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Life-time characterization of LEDs

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Abstract. The paper's purpose is to describe and discuss the study of LED diodes, measured with the help of the TERALED system. A short description of the measurement system is given. Four batches of 5 mm LEDs and two batches of PowerLED diodes are measured and the comments and discussion of the measured results are given. The experiments show clearly that some manufacturer's LEDs do not match the parameters given in the datasheet. The reasons are not clear, but it seems to us that the problems of degradation of the construction materials of LEDs are not connected with the degradation of the semiconductor material itself.

Key words: LED, luminous flux, lifetime test, ageing.

1. INTRODUCTION

Despite considerable progress in LED technology, it is still in a stage of development. Today we already see devices, where one tiny, high-power LED is able to produce a brighter and better quality light output than the earlier and the massive arrays, containing 96 or more through-the-hole LEDs.

Regardless of the fact that the electroluminescence was first observed in 1907 by the British experimenter Round of Marconi Labs, using a crystal of silicon carbide and a cat's whisker detector [1] and the Russian Losev independently reported on the creation of an LED in 1927 [2], no practical use was made of the discovery for several decades [3]. Braunstein of the RCA reported on infrared emission from GaAs, GaSb, InP, and SiGe and other semiconductor alloys in 1955 at room temperature and at 77 K [4]. The first practical visible-spectrum (red) LED was developed in 1962 by Nick Holonyak Jr. [5], titled as the "father of the light-emitting diode". The first commercial LEDs were commonly used as replacements for incandescent and neon indicator lamps, and in seven-segment displays first in expensive laboratory and electronics test equipment, then later in such appliances as TVs, radios, telephones, calculators and even watches. These red LEDs were bright enough only for use as indicators, as the light output was not enough to illuminate an area. The first high-brightness blue LED was demonstrated by Nakamura and was based on InGaN borrowing on critical developments in GaN nucleation on sapphire substrates. Nakamura was awarded the 2006 Millennium Technology Prize for his invention. The development of LED technology has caused their efficiency and light output to rise exponentially, with a doubling occurring about every 36 months since the 1960s, in a way similar to Moore's law. This trend is normally called Haitz's Law [[6]]. In September 2003, a new type of blue LED was demonstrated by the company Cree Inc to provide 24 mW at the current of 20 mA. This produced a commercially packaged white light giving 65 lm/W. Practical general lighting needs high-power LEDs, of one watt or more. Typical operating currents for such devices begin at 350 mA. Cree issued a press release on 3 February 2010 about a laboratory prototype LED, achieving 208 lm/W at room temperature. The correlated colour temperature was reported to be 4579 K [[7]].

There are two primary ways of producing high-intensity white light using LEDs. One is to use individual LEDs that emit three primary colours – red, green, and blue – and then mix all the colours to form white light. The other is to use a phosphor material to convert monochromatic light from a blue or UV LED to broad-spectrum white light, much in the same way as a fluorescent light bulb works. Due to metamerism, it is possible to have different spectra that appear white. White light can be formed by mixing differently coloured lights, the most common method is to use red, green and blue (RGB). Hence the method is called multicoloured white LEDs (sometimes referred to as RGB LEDs). Because these LEDs need electronic circuits to control the blending and diffusion of different colours, they are seldom used to produce white lighting. Nevertheless, this method is particularly interesting in many uses because of the flexibility of mixing different colours [[8]], and, in principle, this mechanism also has higher quantum efficiency in producing white light.

