CHANGE OF CONDUCTANCE OF SELENIUM DUE TO ELECTRONIC BOMBARDMENT

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Abstract

Effect of electronic bombardment on the conductance of selenium.—A low-resistance selenium cell about 1 inch square made by pressing Se between twenty double turns of fine Pt wire, was mounted in a vacuum tube with a grid and an oxide-coated, equipotential, electrically heated cathode and subjected to bombardment by electron currents up to 400μ-amp. at potentials up to 95 volts. The increase of conductance ΔC with current I and with voltage V, is found to agree well with the theoretical formula $\Delta C/C=\sqrt{1+kIV}-1$, derived on the basis of the *free electron theory of conduction*, assuming that the impinging electrons increase the number of free electrons throughout the whole volume of the Se by ionizations proportional both to the number of electrons and to the energy of each, i.e. to IV. The constant k is the ratio of the ions created per watt to the number of ions produced spontaneously per sec. and comes out 98.5.

Theory

According to the electron theory of metallic conduction the current is carried by the free electrons in the conductor, and the conductance is directly proportional to the number n of free electrons per unit volume. After the conductor has been left sufficiently long under unchanged external conditions, a state of equilibrium must exist between the un-ionized atoms, the ionized atoms, and the free electrons; i.e. the number of free electrons produced per unit volume every second must be equal to the number of free electrons recombining per second per unit volume.

In the case of selenium only a very small fraction of the atoms ever becomes ionized, and the number of un-ionized atoms per unit volume can therefore be regarded as constant. Let n be the number of ionized atoms per unit volume, and therefore the number of free electrons per unit volume. The chance of a recombination is proportional to n^2, and therefore the number of recombinations per unit volume per second may be put equal to a_1n^2.

In the case here dealt with, of selenium subjected to bombardment by electrons, in addition to the ions produced by thermal agitation and by the constant illumination from the filament, whose number per unit volume per second we shall denote by a_2, we may suppose ions are pro-

duced by the impinging electrons uniformly throughout a surface layer of depth d. Let the conductance of this surface layer be changed by the bombardment from C_0 to C_1. It is reasonable to assume that the number of ions produced is proportional to the number of impinging electrons, i.e. to the current I falling on the cell, in future simply called the plate current, and also proportional to the energy of each electron, i.e. to the difference of potential V through which it has fallen and which we shall speak of as the plate potential, therefore proportional to the product IV. For equilibrium in the surface layer we must have, therefore,

$$a_1 n^2 = a_2 + a_3 IV$$

or

$$n = \sqrt{(a_2 + a_3 IV)/a_1} \, .$$

Therefore the conductance of this layer is

$$C_1 = \sqrt{b_1 + b_2 IV}$$

where b_1 and b_2 are constants. When no electrons are falling on the cell other conditions remaining unaltered, the conductance of this layer is

$$C_0 = \sqrt{b_1} \, ,$$

so that

$$C_1 = \sqrt{C_0^2 + b_2 IV} \, . \tag{1}$$

For the ratio of the change in conductance ΔC to the original conductance of the whole cell C, we have

$$\frac{\Delta C}{C} = \frac{C_1 - C_0}{C} = \sqrt{\frac{C_0^2}{C^2} + k_2 IV} - \frac{C_0}{C} = \sqrt{k_1^2 + k_2 IV} - k_1 \tag{2}$$

where $k_1 = C_0/C$ and k_2 is a constant independent of I and V.

If the product IV is sufficiently small, we may write,

$$\Delta C/C = \tfrac{1}{2}(k_2/k_1) IV \, . \tag{3}$$

Apparatus

The selenium cell used had a dark resistance of about 3500 ohms. It was made by winding 20 turns of each of two platinum wires, about .01 cm in diameter, side by side on a slab of insulating material about 2.5 cm square, and pressing the selenium between the wires on one side. A shellac coating on the other side prevented the wires from touching. The source of bombarding electrons consisted of a heating strip of platinum, .025 mm thick, 3 cm long, and .1 cm wide and an outer platinum strip, .05 mm thick, insulated from the inner one by a sheet of mica. The outer

strip was coated with a half and half mixture of barium oxide and strontium oxide and connected to one terminal of the inner one, thus forming an equipotential emitting surface when a heating current flowed through the inner strip. Cell C and filament F together with a grid G were mounted on the lead-in wires passing through the ground glass stopper of the glass tube (Fig. 1). The grid was 3.5 cm on edge, having approximately 2 wires per cm. The tube was kept evacuated by means of a rotating mercury pump and a mercury diffusion pump in series, a mechanical pump serving as fore-pump. The mercury vapor was frozen out in a trap surrounded by carbon dioxide snow or a mixture of carbon dioxide snow and acetone, the last traces being removed by a piece of gold foil inserted in the exit of the vacuum tube. This was found to be very important, not only because the vapor would give rise to ionization at high plate

