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Abstract

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STIMULATED CURRENTS AND ELECTROLUMINESCENCE IN SUBLIMATED ZINC SULFIDE FILMS AT 77° K

Recently, electroluminescent sandwich cells with sublimated zinc sulfide films, made in our laboratory, were described. Their characteristic feature was continuous electroluminescence from anode to cathode and a very steep dependence of brightness on voltage: the brightness is proportional to the 13th power of the voltage ([1]).

In studying them at a temperature of 77° K, it was found:

1) When the voltage is increased to a critical value, the cell becomes a negative resistance.
2) Lowering the voltage after passing through the critical value establishes a new state of the cell with stimulated conductivity, which in some cells exceeds the conductivity at room temperature by a factor of 50.
3) The stimulated state is stable, persists for a long time, and its current-voltage characteristic is reversible.
4) The stimulated state can also be established by preliminary ultraviolet irradiation of the cell at 77° K.
5) The stimulated state can be eliminated by heating and then restored again by one of the methods indicated. In this case a characteristic identical with the previous one is restored.
6) In the stimulated state, as in the ordinary state, the current is proportional approximately to the 7th–8th power of the voltage.
7) The brightness of electroluminescence in the stimulated state (as in the ordinary state) is superlinear as a function of current. The brightness is proportional to the current to a power close to 2.
8) Owing to the comparatively strong currents in the stimulated cell, brightnesses are attained that exceed by tens of times the limiting brightness at

Fig. 1 and Fig. 2: Current-voltage characteristics

Figure 1: Fig. 1 and Fig. 2: Current-voltage characteristics

room temperature.

Below we present the experimental data obtained by us.

1. The sandwich cell consists of a sublimated ZnS film on glass; aluminum electrodes were deposited on the film by evaporation, with a distance between them of 1 mm. A constant voltage was applied to the cell (from 100 to 2500 V), and a protective resistance was connected in series. The greatest average field strength was $1 \div 2 \cdot 10^4$ V/cm. The cell was immersed in a cryostat in liquid nitrogen, and an FEU-19M photomultiplier was moved up to the cryostat window.
2. Figure 1 gives, in logarithmic coordinates, the dependences of current on voltage. At liquid-nitrogen temperature, the dependence obtained after cooling is the initial one (curve *I*). When the voltage was increased on the specimen cooled to 77° K, the current followed curve *I*. At a voltage of 1360 V in cell No. 6, a sudden rapid increase of current occurred with a simultaneous decrease in voltage: at 1360 V the current was 0.8 μA, and at the next reading (2 min later) it was 630 μA, but at a voltage of 960 V. At the reduced voltage it was possible to stabilize the current, after which a new stable dependence of the current was obtained.

of voltage (see curve II). The voltage at which a sudden rapid increase in current occurred we shall call critical, and the new state of the cell, in which the currents passing through it are thousands of times greater than the initial ones, the stimulated state. In the present example, in the stimulated state the cell conducted 50 times better than at room temperature. The stimulated state has a stable current-voltage characteristic. For example, for cell No. 5 the voltage was first lowered from 2400 to 760 V, and then raised again to 2400 V.

Fig. 1. Current-voltage characteristics of electroluminescent cell No. 6. I —at a temperature of 77°K before stimulation; II —at a temperature of 77°K after stimulation by voltage; III —at room temperature

Fig. 2. Current-voltage characteristics of cell No. 6 at 77°K. I —after stimulation by ultraviolet irradiation at increasing voltage; II —immediately afterward with decreasing voltage; III —stable characteristic of cell No. 6 in the stimulated state

In both cases the current values for the given potential were the same. After 15 min, upon repeated measurement of the currents, with the voltage increased from 760 to 2400 V, values were obtained that were on average 8% lower than the preceding ones.

After the cell was heated to room temperature, the stimulated state was eliminated and its initial characteristic was restored. After a new stimulation by

Figure 3

Figure 2: Figure 3

Figure 4

Figure 3: Figure 4

the critical voltage, a characteristic was obtained that was very close to that measured earlier for the stimulated state. We give one example of such measurements:

	2160	2030	2000	1920	1840	1760	1680	1600	1520
V, V	2160	2030	2000	1920	1840	1760	1680	1600	1520
i_1, μA	68	50.5	31.2	21.5	12.2	6.8	3.55	1.62	0.97
i_2, μA	68	50.5	34	21.5	12.3	6.5	3.5	1.67	0.94

Here i_1, i_2 are the current values, respectively, in the first measurement and after the cell (No. 5) had been heated, then cooled, and again stimulated.

Thus, the stimulated state is stable, persists for a long time, and is readily reproducible.

The course of the dependence of current on voltage, as seen from Fig. 1, can be represented by the expression $I = AV^a$, where A is a constant.