The most common symptom of LED failure is the gradual lowering of light output and loss of efficiency. Sudden failures, although rare, can occur as well. With the development of high-power LEDs the devices are subjected to higher junction temperatures and higher current densities than the traditional ones. This causes stress on the material and may cause early light output degradation. To quantitatively classify lifetime in a standardized manner, it has been suggested to use the terms L75 and L50 which is the time a given LED needs to reach 75% and 50% light output, respectively. Another technical problem for multicolour-based LEDs is that the emission power decays exponentially with rising temperature [[9]], resulting in a substantial change in colour stability. Thus, many new package designs, aimed at solving this problem, have been proposed and their results are now being reproduced by researchers and scientists. The greatest barrier to high efficiency is the seemingly unavoidable Stokes energy loss. However, much effort is being spent on optimizing these devices to higher light output and higher operation temperatures. For instance, the efficiency can be raised by adapting better package design or by using a more suitable type of phosphor. Philips Lumileds' patented conformal coating process addresses the issue of varying phosphor thickness, giving the white LEDs a more homogeneous white light [10]. With the development ongoing, the efficiency of phosphor-based LEDs generally rises with every new product.

The aim of this work is to detect the existence of gradual lowering of light output of LEDs and to make an attempt to lead it back to the possible construction or manufacturing mistakes.

2. THE EXPERIMENT

Light sources are characterized by their photometric, colourimetric and radiometric parameters. All these parameters can be measured by the measurement system TERALED (ThErmal and RAdiometric characterization of LEDs) used in all measurements of this research [11]. A very important parameter for LEDs is also the junction-packaging thermal resistance. For regular semiconductor devices, the electrical power consumed is dissipated as heat. In case of LEDs, only about 10%–35% of the consumed electrical energy is emitted as light. This might lead to serious heat-sink problems.

The major part of the TERALED system is the 300 mm diameter integrating sphere, equipped with a reference LED, a Si photovoltaic cell, a computer-controlled filter bank and a temperature-controlled device under test (DUT) fixture. The reference LED, used for self-calibration, and the photometric detector are temperature stabilized. Due to the specific construction and coating of the inner surface with a BaS_4 layer, a higher than 98% reflectance is achieved from the integrating surface. The measurement system is shown in Fig. 1.

The main quality criteria of the measurement system is the photometric detector's spectral match to the CIE $V(\lambda)$ function. For example, the photometric detector, realized by the Si photovoltaic cell, and the $V(\lambda)$ filters, used in

(a) (b) (c)

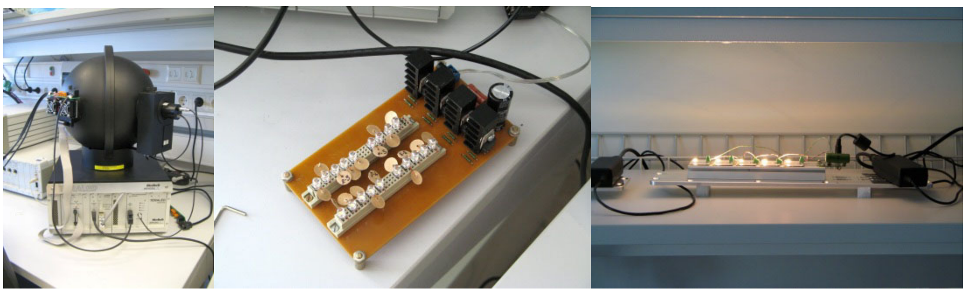


Fig. 1. The experiment: (a) the TERALED system; (b) the durability test rack of 5 mm LEDs; (c) the durability test rack of high-power LEDs.

the TERALED system, are matched to the CIE $V(\lambda)$ function with an error class $f_1 = 1.5\%$. The spectral response is shown in Fig. 2.

The TERALED system with the filter bank of 6 filters allows the measurement of the radiometric flux (flat response filter in the range of 380 to 780 nm), luminous flux ($V(\lambda)$ filter), scotopic flux ($V'(\lambda)$ filter), and the tri-stimulus values X, Y and Z. The filters for measuring the tri-stimulus values fit the CIE colour matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$. To improve accuracy, $\bar{x}(\lambda)$ is achieved by using two separate filters, optimized for $\bar{x}_{\text{long}}(\lambda)$ and $\bar{x}_{\text{short}}(\lambda)$, respectively.