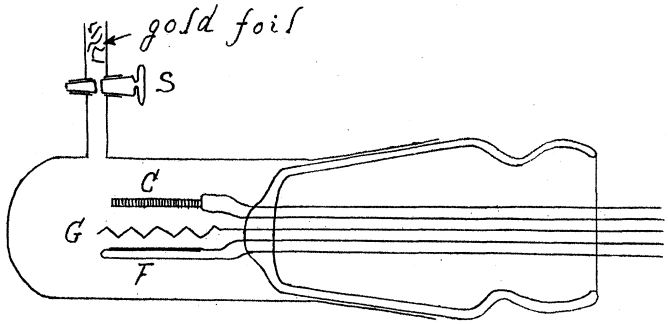

Fig. 1. Diagram of vacuum tube containing selenium cell C, grid G and Wehnelt cathode F.

potentials, but also because it affects the surface of the selenium, greatly increasing its conductivity. A stop cock S was therefore inserted in the tube leading from the vacuum chamber and was opened only after the cooling mixture had had sufficient time to remove the mercury vapor. The pressure in the tube was read on a MacLeod gage; it ranged around 10^{-5} mm. The outside light was excluded by means of a black cloth so that the cell was exposed only to the constant illumination from the filament. The voltage between cell and filament could be varied from a potentiometer connected to a storage battery. An adjustable voltage on the grid regulated the plate current without altering the filament current.

The cell was inserted in one arm of a Wheatstone bridge in parallel with a known resistance r, whose midpoint was connected through the plate voltage supply to the equipotential filament, a galvanometer or microammeter A serving to read the plate current (Fig. 2.) and a volt-

meter V indicating the plate potential. The resistance r was necessary in order that none of the plate current might flow through the bridge galvanometer. Furthermore, in order that the electrons striking the cell should all have the same velocity, say within .1 volt, the drop across the cell due to the bridge current was kept as small as possible, never exceeding .1 volt. It was on this account that a low-resistance cell was used, because with so small a voltage no precision could otherwise have been obtained in the resistance measurements.

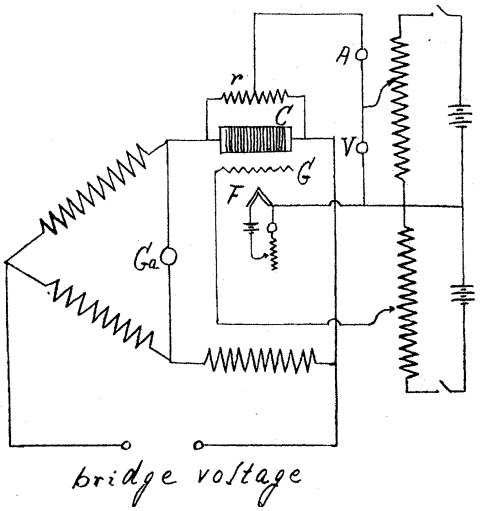

Fig. 2. Electrical circuits used in measuring the resistance of the selenium cell, and the plate current and the plate and grid voltages.

