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Computer modeling of transient processes in LED modules

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In this paper, a theoretical analysis and a practical study of the transient processes occurring when the LED modules are switched on are carried out. Light-emitting diode (LED) modules are a parallel, serial or mixed connection of individual light-emitting diodes in a discrete or integrated design. The non-uniformity of the voltage drop at the moment of switching on series-connected LEDs or series-connected LED cells containing parallel-connected LEDs is shown. This may be the reason for a short-term electrical breakdown of their p-n junctions. The obtained results can be useful for predicting the durability and reliability of LED devices.

Keywords: LED, LED module, simulation of transient processes in LED modules.

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Introduction

LED modules with different LED connection configurations are widely used in many industries. Studies of transient processes at the moment of turning on LEDs are interesting because they can help increase their service life. The functioning of LEDs, both individual and LED modules with different types of connections, is described in the literature, in particular in [1-4].

It is shown that when a direct voltage is applied to the p-n light-emitting diode, there is a delay in its activation (delay of direct switching). However, the effect of this delay on the magnitude of the voltage drop at the p-n junction during transient processes and the probability of electrical breakdown is not indicated.

The literature describes transient processes at the initial moment of inclusion of serially connected elements [5]. But transient processes at the moment of switching on series-connected light-emitting diodes are not sufficiently considered. This work is devoted to the theoretical analysis and practical study of the effect of the delay of turning on the light of the diode on the magnitude of the change in the voltage drop at its p-n junction. This applies to both single and serially connected light-emitting diodes and the probability of their electrical breakdown at this moment [9-12]. Possible limit values of the voltage drop at p–n junctions of light-emitting diodes in real devices are also determined.

I. Theoretical analysis of transient processes in LED modules

Transient processes at the stage of turning on the LEDs.

Methods of connecting light-emitting diodes (parallel, series or mixed), transient processes that occur when they are turned on, as well as the effect of temperature on thermal breakdowns and longevity of LEDs are described in [1-4].

It was shown in [5-6] that when a voltage is applied to the p-n junction of the light diode, a change in the mutual location of the energy zones and their subsequent filling with electrons or holes begins until the moment of recombination with the subsequent emission of light quanta, i.e. there is a delay in turning on the light diode. However, the results of the effect of this switch-on delay on the magnitude of the voltage drop at the closed p-n junction are not given.

Therefore, transient processes at the initial stage of inclusion do not occur instantly, but with a certain delay. That is, at the moment of closing the key K (Fig. 1), while the p-n junction is still closed, only the loss current Iw flows (moment of time t1, Fig. 2). This current is several orders of magnitude smaller compared to the direct operating current of the open light diode Ivd. in glow mode. At the moment of time tv, when the p-n transition of the LED VD1 became open and it emits light, the voltage Uvd drops on it, with a value within the range of 3.3V. The value of the voltage of the power supply Ug = Uvd + Uo, where Uo = R1Ivd. The value of the voltage of the power source is selected under the condition Ug>Uvd, i.e. Ug = gUvd. Where g is a coefficient equal to or greater than 1.3. If g = 1.3 is selected, then Ug = 1.3Uvd. And the value of the limiting resistor R = 0.3Uvd/Ivd.

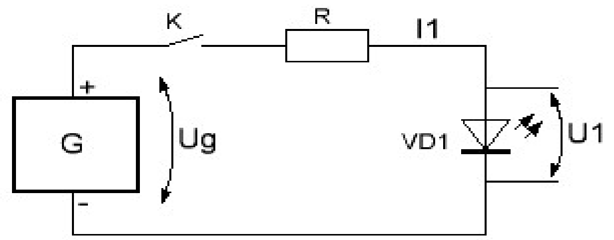


Fig. 1. Electrical connection diagram.

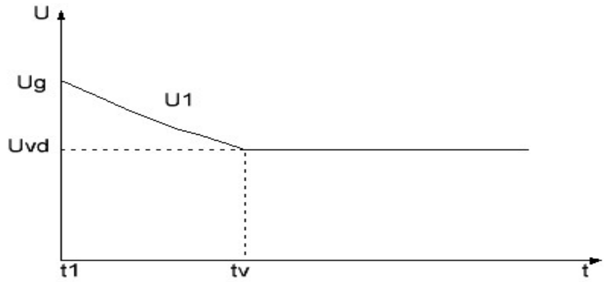


Fig. 2. Timing diagram of the process of changing the drop the light of the diode to the power source. voltage U1 to light the diode at the moment of switching on.