Efficacy (also known as luminous efficiency) can be calculated as:

$$\eta = \frac{\Phi_v}{P_{\text{el}}}, \tag{1}$$

where Φ_v is the measured luminous flux and P_{el} is the applied electrical power.

To display the results in the CIE 1931 colour space chromaticity diagram, the colour coordinates x and y can be calculated as follows:

$$x = \frac{X_{\text{long}} + X_{\text{short}}}{(X_{\text{long}} + X_{\text{short}}) + Y + Z}, \qquad y = \frac{Y}{(X_{\text{long}} + X_{\text{short}}) + Y + Z}. \tag{2}$$

The selection of the 5 mm LEDs consisted of 10 pieces of Lucky Light LL-504WC-W2-2CC, 5 pieces of OptoSupply OSPW5161A-PQ white LEDs and 5 pieces of blue LEDs. The high-power LEDs were selected as 1W SMD PowerLEDs from Optek OVSPWBCR44, Malaysia, and Cree XREWHT-L1-0000-008E7, USA. The supply current was chosen according to the datasheets, 20 mA for 5 mm LEDs and 350 mA for PowerLEDs. A special PCB board was designed for high-power LED measurements.

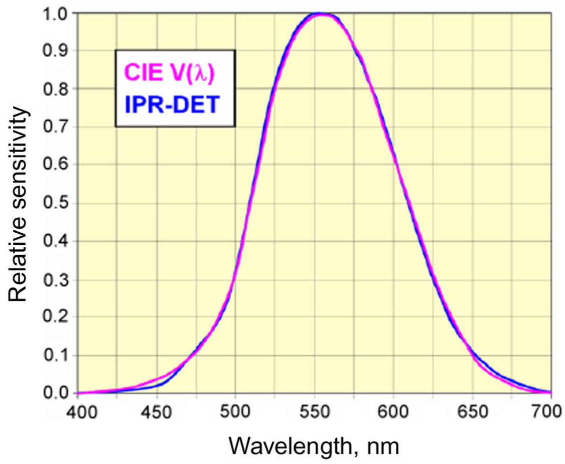


Fig. 2. The spectral response of the photometric detector in the TERALED system.

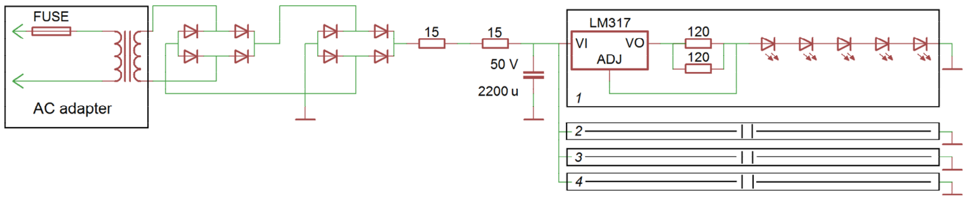


Fig. 3. The block scheme of the LED durability test rack.

The durability test required a special rack for the experiment. The main elements of the rack for 5 mm LEDs were a 220 V AC adapter, two full-wave rectifiers and four LM317 voltage regulators for providing a supply current for each branch of LEDs. In each branch, 5 LEDs (of the same batch) were connected in series. The calculated driving current was 20.7 mA. The block scheme of the rack is shown in Fig. 3.

