INJECTION AND THERMAL EFFECTS IN SELENIUM RECTIFIERS UNDERGOING REVERSE CURRENT FLOW

V. I. Loiko

UDC 621.314.634:536

The change with time of the voltage drop across a selenium rectifier passing a constant current is studied. For high current densities a thermal relaxation mechanism is assumed and the thermophysical state is formulated for this case.

It is well known [1] that if a constant current is passed through a selenium rectifier, the voltage drop across the rectifier varies with time (it "creeps"). For currents of 8-100 μA, the voltage increases with time (positive creep); for currents of 150-250 μA, in addition to the voltage rise there appears a partial fall in voltage with time; and at currents of 0.5-1 mA only a voltage drop with time occurs in the temperature range studied (negative creep). In all these cases, after a long period of current flow (20 min), connection of the specimen to a potentiometer revealed the presence of an emf of the same polarity as the potential initially applied. Connection of the specimen to a galvanometer with low internal resistance in the external circuit produced a current flow opposite in direction to the inducing current. This indicated the presence of injection of charge carriers from the electrodes into the specimen, which is the cause of the positive creep effect. The cause of negative voltage creep, and consequently, degradation of rectifier action, may be the heating of the specimen during the time of current flow.

This study will analyze the reverse portion of the volt–ampere characteristic of series G selenium rectifiers in a static mode, recording the curves being taken by means of a CI-19 oscilloscope 2 sec (unformed) and 20 min (formed) after connection of the voltage source. The area of the specimens studied was 2.54 cm^2. The specimens were studied for ambient temperatures in the range 0-52°C. All changes in characteristics were reversible. The relationship between reverse current and applied voltage for currents of 8-50 μA, measured 2 sec (dashed lines) and 20 min (solid lines) after connecting the voltage source is shown in semilogarithmic coordinates in Fig. 1. From Fig. 1 it is evident that if the straight portions of the various current curves are extended to their intersection, then the current–voltage dependence can be written in the form

$$j = j_{\text{inv}} \exp\left[2.3B(T)\left(\sqrt{V} - \sqrt{V_{\text{inv}}}\right)\right], \tag{1}$$

where j_{inv} and V_{inv} are the values of current and voltage at the point of intersection, and B(T) is the tangent of the angle of inclination of the straight lines at various temperatures. If, for the respective families (formed and unformed) of lines, we calculate B(T) for the ambient temperature values studied and define the function $B = f(1/T)$, we obtain a linear relationship, and the magnitude of the tangent of the angle of inclination as a function of inverse temperature can be written as

$$B(T) = \frac{A}{T} - b, \tag{2}$$

where A and b are constants.

The change in tangent value after long passage of current apparently occurs as a result of redistribution of the voltage drop in the specimen due to injection of electrons from the cathode.

In series G selenium rectifiers there is no region of inverse current saturation. The reason for the absence of a saturation current in these rectifiers is that the ionization energy of the alloy atoms changes under the influence of the electric field within the specimen.

Lenin Belorussian State University, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 19, No. 2, pp. 312-318, August, 1970. Original article submitted October 28, 1969.