That is, at the initial moment of time t1, the current Iw<<Ivd, and the voltage drop across the limiting resistor R will be equal to Uo=R Iw and can be neglected. Then the voltage U1=Ug drops on the LED VD1. If the supply voltage Ug will be higher than the breakdown voltage p-n junction Up, then an electrical breakdown occurs. Types of p-n junction breakdowns are described in [6-10]. The time of electrical breakdown depends on the speed of switching on the LED.

Figures 1 and 2 indicate: G – power source; VD1 – LED; K is a key; R is a limiting resistor; Ug – power supply voltage; U1 – voltage drop across the diode light; Ivd and Uvd, respectively, are the current and voltage on the switched-on LED after the end of the transient process; t1 is the time when the key K closed the circuit; tv is the time when the transient process ended and the diode light turned on.

When several LEDs are connected in parallel, the situation remains similar, i.e. U1 = Ug. And when the supply voltage Ug is greater than the electrical breakdown voltage Up of one of the light-emitting diodes, then a short-term electrical breakdown of the p-n junction of this light-emitting diode occurs.

For series-connected LEDs, provided that their parameters are the same, and the voltage of the power source is selected as Ug=1.3nUvd, where n is the number of series-connected light-emitting diodes.

Then at the initial moment of time t1, when only the loss current Iw flows, the same voltage Um is applied to their p-n junctions, the value Um = Ug/n = 1.3Uvd (Fig. 3). That is, Um = U1 = U2 = … Un.

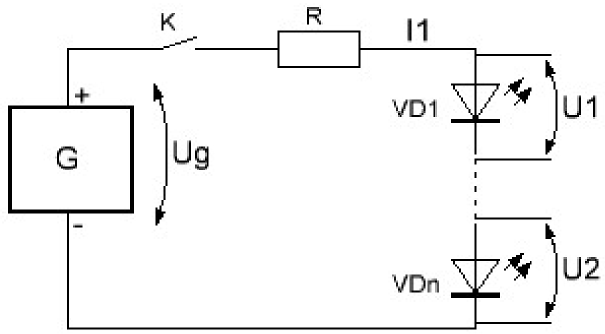


Fig. 3. Electrical diagram of serially connected n- LEDs.

Approx. If the value of the voltage of the power source Ug is greater, namely g > 1.3. In this case, Ug > 1.3nUvd. Then the results of the analysis will be different, and the magnitude of the voltage drop at the p–n junction during the process of turning on the diode light will also be greater.

In real LEDs, the parameters are different, so we will consider the following cases:

a). LEDs have different loss currents when the p-n junction is closed. Suppose that these currents were distributed as follows, the largest in the first light diode, and the smallest in the nth. That is, Iw1 > Iw2 > ... > Iwn. Then, at time t1, the voltage drop across their p-n junctions will be inversely proportional to their loss currents. That is, Un > Un-1 > ... > U1, and on some light-emitting diodes, the value of the voltage drop will be greater, and on some it will be less than Um. Therefore, the probability of an electric breakdown of a closed p-n junction increases for those LEDs whose voltage drop is greater than Um and exceeds the value of the breakdown voltage Up.

b). Light diodes have different turn-on delays. Let's assume that one light diode has the largest turn-on delay τ1, and all the others have a smaller and the same delay. Example,

$$\tau 1 > \tau 2 = \tau 3 = ... = \tau n.$$

At the moment of time t1, the magnitude of the voltage drop on the LEDs will be distributed according to point a). But at the next moments of time, the magnitude of the voltage drop on the LEDs will depend on the magnitude of the delay in their inclusion, because LEDs with a shorter inclusion delay undergo faster changes in the relative location of the energy zones and their filling with electrons or holes. The magnitude of the voltage drop across an LED with a shorter turn-on delay will rather approach the magnitude of the on-LED voltage Uvd.