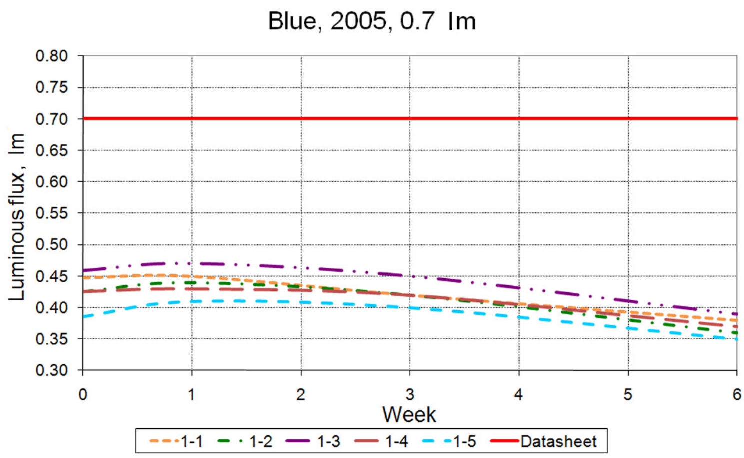
For high-power LEDs, a different current source was used, because 350 mA supply current was needed for the experiment. Additionally, the PCBs for high-power LEDs were connected to a heat sink to avoid or to minimize the influence of temperature rise during the experiments.

3. RESULTS AND DISCUSSION

First, the blue LEDs were examined. It is known that blue LEDs have significantly lower light output than white LEDs. Figure 4a shows clearly that for blue LEDs the gradual lowering of light output and loss of efficiency takes place already during 6 weeks. It can be seen that the quality of the LEDs already differs immediately after the manufacturing process. Also, the initial light output is considerably lower than the value stated in the datasheet. The difference between the lowest and highest value of the luminous flux is about 0.07 lm, which accords with about 15% of the luminous flux of the brightest blue LED. The experiments show that during the first week the measurement results improve itself of about 0.01–0.02 lm, but afterwards a clear decrease of the light output takes place. At the same time, the initial imbalance has slightly improved, but the luminous flux has strongly decreased. The main reason for such a behaviour can be lead back to the quality of the manufacturing process and the passivation layer around the emission junction of the diode.

Figure 4b shows the behaviour of the OptoSupply white LEDs. This selection of extremely cheap LEDs shows also the low quality level of the diodes themselves. It is clearly seen that for the majority of the selection, the initial luminous flux is twice lower than the datasheet predicts. And the difference in the light output between the LEDs in the batch is almost three times. After the first week, the luminous flux has decreased around 1 lm and after 6 weeks the light output of the whole batch is less than one third of the value given in the datasheet.

(a)



(b)

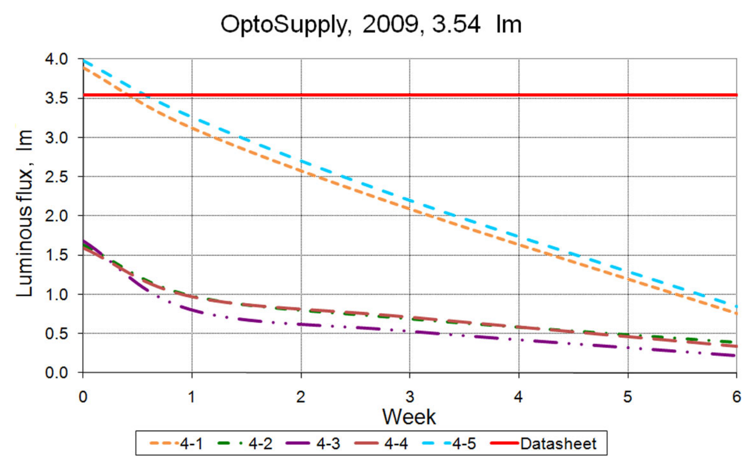
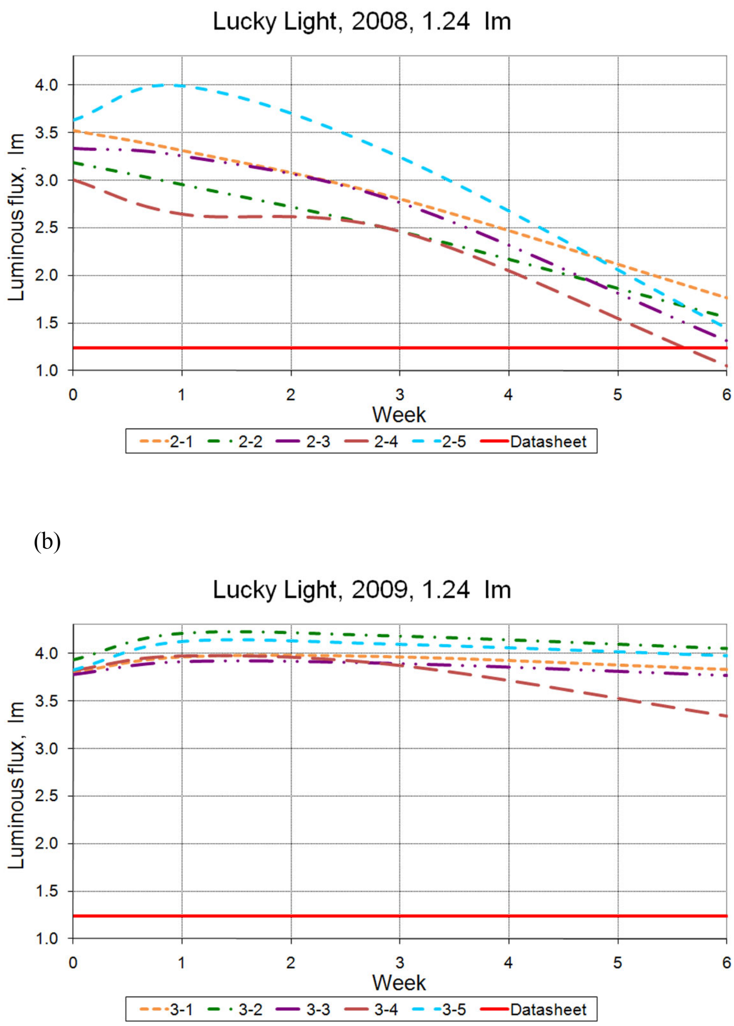