Results

The resistance of the combination C and r in parallel was measured for different constant plate currents, varying the plate voltage up to 100 volts, and from this resistance X' the resistance X of the cell was computed, and then the ratio $\Delta C/C$ plotted as a function of the plate voltage V. Fig. 3 shows three characteristic curves for constant plate currents of 50, 150, and 400 micro-amperes respectively. Similarly Fig. 4 shows three characteristic curves obtained by keeping the plate voltage V constant and finding the ratio $\Delta C/C$ as a function of the plate current I, the curves corresponding to values of V of 20, 50, and 80 volts respectively. From the curves it is evident that for sufficiently small values of I and V the curves are practically straight lines and can therefore be represented by a formula of the type of Eq. (3),

$$\Delta C/C = \tfrac{1}{2} kIV$$

For larger values of plate currents and plate voltages the values found for $\Delta C/C$ are in good agreement with the formula

$$\Delta C/C = \sqrt{1+kIV} - 1 \tag{4}$$

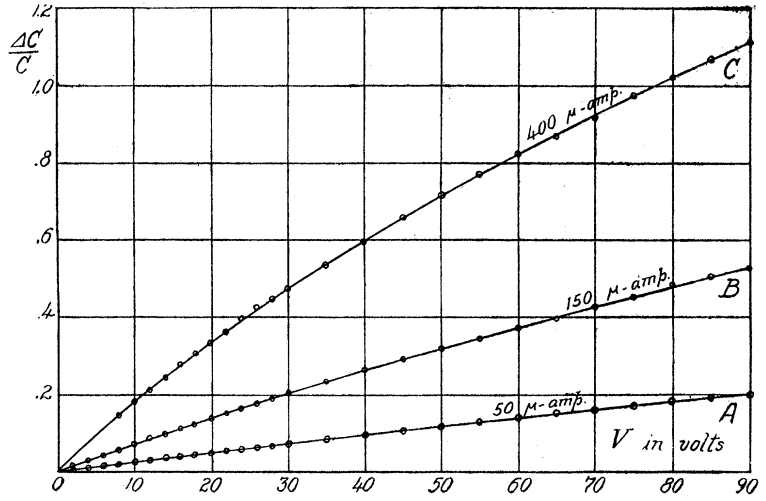

Fig. 3. Ratio $\Delta C/C$ as function of the plate voltage for constant plate currents of 50(A), 150(B) and 400(C)μ-amp.

which is identical with Eq. (2), if $k_1=1$. For if the values of $\Delta C/C$, I, and V are used to compute k, it comes out constant over the range of observations, (see Table I). We therefore find that k_1 of the theoretical

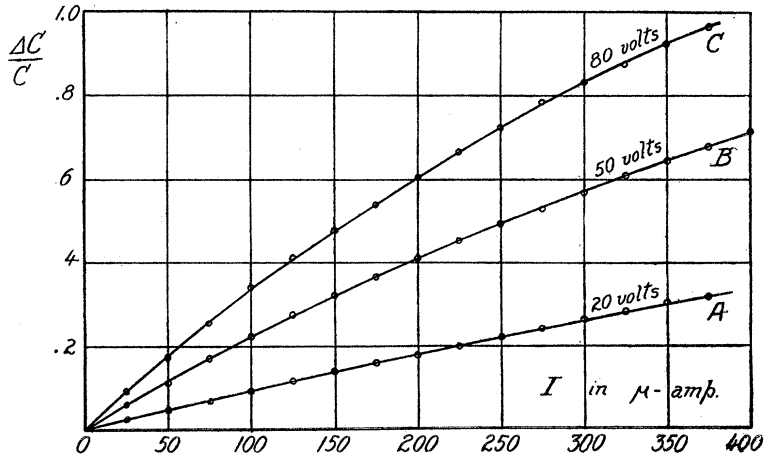

Fig. 4. Ratio $\Delta C/C$ as function of the plate current for constant plate voltages of 20(A), 50(B), 80(C) volts.

derivation is equal to unity. Therefore $C_0 = C$, or the original conductance of the affected layer is equal to the original conductance of the whole cell. In other words ionizations due to the impinging electrons take place throughout the entire material at approximately the same rate and do not confine themselves to a surface layer. This is in excellent agreement with observations by Brown,[1] which indicate that the change in conductance due to illumination of selenium spreads from the illuminated regions of the material to the unilluminated portions, sometimes as much as 10 mm. The explanation for this behavior, i.e. the mechanism for the necessary transfer of energy will probably have to be sought in the production of secondary radiation.

TABLE I

V (volts)	I (micro-amperes)	k
20	100	98.7
20	200	98.0
20	300	97.5
50	100	99.3
50	200	99.0
50	300	97.7
80	100	99.3
80	200	98.3
80	300	98.5

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[1] F. C Brown, Phys. Rev. **5**, 404 (1914)