Let's consider the moment when the value of the voltage drop on the light diodes with a shorter delay approached the value of its turn-on voltage Uvd, although the turn-on itself has not yet occurred. Then, at this moment in time, the magnitude of the voltage drop across the diode with a longer turn-on delay Ux is determined as follows:

$Ug = (n - 1)\, Uvd + Ux$; then $Ux = Ug - n\, Uvd + Uvd$;

If $Ug = 1.3n\, Uvd$; then $Ux=(1+0.3n)\, Uvd$; This is the maximum possible value of the voltage drop on a closed p–n junction at the moment of its inclusion. It can cause a short-term electrical breakdown of the p-n junction. If LEDs have a different turn-on delay value $\tau = tv - t1$, for example, $\tau 1 > \tau 2 > \tau 3 > ... > \tau n$, then the value of the voltage drop at their p – n junctions will be different, i.e. $Un < … < U3 < U2 < U1 < Ux$; and in the part of the LEDs, with a longer turn-on delay, an electrical breakdown may occur. Since the electrical breakdown of p-n junctions in LEDs is short-lived, it can be assumed that it is reversible and can be restored. However, after a large number of short-term electrical breakdowns of the p-n junction, the LEDs experience a catastrophic failure or decrease in brightness.

II. Computer simulation of transient processes in elements of light diode modules

The technique of the scheme for modeling transient processes in the elements of light-emitting diode modules was carried out in CAD LT SPICE, and modeling taking into account the features of the topology of light-emitting diodes in an integrated design - in CAD Micro Wind. For computer modeling, an equivalent electrical circuit of a light diode is proposed, shown in Fig. 4. The scheme contains an inductor L1(3mkH), a resistor R1 (10 Ohm), (equivalent to the resistance of a light-emitting diode) resistor R2 (equivalent to the resistance of a light-emitting diode), Vin – a power source for a light-emitting diode, R3 (10 Ohm) – a limiting resistor power sources. Loss resistance is approximately 1 MOm. The approximate values of the quantities are indicated on the equivalent diagram.

III. A practical study of the results of the influence of transient processes at the moment of turning on the light of diodes on their work

A computerized hybrid microsystem for biomedical applications [7] containing a precision operational amplifier based on CMOS transistors and the principle of digital current measurement described in [8] can be used for practical research of individual light-emitting diodes.

The study was conducted on three types of household lighting devices with light diodes, these are:

a). Light bulbs powered by a 220 V alternating current network. In operation for about three years.

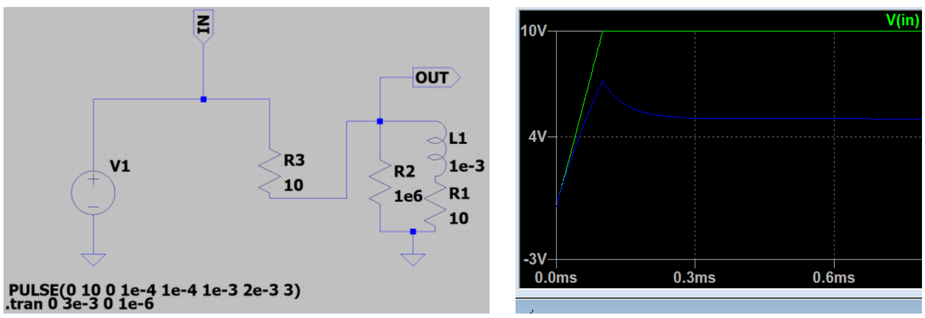
d). Lamps powered by 220 V alternating current network. In use for about two years.

e). Tapes powered by a 12 V DC source. In operation for about eleven years.

The operation of the devices was monitored during their operation. It was found that the breakdown of some devices occurred when they were turned on, and others during their operation.

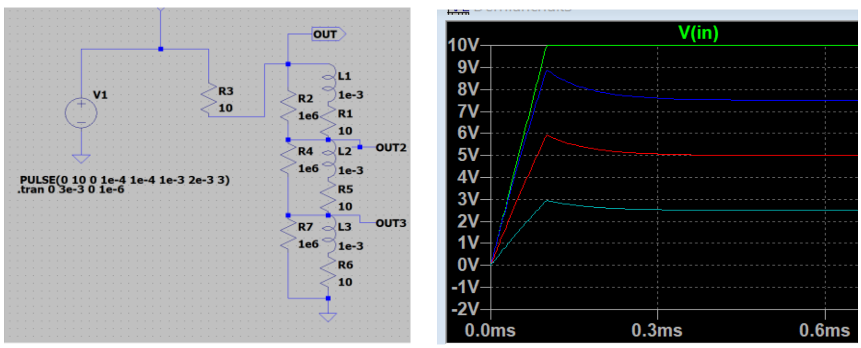
Analysis of results.