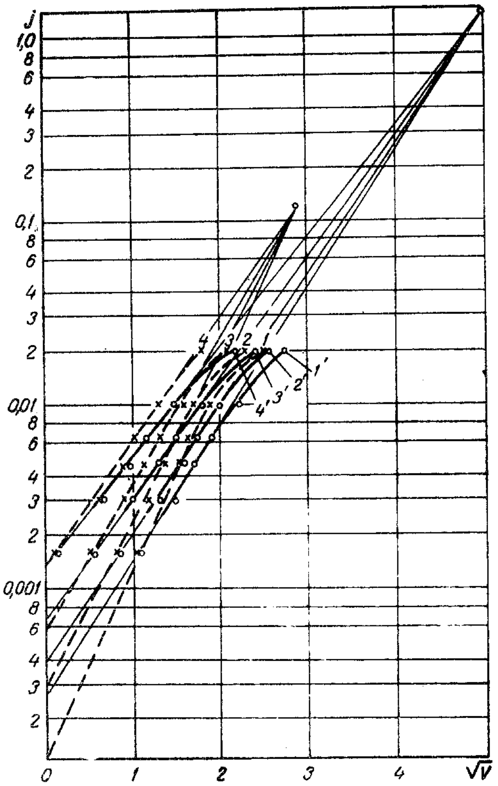

Fig. 1. Current density j, mA/cm^2, against $\sqrt{V}$, $V^{1/2}$, for different temperatures (dashed lines, 2 sec, solid lines, 20 min, after applying voltage): 1-1') 0°C; 2-2') 20°C; 3-3') 36.5°C; 4-4') 52°C.

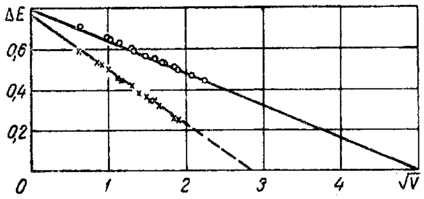

Fig. 2. Ionization energy of alloy atoms ΔE against voltage applied to sample, $V^{1/2}$. Dashed line, 2 sec, solid line, 20 min after applying voltage.

Since a selenium rectifier is a Se–CdSe heterojunction (an inhomogeneous crystalline system consisting of an Se matrix with inclusions of CdSe, Bi_2Se_3, etc.) the alloy atom ionization energy as calculated from the inverse current volt–ampere characteristics is the effective value for the entire system, and is dependent on the ionization energy and interaction of the individual regions.

As shown by capacitance measurements [3], the thickness of the p–n junction in selenium rectifiers is approximately 10^{-5} cm. In the reverse direction the resistance of the rectifier is determined mainly by the resistance of this junction. Therefore, the applied voltage is almost completely across the p–n junction. In view of the small junction thickness for low applied voltages a strong electric field of the order of 10^4-10^5 V/cm exists.

In the case of selenium rectifiers the theory of thermal ionization of alloy atoms in the strong electric field can be employed. It is assumed that the action of the field increases the concentration of charge carriers, rather than their mobility [2, 3].

The ionization energy value changes from 0.78 eV for $\sqrt{V} = 0$ to 0 for $\sqrt{V} = 2.9$ for an unformed specimen (dashed line) and from 0.8 eV for $\sqrt{V} = 0$ to 0 for $\sqrt{V} = 4.98$ $V^{1/2}$ for a formed specimen (solid line). It is evident from Fig. 2 that the magnitude of the ionization energy decreases linearly with increase in applied voltage, which is characteristic for high fields. After a long period of current flow (formation) the ionization energy increases due to the counteraction of the field by the injected charge carriers. Consequently, the current in the specimens studied is conditioned by field ionization of alloy atoms in the Se–CdSe heterojunction layer. Emission of charge carriers from the electrode leads to a redistribution of voltage in the sample, which causes a change in the electric field at the Se–CdSe heterojunction and a change in the ionization energy of the alloy atoms. For currents of 100 μA and more, taken at 2 sec, log j is linearly dependent on voltage (Fig. 3). Such a relationship is probably conditioned by the fact that, at these voltages, the p–n junction is completely filled by capacitance charge. If we extend the straight portions of these curves to their intersection, the relationship between current density in the sample and voltage will be of the form

$$j = j_{\mathrm{inv}} \exp\left[2.3\, B(T)\, (V - V_{\mathrm{inv}})\right]. \tag{3}$$

In this case it has been established that the ionization energy decreases linearly with increase in applied voltage.

