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Development of modeling methods and algorithm for calculating the current-voltage characteristics of LED modules

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Abstract. Current-voltage characteristics of real high-power LED chips and their defects were studied. Process of modeling LED matrix by using Monte Carlo method based on the measured real LED chips was considered and performed. It was shown that the risk of variating LED chip parameters for stability of a final LED matrix as a result of the non-uniform heating up of individual elements in a series-parallel circuit. The solution allowing to significantly reducing the influence of LED chips input parameters variation on the final parameters of LED matrix was proposed.

Keywords: LED, modeling, current-voltage characteristics.

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Transition from the LED chips to LED modules has led to the need to solve a number of additional tasks – analysis of heat distribution in a similar module [1-3], but it ignores the fact that the LED chips that are the basis for LED modules have variation of parameters, which leads to the non-uniform current flow. To estimate this factor, it is necessary to have software to predict the effect of the connecting the real LED chips on the parameters of the future LED module. It is important to take into account the possible defects of LED chips (their errors on quality control, the influence of defects location, variation of parameters) and to calculate their effect on the general characteristics of the final LED module. This paper describes the stages of creating and first results of operating such a program that allows to simulate the behavior of the final LED module, in dependence on the number and characteristics of the elements in each circuit of series-parallel connection.

To obtain information about the actual LED chips, the LED modules prepared in the conditions of domestic production based on the chips of company "EDISON Optocorporation" before filling them with phosphor described in [4] were investigated. An appearance of the LED module is shown in Fig. 1. The module is made on the basis of the printed circuit board with an aluminum basis, on which LED chips were mounted and connected to each other by a series-parallel circuit shown in Fig. 2. Two identical modules were studied.

To study the current-voltage characteristics (CVC) of real chips on the given module, the connect tracks of one LED module were cutted and wire terminals were connected to each individual chip. The direct measurements of each chip were performed with taking into account the chip location on the printed circuit board and its connection.

The CVC measurements of LED module chip are shown in Fig. 3. A number of anomalies in the current-voltage characteristics were detected. These anomalies were caused by soldering defects (Fig. 3a, chips with abnormally low currents at the applied voltage 3 V, their photo is shown in Fig. 4), as well as defects in these chips (Fig. 3, three curves for relatively high direct currents with the applied forward (*a*, *b*) and reverse (*c*) voltages 1 V), which can accelerate their degradation.

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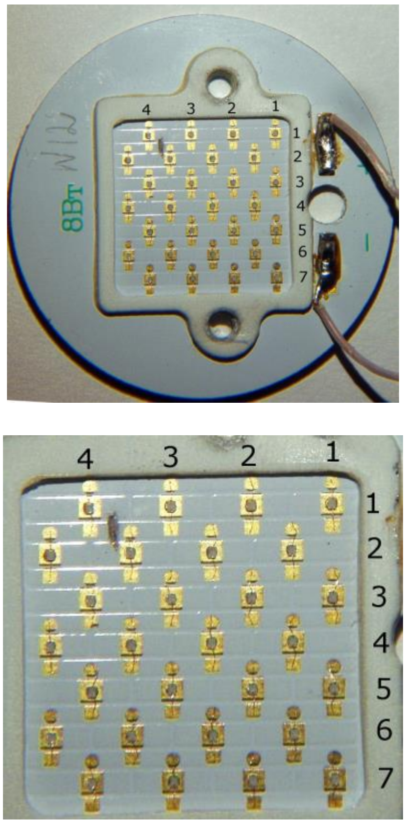


a)

b)

Fig. 1. Appearance of the LED module (*a*), the numbering chips (*b*).

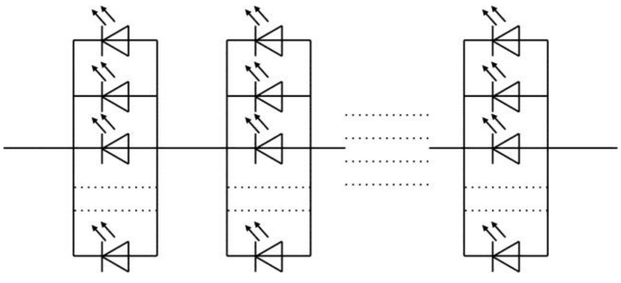


Fig. 2. The series-parallel circuit connection of chips in the LED module.

Two chips with higher values of series resistance attracted attention to them (see the dotted curves in Fig. 3a). The current through these chips was significantly lower than that through the middle chips. It leads to overloading the neighboring, parallel to them, LED chips and, as a result, to acceleration of their degradation during operation.