Out of more than fifty defective devices, about forty



a) b)

Fig. 4. Equivalent electrical circuit (a) and computer simulation results of one light diode (b).



a) b)

Fig. 5. Equivalent electrical circuit (a) and computer simulation results of three series-connected light-emitting diodes (b).

were selected for the study. These are those in which the power supply units (drivers) were working, but the light diodes did not work. Thus, devices whose diode light could be damaged by faulty drivers were excluded from the study. In the devices that broke down when the power source was turned on, as a rule, breaks were detected in one or more light-emitting diodes. Visually, their appearance did not undergo changes, that is, an electrical breakdown of the p-n junction occurred. In some cases, it was found that in addition to the light diodes with an electrical breakdown, a light diode was connected in series and had a short circuit (thermal breakdown, blackened light diode is visually visible).

If the device breakdown occurred during a certain time of operation, then thermal breakdowns were detected (blackened or destroyed light diodes are visually visible). In some devices, one of the serially connected light diodes had a thermal breakdown. The diode had a break. Also, in some cases (in cells with parallel light-emitting diodes), one light-emitting diode had a thermal breakdown (blackening and breakdown), and the rest had electrical breakdowns (breakdown, without visually visible changes).

You can single out such cases as a decrease in the brightness of the diode light. Visually, external changes are not visible, which indicates partial damage to the light diode during electrical breakdowns. When such a breakdown occurred, whether at the time of switching on or during operation, it was not possible to establish.

Approx. It is possible that thermal breakdowns could be the consequences of previous electrical breakdowns. Types of light diode failures in such devices as:

a). Light bulbs. About 25 light bulbs were studied. In them, as a rule, light diodes are connected in series. Their number is from 4 to 30, and depends on the power of the light bulb. Greater radiation power - more diode light. Drivers are diverse. From simple, with a limiting capacitor on the mains current, to complex electronic constant current stabilizers. Fig. 6, 7 show the internal structure of some light bulbs.

Electronic driver. on the limiting capacitor.

The following malfunctions of light diodes were detected:

- electrical breakdown (break) in one or several series-connected light-emitting diodes. The breakdown occurred when the device was turned on.

- thermal breakdown (break) in the light diode. The breakdown occurred during the operation of the device.

- thermal breakdown (short circuit) in the light-emitting diode, and electrical breakdown (break) in one or more other series-connected light-emitting diodes. The breakdown occurred when the device was turned on. The thermal breakdown of the light diode, most likely, occurred earlier, but its short circuit did not significantly affect the functioning of the device. Because in a series circuit, a short circuit of one or more light-emitting diodes does not exclude the continuation of current flow through the working light-emitting diodes.

Approx. As an example, let's analyze the breakdown of a light bulb with six ($n = 6$) light diodes, shown in Fig. 6. The breakdown occurred at the moment of switching on. One of the LEDs is broken, but its appearance has not changed. The value of the output voltage of the driver, without load, is about 200V. That is, the manufacturer selected the value of the voltage of the power source with the coefficient $g > 1.3$ ($g = Ug/ nUvd = 200/6*3.3 = 10.1$).

f the parameters of these light-emitting diodes in the light bulb were the same, then the maximum possible value of the voltage drop at the closed p–n junction, at the moment of switching on, is

$Um = Ug/n = 200/6 = 33.3$ V. With different parameters of the light diodes, the value of the voltage drop at the closed p–n junction could reach the value

$Ux=Ug – n\ Uvd + Uvd = 200-(6*3.3)+3.3=176.9$V.

Such magnitudes of the voltage drop on the light diodes at the moment of switching on led to the failure of the light bulb.

b) Lamps. In the lamps, several lines with serially connected cells of light diodes are used. The number of cells in the line is 7-10 pcs. Each cell has several light-emitting diodes connected in parallel. The number of lines, cells and the light of the diodes in the cell depends on the radiation power of the lamp. Power comes from the driver (DC stabilizer). Various types of drivers were used in the lamps. The study was conducted on ten lamps. Fig. 8, 9 show parts of the lines with faulty LEDs.