Fig. 4. Ageing results for LEDs (luminous flux versus time): (a) selection blue; (b) selection OptoSupply white.

Figure 5 shows the experimental results of two different batches of Lucky Light white LEDs, manufactured in different years (the purchasing years were 2008 and 2009). For the first selection (2008) the measurement results show that the difference in luminous flux between the LEDs is about 0.5 lm. It is clearly seen that for one LED, there is an increase in the light output after one week; for the rest of the diodes the luminous flux starts to decrease immediately. After 6 weeks the luminous flux is only a half of the initial value. It is interesting to mention that it is still in accordance with the given values in the datasheet. The initial light output turns out to be twice as high as the datasheet promises and

(a)



(b)

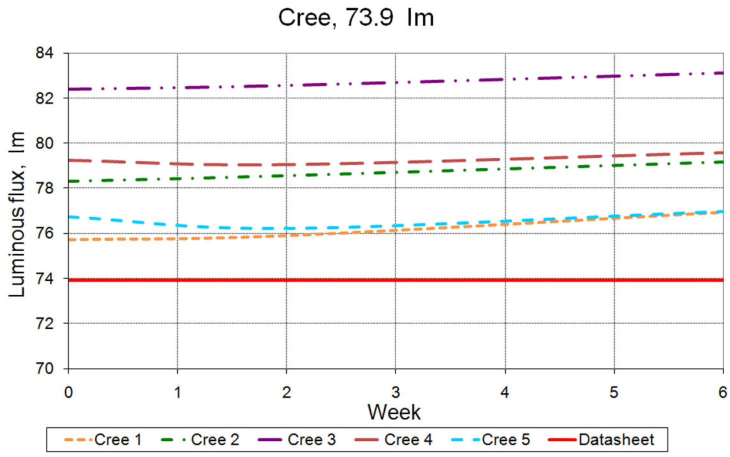
Fig. 5. Ageing results for Lucky Light white LEDs (luminous flux versus time): (a) selection 2008; (b) selection 2009.

after six weeks the values of the datasheet are achieved. Such a behaviour indicates clearly to the so-called run-in behaviour of some materials (probably phosphorus-based filter lenses in the construction of the LED).

