and reflexion with the surface of the cone. Then, since P R is parallel to the axis of the cone, the angle $\angle S P R = \angle Q P O = \theta$, and the triangle O Q P is isosceles. Hence the exterior angle $\angle P Q M = 2\theta$. If P M be drawn from P perpendicular to the axis, its length, which we may call a , will be that of the half-aperture.

Fig. 1.



Now $\sin P Q M = \sin 2\theta = \frac{a}{P Q};$

therefore $a = P Q \sin 2\theta,$

$$a = l \sin 2\theta.$$

Hence if l be constant, a will be a maximum when $\frac{da}{d\theta} = 0$.

Now $\frac{da}{d\theta} = l \cos 2\theta$; and equating to zero we find

$$\cos 2\theta = 0,$$

$$2\theta = 90^\circ,$$

or

$$\theta = 45^\circ.$$

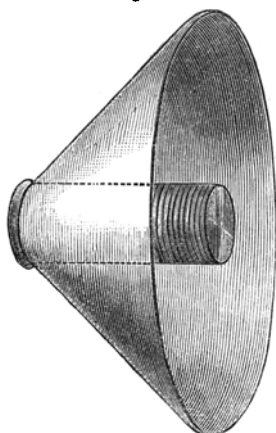
In other words, the mirror cone must have an apparent vertical angle of 90° , and its development will be a sector of $254^\circ 33'6''$ ($= \frac{360^\circ}{\sqrt{2}}$) cut from a circle whose radius is $\sqrt{2} \times O Q$.

If the cylinder cell have itself a radius r , then the whole diameter of the linear aperture will be equal to $2(l+r)$; and the cone may be conveniently truncated at a distance along the axis from O equal to r , which would leave a circle of $2r$ diameter just fitting the posterior end of the cylinder.

It may be remarked that the anterior end of the cylinder will, when it is placed in position, be in the same plane as the

circular mouth of the mirror cone, and the general appearance

Fig. 2.



of the mirror and cylinder will be that presented in figure 2.

With an angular aperture less than 90° , the depth of the mirror from back to front must be greater than the length of the cylinder; and the mirror, however prolonged, could not bring more rays to the surface of the cylinder except they underwent more than one reflexion.

If the angular aperture should be greater than 90° , the diameter of the cone

that will reflect the effective rays will be less than that of the 90° cone, and hence cannot gather as much light.

One advantage possessed by such a mirror cone of the form specified above over any other form, parabolic or otherwise, is that all the rays meet the sensitive surface of the cylinder at normal incidence, and the loss by reflexion will be therefore a minimum.

(7) In preparing to repeat the Photophone experiments, the author has constructed sundry cells in a manner somewhat differing from that adopted by Professor Bell.

Finding it laborious to cut and fix the alternate disks of mica and brass, he constructed a cell by winding brass wires spirally round a glass tube so that the successive convolutions did not quite touch. Selenium was afterwards applied in the interstices, and alternate convolutions were connected metallically, the wires being cut and then soldered with alternate junctions. Afterwards two parallel wires, wound side by side as in a double-threaded screw, were employed. One of these cells was found by the author on Oct. 19th to have as small a resistance (in the dark) as 240 ohms. On account, however, of the wire not adhering firmly to the glass, and from other causes, the arrangement, though far more easily constructed than the built-up cell, was not satisfactory. Taking a hint from Mr. Shelford Bidwell, who has recently published a communication on the Photophone in 'Nature,' the author has constructed cylinders of slate grooved with a fine double-threaded screw, in which the parallel wires are laid. These cells prove much more satisfactory. Experi-

ments are now proceeding with cells of this kind varying in length from two to eight inches.

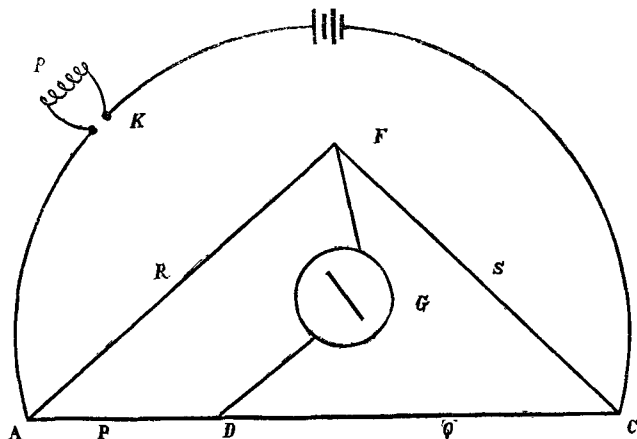
(8) The theorems enunciated above concerning the advantages of enlarging the size of the selenium-cell can readily be put to experimental test with cells such as described. There is of course a practical limit beyond which further increase of size will be of no advantage—such a limit being determined in particular cases by the resistance of the telephones and of the telephone-circuit, and by the other conditions, electrical and optical, of the experiment.

University College, Bristol,
Nov. 24, 1880.

XXXIX. *On the Measurement of Small Resistances.* By R. T. GLAZEBROOK, M.A., Fellow of Trinity College, and Demonstrator of Experimental Physics at the Cavendish Laboratory, Cambridge*.

WHILE measuring some small resistances with a Wheatstone's bridge at the Cavendish Laboratory, Mr. W. B. Allcock observed that the apparent measure of the resistance varied with the resistance in the battery circuit.

Let A D C be the bridge-wire, D being the point at which



the sliding contact is to be made. Let P be the resistance

* Communicated by the Physical Society, having been read at the Meeting on January 22, 1881.