For further analyzing, each CVC of LED chip seemed to be approached in the approximation of two parallel ideal diodes and serial nonlinear resistance (Fig. 5).

In this case, CVC of high-power LED is described by the equation (1)

$$I = \left(\frac{1}{I_0 e^{C_0 \cdot U} + I_1 e^{C_1 \cdot U}} + \frac{1}{R_0 + R_1 U + R_2 \cdot U^2} \right)^{-1}, \qquad (1)$$

where I_1 and I_0 are the cut-off currents for diodes D1 and D0, C_0 and C_1 are the corresponding exponential factors, R_1 is the coefficient associated with resistance as well as R_0 and R_2 take into account the non-linearity of the resistance on heating.

In the program, to simplify the calculations, this formula evolves to the form

$$I = \left(\frac{1}{10^{i_0} \cdot 10^{C_0 \cdot U} + 10^{i_1} \cdot 10^{C_1 \cdot U}} + \frac{1}{R_0 + R_1 \cdot U + R_2 \cdot U^2} \right)^{-1}. \qquad (2)$$

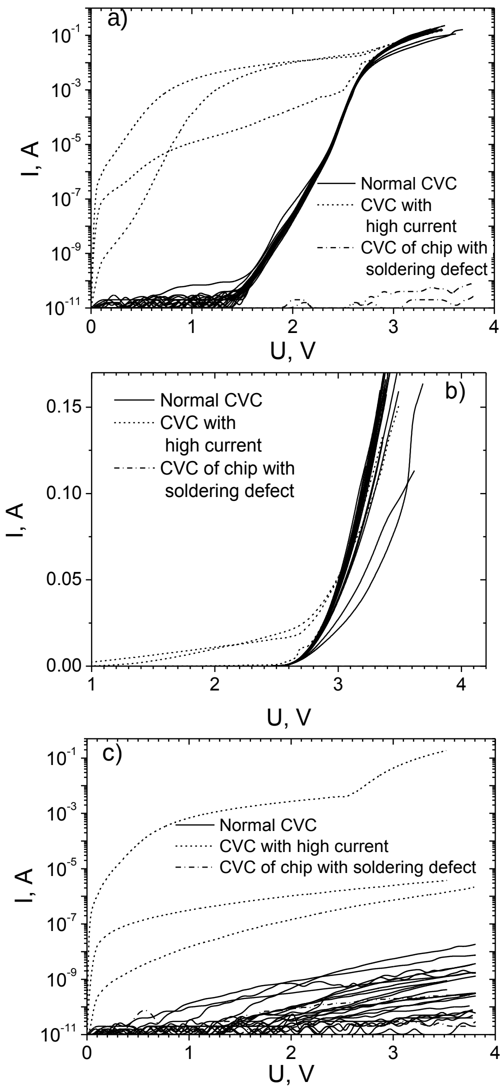
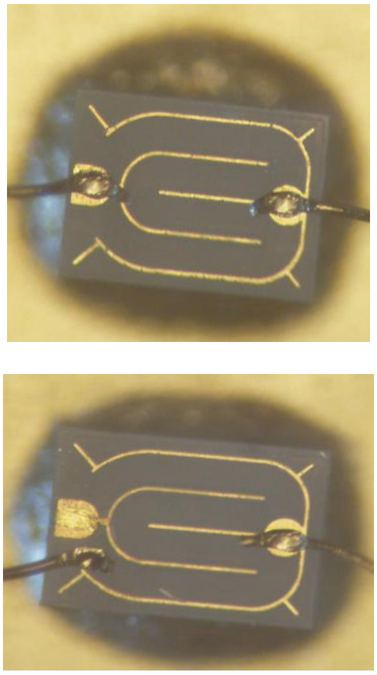


Fig. 3. Forward (*a*, *b*) and reverse (*c*) branches of CVC of LED module chips: (*a*) in linear coordinates, (*b*) in semi-logarithmic ones. The numbering is the same as that in Fig. 1b.

Study of coefficients of real chips indicated the clear (more than 0.95) linear correlation between the parameters of each element model (i_0 and C_0, i_1 and C_1, R_0, R_2 and R_2, respectively). Basic values of coefficients are listed in Table 1.

Table 1. Parameters approximation coefficients of the 21 LED chips in (2).

Parameter	The arithmetic mean	Median (most probable)	Standard deviation	Asymmetry coefficient
i_0	–27.6983	–27.7038	0.600160	0.635762
i_1	–19.4955	–19.4671	0.646147	1.341593
R_0	1.5737	1.6687	0.374458	–0.914235



a) *b*)

Fig. 4. Photos of chips with drawn contacts (*a*) and defect of soldering the contact (*b*).