For curve I, $a = 7.8$; for curve II, $a = 6.7$. For our cells, the characteristic change of current is approximately proportional to the 7th power

voltage. For cell No. 6 the 7th power was retained up to a current of 100 μA; at larger currents the value of a decreased to 4–5. On curve III, at voltages of 280–700 V, a is close to 4.9 and then increases to ~ 9. When the cell is irradiated with short-wave rays, an increased conductivity arises—greater than with the stable stimulation characteristic. Thus, with cell No. 6, a current of 1 μA on the stable stimulation characteristic was obtained at 420 V, whereas after ultraviolet irradiation the same current was obtained at 170 V. However, the state of the cell after irradiation is unstable: the conductivity decreases, and after several minutes the same current was obtained approximately at

Fig. 3. Dependence of the brightness of electroluminescent cell No. 6 on voltage.
I—at 77°K before stimulation; II—at 77°K after stimulation by voltage; III—at room temperature

Fig. 4. Dependence of the brightness of cell No. 6 on the current through the cell at 77°K.
I—after stimulation by voltage; *II*—after stimulation by ultraviolet irradiation

403 V. Gradually the cell approaches a stable, long-preserved stimulated state (see Fig. 2).

4. As the current during stimulation increases, the brightness of the cell’ s electroluminescence also increases. At the same voltage the brightness after stimulation proved to be 300,000 times greater than before stimulation and approximately 1000 times greater than at the same voltage at room temperature. However, at the highest attainable brightnesses, i.e., on approaching the critical voltage, this ratio decreased to 15–20, since the increase in the stimulated brightness became less steep.

In Fig. 3, the dependence of brightness on the voltage across the cell is presented in logarithmic coordinates. The dependence of the brightness B on the voltage across the cell can be expressed by the equation $B = B_0 V^b$, where b is a constant. For curves I, II, III (Fig. 3) we have, respectively: $b = 14.3$, $b = 12.5$, and $b = 14.3$. The value of the exponent b at the temperature of liquid nitrogen, both in the unstimulated and in the stimulated state, is approximately the same as at room temperature.

From the proportionality of the brightness to the 13th–14th power of the voltage and from the proportionality of the current to the 7th–8th power of the voltage it follows that the dependence of the electroluminescence brightness on the current must be approximately proportional to the square of the current. In Fig. 4, in $\log B$—$\log I$ coordinates, the values obtained with cell No. 6 during the stimulation described in item 2 are plotted as points, and the values obtained with the same

cell after ultraviolet stimulation, when it had approached a steady state (corresponding to curve II in Fig. 2). The experimental data (from 0.2 to 400 μA) are satisfactorily arranged along the straight line $\log B = A + 1.75 \log I$, where A is a constant.

At the same current, at room temperature the brightness obtained was 6–7 times greater than under conditions of stimulated conductivity; however, the latter makes it possible, at the same voltage, to pass a considerably stronger current (for example, for cell No. 6 at 1160 V, about 500 μA instead of 20 μA at room temperature), and accordingly to obtain a brightness tens of times greater than at room temperature (in the example cited, 34 times greater). The exponent in the dependence of brightness on current was measured in 10 cells at room temperature, the values obtained being: 2; 1.9; 2; 1.9; 2.25; 2; 2.4; 2.5; 2.4; 2.3, with an average of 2.17; and in 3 stimulated cells, in which the values found were: 2.1; 1.9; 1.87, with an average of 1.96 (overall average 2.11). Thus, the dependence of cell brightness on current is close to quadratic.

5. The high exponent in the dependence of current on voltage finds a theoret-

> ical basis in Lampert' s simplified theory of space-charge-limited current (²), namely, as injection current with substantial filling of traps, including, in particular, deep traps. Negative resistance is justified in Lampert' s theory of double injection (³). Therefore the critical potential may be regarded as an indicator of substantial injection of holes in ZnS.

Stimulated conductivity—namely, conductivity strongly increased by stimulation at low temperature and retained for a long time—has been observed in various objects. P. G. Borzyak reported (⁴) stimulation of the conductivity of an Sb—Cs film: the conductivity increased by no less than 10^5 times and persisted in the dark for quite a long time; the passage of current through the film had no effect on the conductivity. Litton and Reynolds (⁵,⁶) discovered stimulated conductivity in one class of cadmium sulfide single crystals. In their experiments, under stimulated conductivity, phenomena of double injection and negative resistance were observed.

We have established stimulated conductivity at 77°K in zinc sulfide films. The characteristic features of the phenomena we describe differ substantially from those described by Litton and Reynolds for CdS single crystals. Thus, Litton and Reynolds obtained luminescence only after stimulation of the crystals; in the films, luminescence followed the same law in stimulated and unstimulated films. The current-voltage characteristics of the crystals of Litton and Reynolds were irreversible, and for a given level of stimulation the characteristic was not reproducible. The current-voltage characteristics of the stimulated state of our films are reversible and well reproducible.

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Note: Figure translations are in progress. See original paper for figures.