



---

Soviet-era science, translated into English

# LIGHT-EMITTING DIODES WITH EMISSION HYSTERESIS

PHYSICS

1969

SovietRxiv

---

View the original and related papers at <https://sovietrxiv.org/items/ru-196901.05226>

Source: Math-Net.Ru and CyberLeninka. Machine translation. Verify with the original.

Fig. 1

Figure 1: Fig. 1

**Abstract****Full Text**

UDC 621.382.2 : 546.28' 26 + 539.293.4 : 535.37

**PHYSICS**

Academician of the Academy of Sciences of the Uzbek SSR É. I. ADIROVICH,  
A. I. LUK' YANOVA, Sh. A. MIRSAGATOV,  
V. V. MOROZKIN, V. M. RUBINOV

## LIGHT-EMITTING DIODES WITH EMISSION HYSTERESIS

1. The light-emitting diodes were fabricated from cubic silicon carbide of  $n$ -type, doped with phosphorus ( $\rho \cong 1 \Omega \cdot \text{cm}$ ), by fusing in platinum and boron according to the technology described in <sup>(1)</sup>. Earlier studies of the current-voltage and capacitance-voltage characteristics at room temperature <sup>(2)</sup> made it possible to conclude that the light-emitting diodes under investigation have a  $p^+ - p - n$  structure.

*Fig. 1*

The emission of the light-emitting diodes arises when current passes in the forward direction. At room temperature the ampere-lumen characteristics  $\Phi(I)$  are well approximated by an exponential or, for some light-emitting diodes, by a power function with a high exponent <sup>(2)</sup>.

At a temperature of 77°K the character of the ampere-lumen characteristics changes sharply. In most specimens a strongly pronounced emission hysteresis is observed; the dependence of the diode brightness on current or voltage becomes non-single-valued. According to the character of this hysteresis effect, the light-emitting diodes studied can be divided into two types. The corresponding ampere-lumen characteristics (a.-l.c.)  $\Phi(I)$  and volt-lumen characteristics (v.-l.c.)  $\Phi(V)$  are given in quadrants  $I$  and  $IV$  in Figs. 1 and 2. There, in quadrants  $II$ , are given the current-voltage characteristics (I-V characteristics) of light-emitting diodes of the first and second type.

2. Specimens of the first type (Fig. 1) have I-V characteristics with a region of negative conductivity <sup>(3)</sup>. Under current control, at point  $A$  of the I-V characteristic a breakdown occurs (jump  $AB$ ), accompanied by a flash of luminescence (segment  $A'B'$  on the a.-l.c.). If the current is then reduced, the light-emitting

Fig. 2

Figure 2: Fig. 2

diode does not go out at once, but only at point  $C$  of the I-V characteristic. As a consequence, a hysteresis loop  $C'A'B'C'$  arises on the a.-l.c.

Under voltage control, naturally, there are no breakdowns on the I-V characteristic. In this case no noticeable luminescence arises at point  $A$ . The light-emitting diode remains dark also on segment  $AC$ , and only at point  $C$  does luminescence appear, gradually increasing with increasing voltage. When the voltage is decreased, the luminescence intensity passes through the same values in the reverse order; i.e., in contrast to the a.-l.c., the v.-l.c. of such light-emitting diodes has no hysteresis.

From comparison of the a-l characteristics  $\Phi(I)$  and v-l characteristics  $\Phi(V)$ , it follows that, in light-emitting diodes of the type considered, the luminescence is determined not only by the current flowing through them, but also by the applied voltage. The hysteresis observed in the a-l characteristics is the result of the nonuniqueness of the dependence  $V(I)$  for these light-emitting diodes.

3. Samples of the second type have completely different characteristics (Fig. 2). In the current-control mode, a hysteresis loop  $FBCEF$  arises in the current-voltage characteristic; under conditions close to voltage-control mode, a hysteresis loop  $HBDEH$  arises. Owing to the double-valuedness not only of  $V(I)$ , but also of  $I(V)$ , hysteresis and jumps exist in the current-voltage characteristics both under current control and under voltage control. Obviously, for this reason no regions of negative resistance or negative conductance can be detected on the static current-voltage characteristic in any mode. It is interesting to note that such a region cannot be traced even hypothetically inside the hysteresis loop, since the straight line  $BE$ , connecting the jump points, has a positive slope. The observed hysteresis can be explained if it is assumed that the true current-voltage characteristic has the form shown in Fig. 3.

### Fig. 2

The stable segment  $B_2E_2$  on such a current-voltage characteristic will not be observed because it is separated from the two other stable regions  $AB_1$  and  $DE_1$  by segments of negative differential resistance  $B_1B_2$  and  $E_1E_2$ , on each of which jumps inevitably occur.