The following malfunctions of light diodes were detected:

- electrical breakdown (break) in all LEDs of one or more cells. The breakdown was recorded when the lamp was turned on (Fig. 8).

- a thermal breakdown with a short circuit in one light-emitting diode of the cell and an electrical breakdown (break) in the rest of the light-emitting diodes connected in parallel (left line of Fig. 9). The breakdown was detected visually, during the operation of the lamp. The device was functioning, but one of the cells was visually broken.

- a thermal breakdown with interruption of one light diode in the cell and electrical breakdown in the remaining parallel connected light diodes (right line of Fig. 9). The breakdown was discovered during operation, when the lamp went out. It can be assumed that the root cause of the

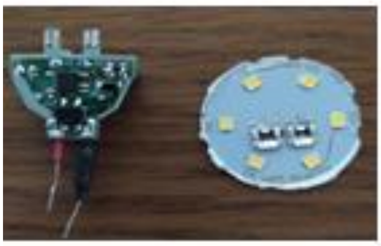


Fig. 6. Light bulb with 6 - th light diodes.

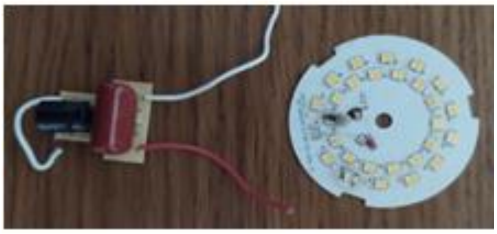


Fig. 7. Light bulb with 28 light diodes.Electronic driver. on the limiting capacitor.

Fig. 8. Part of rulers with electric of the diode light in the cell (4 in parallel. connected LEDs).

Fig. 9. Part of rulers with thermal breakdown of the cell.

thermal breakdowns was the electrical breakdown of all but one of the light-emitting diodes connected in parallel. And then, during work, a thermal breakdown of the surviving light diode occurred. This happened because the total current began to flow through it, its working plus currents of parallel light diodes with a break.

Approx. In the devices considered in points c) and e), in addition to the listed breakdowns, there were also diode lights with reduced brightness.

c). Tapes powered by a 12V DC source. Different numbers of cells connected in parallel are used in the tapes. Each cell consists of three series-connected light-emitting diodes connected through a limiting resistor of 110-150 Ohms to the power source.

In this study, tapes (5 pcs.) containing from forty to one hundred cells were analyzed. The tapes received power from different types of sources. In two tapes, during switching on, one defective cell was detected (Fig. 10).

Fig. 10. Part of a light diode tape with a faulty cell.

In each of the faulty cells, there was an electrical breakdown (break) of one light diode.

So:

- in addition to thermal breakdown from overheating, in household lighting devices, there is also an electrical breakdown of light diodes, which confirms the results of the conducted theoretical analysis;

- the durability of LED tapes, powered by a 12V DC source, significantly exceeds the durability of devices with a higher voltage supply. This is due to the fact that with any discrepancy in the parameters of the LEDs of the cell, the voltage drop on one of the LEDs is no more than 12V, which reduces the probability of an electrical breakdown;

- electrical breakdown in the LEDs of various lighting devices, from the 220 V alternating current network, does not strongly depend on the type of power sources used;

- a thermal breakdown in the cells may be the result of an electrical breakdown of a part of the LEDs connected in parallel.

Conclusions

As a result of the conducted research and analysis, it was established that in series-connected LEDs, the delay in turning them on can lead to exceeding the allowable voltage on the p-n junction, that is, to its electrical breakdown.

It is noted that:

- in addition to thermal breakdown due to overheating, electrical breakdown of LEDs also occurs in household lighting devices based on light-emitting diodes.

- the durability of LED tapes, powered by a 12 V DC source, significantly exceeds the durability of devices with a higher voltage supply. This is due to the fact that they are less likely to have an electrical breakdown.

- electrical breakdown in LEDs of various lighting devices, from the 220 V alternating current network, depends little on the type of power sources used.

- thermal breakdown of light diodes in cells can also occur due to electrical breakdown of neighboring light diodes connected in parallel.