However, after a 20 min passage of currents of 0.5 mA and greater through the specimen, the dependence of log j on voltage becomes quadratic (Fig. 3). Hence, the quadratic dependence appears upon long-term current passage and is a time-related factor. At the moment the quadratic dependence of log j on V appears, there occurs an anomalous dependence of the reverse current on temperature, or for constant current, an anomalous voltage–temperature relationship. In this case the voltage across the specimen increases with increase in specimen temperature (the specimen temperature is assumed to be equal to the ambient temperature). However, aside from the

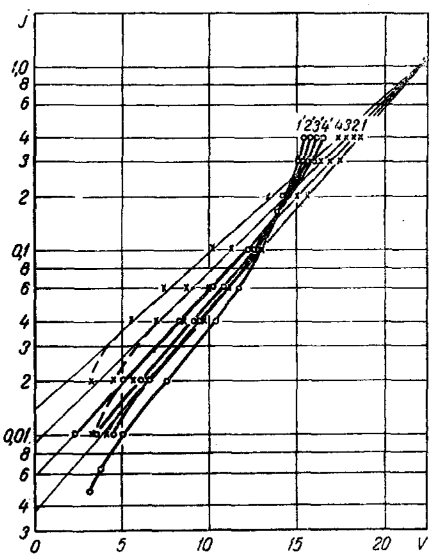

Fig. 3. Current density j, mA/cm^2, versus voltage V, V, measured 2 sec (dashed lines) and 20 min (solid lines) after voltage application. Temperature: 1-1') 0°C; 2-2') 20°C; 3-3') 36.5°C; 4-4') 52°C.

effects of injected charge carriers, after long-term current passage heating of the specimen also takes place (Fig. 4). In this case it is principally the upper (pressure) electrode that is heated. Although the specimen heating, as measured by a thermocouple, was no greater than 1.5°C above ambient, analysis of the experimental data and examination of the thermophysical problem based thereon nevertheless allow it to be assumed that there exist localized conductive channels in the specimen, which undergo significant heating with time at high current flows.

In actuality, if one considers that all the layers of the selenium rectifier are inhomogeneous in composition and include sections that differ from each other by as much as several orders in their resistance [4], it is possible to assume that current flow through the specimen occurs mainly through those segments with low resistance (localized conductive channels). Then in the voltage range where $\log j \sim V^2$ a strong heating of the localized conductive channels can take place. The temperature of the channels was calculated from Eq. (3). For a current flow of 1 mA for a 20 min period, the following channel temperatures were obtained for various voltages: 15.4 V, 374.4°K; 15.8 V, 365.3°K; 16.0 V, 360.3°K; 16.4 V, 349.5°K. From the results obtained it is evident that the voltage across the specimen falls with an increase in channel temperature, i.e., within the specimen the normal temperature dependence of voltage, and consequently, current, exists. Hence, consideration of the mechanism of current flow through the specimen and heating of the localized conductive channels carrying the current leads to a normal temperature dependence for large inverse currents in selenium rectifiers.

For a more accurate determination of current channel temperature, the thermal conductivity of the rectifiers studied was determined by a nonstationary method at the Academy of Sciences of the Belorussian SSR, and proved to be equal to $\lambda = 0.3$ W/cm·deg.

Since upon passage of a current through the specimen it is mainly the upper electrode that becomes heated, we will assume that the heat sources are located close to the upper electrode. Moreover, we will assume that the heat sources are situated in one plane x = 0, and are in the form of discretely placed disks of diameter 2R with δ, the thickness of the specimen.

With the condition that the surface temperature of the specimen is determined by

$$T_s = T_a + \frac{W}{\alpha F}, \tag{4}$$

where T_a is the ambient temperature; W is the power dissipated in the specimen; α is the heat-transfer coefficient with respect to the surrounding medium; and F is the surface area of the specimen; if we regard our specimen as an infinite lamina (this assumption is valid when we consider the specimen thickness $\delta = 0.1$ cm and that its diameter $2r = 1.8$ cm is almost one order greater than the thickness) with cylindrical symmetry, then in cylindrical coordinates in the stationary state the thermal conductivity equation will have the form [5]