In accordance with the nature of the experimental current-voltage characteristics, luminescence hysteresis is observed in light-emitting diodes of the second type not only in the current-control mode, but also under conditions of voltage control. The corresponding a-l and v-l characteristics are shown in Fig. 2. It is obvious that the double-valuedness of  $\Phi(I)$  and  $\Phi(V)$  is a consequence of the double-valuedness of  $V(I)$  and  $I(V)$ ; the luminescence intensity of these light-

Fig. 3

Figure 3: Fig. 3

Fig. 4

Figure 4: Fig. 4

emitting diodes also depends on both the current and the voltage, and not on any one of these characteristics alone.

4. To decide whether, on going from room temperature to liquid-nitrogen temperature, the nature of the radiative transitions in the investigated SiC structures changes, or only the kinetics of the current phenomena changes, emission spectra were studied.

Comparison of the spectra obtained at liquid-nitrogen and room temperatures showed that the spectra are almost symmetric curves with maxima located in the region of 2.28 eV at room temperature and 2.30 eV at the temperature of liquid nitrogen. These values are close to the magnitude of the band gap of cubic silicon carbide <sup>(4, 5)</sup>.

The temperature coefficient of the shift of the emission maximum is  $\cong 10^{-4}$  eV per 1 degree, which is close to the value of the coefficient of change of the band gap of  $\beta$ -SiC, equal to  $-(1 \div 5)10^{-4}$  eV/deg <sup>(6, 7)</sup>. On going from room temperature to liquid-nitrogen temperature, it draws attention to the

attention to a substantial increase in the half-width of the emission spectral curve, expressed in units of  $kT$  (from 4 to  $10kT$ ). With the exception of this fact, which requires special consideration, the shape and position of the emission spectra indicate that both at room temperature and at 77° K the emission is due to interband radiative recombination <sup>(2)</sup>.

5. As far as we know, up to the present time no one has observed hysteresis of the emission brightness of light-emitting diodes as a function of current or voltage. As the above joint consideration of the emission and current-voltage characteristics shows, the hysteresis of the emission

**Fig. 3**

**Fig. 4**

of  $\beta$ -SiC light-emitting diodes is a consequence of the shape of their current-voltage characteristics. The question of the detailed mechanism of the electronic (and, possibly, also electron-photon) processes determining the current-voltage characteristics shown in Figs. 1 and 2 requires the formulation of additional experiments. However, the already available body of experimental data makes it possible to express a number of quite definite considerations concerning the functional structure of the internal connections in light-emitting diodes made of silicon carbide of the  $\beta$ -phase, as well as the idea of an experiment that would

make it possible to reach the “unobservable” segment  $B_2E_2$  of the current-voltage characteristic of diodes with double hysteresis (Fig. 3).

Let us begin with consideration of light-emitting diodes of the second type. Double hysteresis, i.e., a current-voltage characteristic with a multivalued dependence both of current on voltage and of voltage on current, has been observed in silicon diodes (<sup>8–11</sup>). In works (<sup>9–11</sup>) an explanation of the observed current-voltage characteristics was proposed using a model consisting of an element with negative resistance and an element shunting it, whose current-voltage characteristic has a positive slope throughout (for brevity, we shall call the first an unstable element and the second a stable element). If the thermal breakdown which, in the diodes studied in (<sup>9</sup>), serves as the mechanism producing the negative resistance is limited by a series load resistance, then the current-voltage characteristic of these diodes will take the same form as the current-voltage characteristics of the  $\beta$ -SiC light-emitting diodes shown in Fig. 2 of the present article. A certain specificity, due to the fact that in the diodes described in (<sup>9</sup>) the branches  $HB$  and  $BE$  practically merge, is immaterial for the discussion being carried out here. It is interesting to note that in work (<sup>9</sup>), in the region of double hysteresis of the current-voltage characteristic, luminescence of silicon diodes was observed; however, no hysteretic effects of emission were detected.

We shall model the  $\beta$ -SiC light-emitting diode by the same system of parallel-connected unstable and stable elements that was proposed for silicon diodes in works (<sup>9–11</sup>). It is easy to see that if the unstable element has a current-voltage characteristic with negative conductivity (curve 1 in Fig. 4a), i.e., if positive voltage feedback is realized in it (<sup>3</sup>), then summation of the currents in such a model does not change the form of the current-voltage characteristic, but only brings  $I_{\max}$  and  $I_{\min}$  closer together (curve 3 in Fig. 4a). On the contrary, in the case of an unstable element having a current-voltage characteristic with negative resistance (curve 1 in Fig. 4b – internal positive

current feedback with respect to current (<sup>3</sup>), such summation gives, for the system as a whole, current-voltage characteristics with double hysteresis (curve 3 in Fig. 4b). Curves 2 in Fig. 4 are the current-voltage characteristics of stable elements.