- when the series-connected LEDs are turned on, a short-term electrical breakdown occurs on some of them. Therefore, over time, repeated switching on leads to a catastrophic failure, that is, to a break in the light diodes, or to a decrease in their brightness. This applies not only to household lighting devices, but also to others where a series connection of LEDs is used. For example, as in LED TVs, where lines with serially connected LEDs are used to illuminate the screen. They also have similar refusals.

Reducing the number of device breakdowns due to electrical breakdown of LEDs can be achieved:

- Using LEDs from the same batch (where there is a slight deviation in the value of the electrical parameters).

- Equalization of LED loss currents using resistors connected in parallel.

- Using parallel switching of LEDs with power from low voltage sources where possible.

- Production of LEDs with an increased breakdown voltage of the p-n junction.

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[1] Web-source: https://5watt.ua/uk/blog/statti/zastosuvannya-svitlodiodiv-u-osvitlenni Application of light diodes in lighting.

[2] L. V. Odnodvorets, I. M. Pazukha, Materials and components of functional electronics: Sumy State University study guide (Sumy, 2020).

[3] O. V. Borisov, Yu. I. Yakymenko. Solid-state electronics: a textbook (NTUU "KPI", Kyiv, 2015).

[4] How to connect a light diode: parallel and series connection. Web-sources: https://pkf-elektroplast.com.ua/ua/a400222-kak-podklyuchit-svetodiod.html.

[5] P-n junction, its properties, types of breakdowns. Web-source: http://um.co.ua/8/8-5/8-59953.html.

[6] Breakdown of the r-p-transition. Web-source: https://web.posibnyky.vntu.edu.ua/fksa/3pavlov_osnovy_mikroelektroniky/68.htm.

[7] B.S. Dzundza, I.T. Kogut, V.I. Golota, L.V. Turovska, M.V. Deychakivskyi, *Principles of construction of hybrid microsystems for biomedical applications*, Physics and chemistry of the solid state, 23(4), 776 (2022); https://doi.org/10.15330/pcss.23.4.776-784.

[8] A.O. Druzhynin, V.I. Holota, I.T. Kogut, S.V. Sapon, Khoverko, Yu.M. *The device-technological simulation of the field-emission micro-cathodes based on three-dimensional SOI-structures*, ECS Transactions, 14(1), 569 (2008); https://doi.org/10.1149/1.2956075.

[9] Jinmin Li, G.Q. Zhang. *Light-Emitting Diodes Materials, Processes*, Devices and Applications (Springer, Cham, 2019).

[10] Qing Wan., Wenxin Dai., Yili Xie., Qinqin Ke., Chunhui Zhao., Bing Zhang., Zebing Zeng., Zhiming Wang., Ben Zhong Tang. *AIE-active deep red/near-infrared electroluminescent emitters with fine regulation of excited state*, Chemical Engineering Journal. 451(1), 138529 (2023); https://doi.org/10.1016/j.cej.2022.138529.

[11] M. Khan, S. Shah, *Data and information visualization methods and interactive mechanisms: a survey*, Inter. J. Comp. Appl., 34(1), 1 (2011); https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=4ff1f2fff62e899f4b9f507b2eb4bb297b7febc2.

[12] G. Liu, Z. Li, X. Hu, Y. Qin, C. S. Lee, D. Chen, ... & Y. Wang, *Efficient and stable one-micrometre-thick organic light-emitting diodes*, Nature Photonics, 16(12), 876-883 (2022); https://doi.org/10.1038/s41566-022-01084-x.

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Комп'ютерне моделювання перехідних процесів у світлодіодних модулях

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У роботі проведено теоретичний аналіз та практичне дослідження перехідних процесів, що протікають при включенні світлодіодних модулів. Світлодіодні (англ. LED) модулі являють собою паралельне, послідовне чи змішане з'єднання окремих світлодіодів у дискретному або в інтегральному виконанні. Показано нерівномірність падіння напруги в момент включення на послідовно з'єднаних світлодіодах чи послідовно з'єднаних світлодіодних комірках, що містять паралельно з'єднані світлодіоди. Це може бути причиною короткочасного електричного пробою їх p-n переходів. Отримані результати можуть бути корисними для прогнозування довговічності та надійності світлодіодних пристроїв.

Ключові слова: світлодіод, світлодіодний модуль, моделювання перехідних процесів у світлодіодних модулях.