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{\partial^2 T}{\partial x^2} = 0, \tag{5}$$

where r is the radial coordinate. On the surface x = 0 the heat flow density is determined

$$-\lambda \left.\frac{\partial T}{\partial x}\right|_{x=0} = Q(r), \tag{6}$$

where Q(r) is a function characterizing the change in heat flow at the surface x = 0. Moreover

$$T|_{x=\delta} = T_s. \tag{7}$$

We introduce a new variable

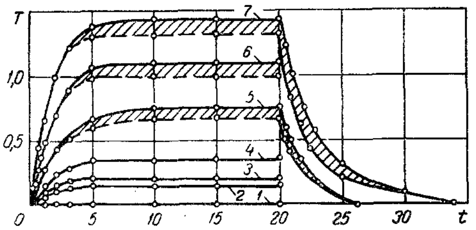

Fig. 4. Kinetics of the temperature, °C, as the current is switched on and switched off (solid line, upper pressure electrode; dashed line, substrate). 1) 8-16 μA; 2) 100 μA; 3) 150 μA; 4) 250 μA; 5) 0.5 mA; 6) 0.75 mA; 7) 1 mA, t, min.

$$T' = T - T_s, \tag{8}$$

whereupon the boundary conditions assume the form

$$-\lambda \frac{\partial T'}{\partial x}\bigg|_{x=0} = Q(r). \tag{9}$$

We apply Hankel's integral transformation to Eq. (5) and the boundary conditions of Eq. (9) over the variable r, and then, going from that representation to the original, we determine the temperature at a point r = 0, $[J_0(p, 0) = 1]$,

$$\Delta T = T(0,\ 0) - T_s = \frac{1}{\lambda}\int_0^\infty q(p)\,\mathrm{th}(p,\ \delta)\,dp,$$
$$q(p) = \int_0^\infty Q(r)\,J_0(p,\ r)\,r\,dr. \tag{10}$$

To obtain a numerical result it is necessary to know the form of the heat flow function Q(r). Since we have a hot disk, heat liberation will drop quickly but smoothly, and so for this case a Gaussian distribution of heat flow will be suitable

$$Q(r) = Q_0 e^{-\left(\frac{r}{R}\right)^2}, \tag{11}$$

where Q_0 is the heat flow at r = 0; and R is the radius of the area through which the largest portion of the heat flow passes (the radius of a conductive channel).

Using Hankel's integral transformation we obtain

$$q(p) = Q_0 \int_0^\infty e^{-\left(\frac{r}{R}\right)^2} rJ_0(p,\ r)\,dr = \frac{Q_0R^2}{2}\,e^{-\left(\frac{pR}{2}\right)^2}. \tag{12}$$

Substituting this value q(p) in Eq. (10) we obtain

$$\Delta T_0 = T(0,\ 0) - T_s = \frac{Q_0R^2}{2\lambda\delta}\int_0^\infty e^{-\left(\frac{R}{2\delta}\right)^2 z^2}\,\mathrm{th}\,z\,dz, \quad (r = 0). \tag{13}$$

The integral of Eq. (13) cannot be obtained in finite form. However, its value may be estimated.

In estimating the value we will consider two cases:

1) $(R/\delta) \gg 1$ (in our case this would be meaningless, since we assume that the contact spot is smaller than the specimen dimensions);

2) if $(R/\delta) \ll 1$,

$$[T(0,\ 0) - T_s] \simeq 0.63\,\frac{Q_0R}{\lambda}. \tag{14}$$

The heat flow density Q_0 is related to the power dissipated in the specimen W by

$$W = m\pi R^2 Q_0,$$

where m is the number of channels, through which the electric current flows; and R is the channel radius. Knowing the experimentally measured channel temperature, the number of channels and their mean effective area can be determined from considerations of thermal balance.

LITERATURE CITED

1. I. G. Nekrashevich, Yu. K. Vishchakas, and V. I. Loiko, in: The Physical Bases of Electrophotography [in Russian], Vil'nyus (1969), pp. 269-273.
2. Ya. I. Frenkel', Collected Works [in Russian], Vol. 2, Moscow–Leningrad (1958), pp. 220-227.

3. V. I. Fistul' and Q. B. Orzhevskii, Fiz. Tverd. Tela, 11, No. 9 (1960).
4. V. A. Dorin and M. M. Kozlov, Radiotekh. i Elektron., 10, No. 8 (1965).
5. H. S. Carslow and J. C. Jaeger, Conduction of Heat in Solids, 2nd Edition, Oxford University Press (1959).