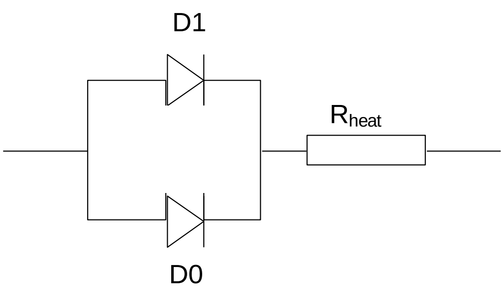


Fig. 5. Model of high-power LED: D0, D1 – ideal diodes, R_{heat} – non-linear resistance responsible for the heating up of a high-power LED during operation.

By comparing the values of the arithmetic mean and the median (Table 1), one can see that the distribution of most coefficients is not significantly different from normal one, although the parameter of nonlinear resistance have small (about 10%) peak asymmetry. It indicates a greater number of small (close to the minimum values) R_0 values. The calculated values of the asymmetry coefficient indicate distributions asymmetry of i_1, i_0 values and median bias towards the smaller values. In general, the data deviation from the normal distribution can be considered as non-significant, which allows to use a normal symmetrical distribution with the calculated median as the expected value in the model.

Because of the complexity to account for the small values of the terms, each of denominators of the fractions were separately calculated, then compared with others, the general current was calculated (Fig. 6) basing on the comparison results.

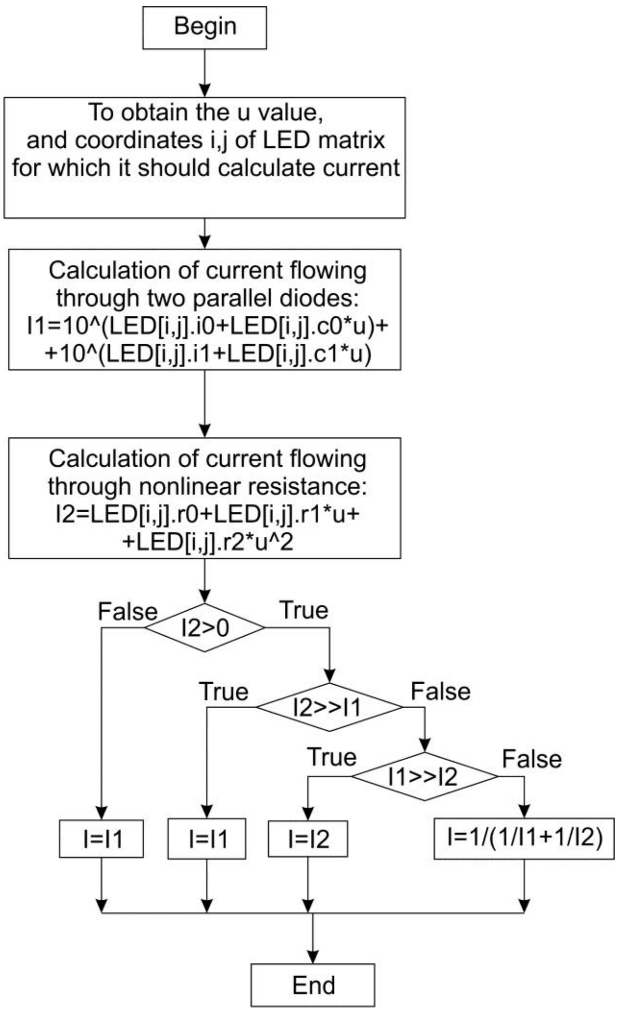


Fig. 6. Algorithm for calculating the CVC for high-power LED with known parameters.

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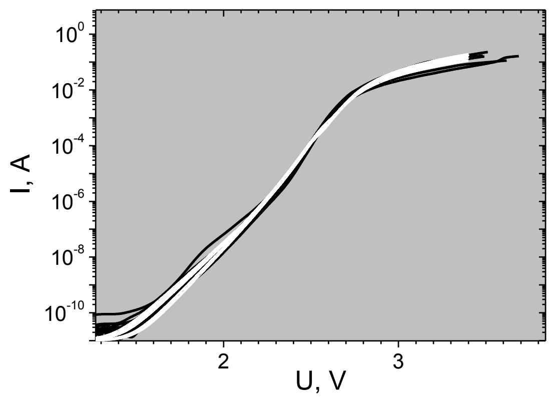

Fig. 7. Real current-voltage characteristics of LEDs (black) and modeled current-voltage characteristics, based on them, by the Monte-Carlo method (white).