Consequently, the model under consideration agrees well with the entire body of experimental data and, in addition, leads to the conclusion that the microprocesses occurring in  $\beta$ -SiC light-emitting diodes can give rise to positive feedback both with respect to current and with respect to voltage. Among the microprocesses leading to the appearance of regions of negative resistance or negative conductance on the current-voltage characteristics of semiconductor two-terminal structures one may point to the effects of double injection (<sup>12–14</sup>), temperature or field modulation of the conductivity of the diode base (<sup>15–17</sup>), reabsorption of recombination radiation (<sup>18</sup>), plasma phenomena (<sup>8</sup>), etc. As we have already noted, a discussion of the detailed physical mechanism responsible for the functional relations considered in  $\beta$ -SiC light-emitting diodes will be undertaken after additional experiments have been carried out. One of the most

interesting and informative experiments would be the investigation of the “un-observed” segment  $B_2E_2$  on the current-voltage characteristics of light-emitting diodes with double hysteresis (Fig. 3). By itself this segment is stable, and its non-observation in experiment is associated with the fact that, for any load resistance, breakdown will occur on the segments  $B_1B_2$  or  $E_1E_2$  leading to it. If, however, one fixes by current some state  $K$  on the “dark” branch of the current-voltage characteristic and then, by a pulsed action, switches the light-emitting diode into state  $L$ , then after removal of the pulse this final state remains stable. In this way one can reach the segment  $B_2E_2$ , and thereafter traverse it by controlling the voltage or the current. The question of the physical nature of the pulse required for the  $KL$  switching is connected with the question of the mechanism of internal positive feedback in the light-emitting diode. If this feedback is thermal, then the  $KL$  and  $LK$  switchings should be caused by pulses of heat and cold, as was done with silicon diodes<sup>(9)</sup>. If, however, the positive feedback is produced as a result of photoactive absorption of the light-emitting diode’s own radiation, i.e., if  $\beta$ -SiC light-emitting diodes of the second type are miniature monolithic solid-state optrons<sup>(19–21)</sup>, then the  $KL$  transition should be effected under the action of an external light pulse. The cycle of such investigations and a physical discussion of its results will be published in a separate article.

The authors express their gratitude to M. B. Reifman for providing silicon carbide crystals.

Physicotechnical Institute named after S. V. Starodubtsev  
Academy of Sciences of the Uzbek SSR  
Tashkent

Received  
9 IV 1969

## REFERENCES

1. E. I. Adirovich, Sh. A. Mirsagatov, V. V. Morozkin, *Dokl. UzSSR*, No. 2, 20 (1966).
2. A. I. Luk’yanova, Sh. A. Mirsagatov, V. V. Morozkin, V. M. Rubinov, in: Proceedings of the III All-Union Conference on Silicon Carbide (in press).
3. S. A. Tararinov, N. D. Abdrakhauz, *Semiconductor Devices with Negative Resistance*, M.–L., 1966.
4. S. A. Dodoyan and others, *Silicon Carbide*, Kiev, 1963.
5. Yu. M. Altaisky, Author’s Abstract, Kiev, 1968.

6. Sh. A. Mirsagatov, V. V. Morozkin, *Izv. AN UzSSR*, No. 2, 46 (1968).
7. R. Dalven, *J. Phys. and Chem. Solids*, **26**, 439 (1965).
8. J. L. Wagener, A. G. Milnes, *Appl. Phys. Lett.*, **5**, 186 (1964).
9. E. I. Adirovich, P. I. Knigin, Yu. S. Korolev, *DAN*, **161**, 70 (1965).
10. G. M. Avak' yants, B. A. Atakulov and others, *Radiotekhnika i elektronika*, **10**, 2037 (1965).
11. L. P. Murganova, A. A. Lebedev, in collection: *Physics of p-n Junctions*, Riga, 1966, p. 351.
12. R. C. C. Leite, A. Yariv, *Proc. IEEE*, **52**, 191, No. 2 (1964).
13. K. Weiser, R. S. Levitt, *J. Appl. Phys.*, **35**, 2431 (1964).
14. M. A. Lampert, *Proc. IRE*, **50**, 1781 (1962).
15. H. Hänsch, E. Nebauer, M. Nikolaus, *Phys. Status Solidi*, **12**, 1, 93 (1965).
16. V. P. Sondaevsky, V. I. Stafeev, *Radiotekhnika i elektronika*, **11**, 2089 (1966).
17. K. W. Böer, *Phys. Rev.*, **139**, 1949 (1965).
18. W. P. Dumke, in *Phys. Semicond.*, Paris, 1964, p. 611.
19. E. I. Adirovich, *Izv. vyssh. uchebn. zaved., Radioelektronika*, **11**, 679 (1968).
20. E. I. Adirovich, D. A. Aronov, N. Yunusov, *Fiz. i tekhn. poluprovodnikov*, **3**, No. 9 (1969).
21. E. I. Adirovich, E. V. Tsibulin, *ibid.*

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

*Source: Math-Net.Ru and CyberLeninka. Machine translation. Verify with the original.*