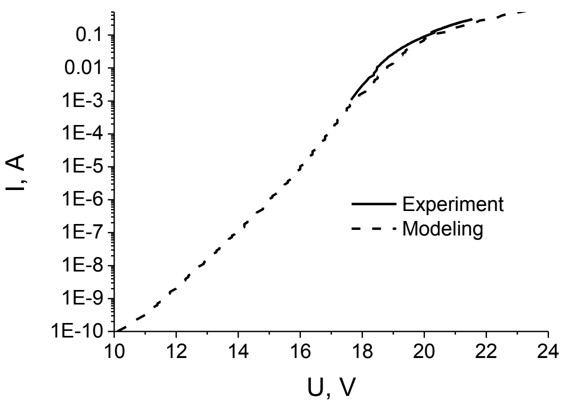

Fig. 8. Comparison of current-voltage characteristics of the LED module in the operation voltage range and the modeled current-voltage characteristics of the LED module with a variation of chip properties.

As in the most programming languages there is only a random number generator with a uniform distribution. For generating variation of LED parameters coinciding with the normal distribution, we used the formula [5]:

$$\xi(x_0,\sigma) = x_0 + \sigma \cdot a \cdot \sqrt{\frac{-2\ln\left(a^2+b^2\right)}{a^2+b^2}} \,,$$

where x_0 is the expected value, σ^2 – dispersion of a random value, a and $b$are random variables with uniform distribution, in which relations $-1 < a < 1$ and $-1 < b < 1$ are valid.

To test the results of modeling the LED CVC by using the Monte Carlo method, we selected group of initial parameters obeying the specified normal distribution (Fig. 7, white curves). For comparison, in the same Fig. 7 CVC of actual LED chips (excepting the anomalous CVC of chips) are represented with black colour. A good agreement of the model with the experiment not only in the operation limits of voltages (2.8…3 V), but also in the wider range is seen.

Table 2. Mean values and deviation of currents flowing through LEDs in the LED matrix.

Number of modeled LED	Mean current, A	Standard deviation	Minimum value, A	Maximum value, A
400	0.248206	0.045829	0.130364	0.390092
400	0.105404	0.017155	0.058014	0.153495
400	0.084945	0.013367	0.049298	0.126556
400	0.075775	0.012356	0.043098	0.115647
400	0.063335	0.009298	0.037065	0.089466
400	0.050814	0.007464	0.029898	0.07512
400	0.025733	0.002934	0.01736	0.033899
400	0.012698	0.000994	0.009763	0.015713
400	0.005002	0.000199	0.004354	0.00559

Calculating CVC of the group of high-power LEDs, the size of the LED matrix and the type of their connection were determined, and then the iterative methods were used. Voltage was calculated on a group of LEDs connected in parallel, and then, on the basis of the obtained results, currents flowing through each LED in the curcuit with accounting the general resistance were measured.

From the obtained data, the flowing current through each LED in the matrix was modeled (Table 2), and the distribution of currents was examined. The results indicate that variation of the initial parameters of the LED chips leads to a greater variation between them immediately during operation, without effecting significantly on the total current-voltage characteristics (Fig. 8). At the same time, the integral luminosity of the matrix is close to the nominal one. Even when an error welding of conduction contacts to the chip occurs, the chips in parallel will shine brighter due to the increased current flow, which will result to 5…7% reduction in the total integrated luminosity of general LED matrix. At the same time, this variation leads to overheating and rapid degradation of the individual LED chips, which can significantly effect on the service life of the LED matrix.

Conclusions

Analysis of the current-voltage characteristics of high-power LED chips of the company "EDISON Optocorporation" in the composition of LED modules had shown the presence of defects in connecting the wires to the chip and abnormally high current flow upon applied low voltages (the first of which is a defect of manufacturer of LED modules, the second – defect of chip supplier).

The developed software allows to simulate numerically the behavior of LED modules connected practically in any combination, to analyze the currents through any part of a modeled switching circuits. Modeling the LED chip by two parallel ideal diodes and consistent nonlinear resistance, manifested in the heating up stage of CVC, had shown high correlation coefficients between the internal parameters of individual elements and close to normal distribution of the basic parameters of these elements. This result confirms the correctness of the chosen model.

Analysis of existing switching-on of chips for a series-parallel circuit had shown that verification of the integrated luminosity or CVC of final product does not allow to identify the defects of supply wires or overvalued current transport due to the redistribution of the current in the LED module. However, this redistribution leads to an increase of current through the neighboring LEDs and their local overheating on the plate, which should lead to acceleration of degradation of the LED module.

Addition of internal sorting lines grouping the LED chips by the current value at operation voltages will allow to reduce variation between the chips and to increase the service life of finished products.

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