For the second selection (2009) the results are different. The light output for unused LEDs is again about twice higher than the values in the datasheet, but among the different samples the difference is small. Also here, during the so-called run-in period, the luminous flux values increase and after 6 weeks the results are very well comparable with the initial values or even better. Only one diode shows a different behaviour, which to our opinion indicates to the problems of the sample quality compared to others.

The next analysis concerns the white-high power LEDs. Figure 6 shows the results for Cree and Optek selections. Figure 6a shows that Cree PowerLEDs have higher initial light output than the value given in the datasheet. The difference of light output between the selected samples reaches maximally 7 lm. After two weeks there is practically no change in the luminous flux and after 6 weeks the light output is even higher. Thus, for the Cree PowerLEDs the so-called run-in time is not observed during the first week. The fact, that after six

(a)



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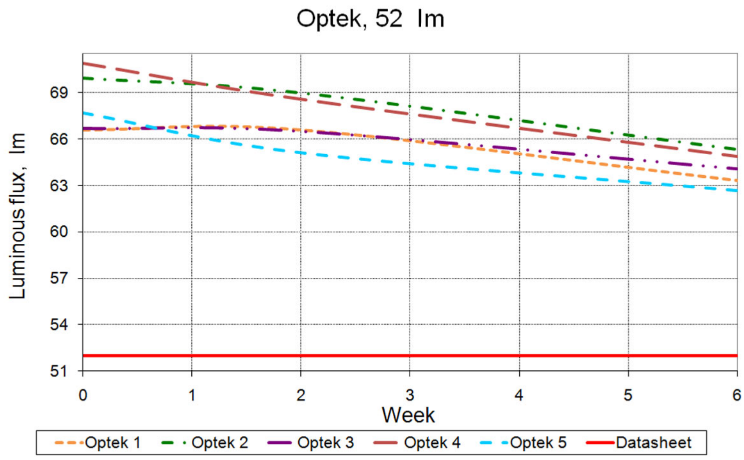

Fig. 6. Ageing of high-power LEDs at 25 °C ambient temperature: (a) Cree PowerLEDs; (b) Optek PowerLEDs.

weeks the measured luminous flux is higher than the initial values, gives a reason to believe that for Cree PowerLEDs the run-in time is a lot longer compared to 5 mm LEDs.

Figure 6b shows the experimental results for Optek PowerLEDs. As one can see, the results differ quite strongly compared to Cree PowerLEDs. The light output shows clear decreasing tendency during ageing of the LEDs. At the same time, the initial measured luminous flux is about 10 lm higher compared with the values in the datasheet. After being driven for 6 weeks, the light output has strongly decreased, but is still higher than that declared in the datasheet. The difference between the selected samples in measured luminous flux is about 2–4 lm. The measurements show another interesting behaviour of the diodes, which cannot be explained by the physics of the devices. Namely, if the Cree PowerLEDs show an increase of the luminous flux with the increase of the voltage drop over the devices, about 0.01–0.02 V, then with the Optek PowerLEDs the luminous flux decreases with the increase of the voltage drop. The voltage drop on LEDs is different from the values given in the datasheets: Cree PowerLEDs have a lower voltage drop of about 0.2 V and the Optek PowerLEDs even 0.5–0.6 V.

Finally, the measured colour coordinates of the high-power LEDs are depicted in the CIE 1931 colour space chromaticity diagram (Fig. 7).

Figure 7 can be used to explain the response of the human eye when looking at lighted LEDs. In Fig. 7a, the Cree PowerLEDs' colour coordinates' crossing point ($x = 0.433$, $y = 0.410$) is between the yellow and red area, so the light output feels "warm". In Fig. 7b, the Optek PowerLEDs' color coordinates' crossing point ($x = 0.330$, $y = 0.370$) is between the blue and green area, thus the light output feels "cold".

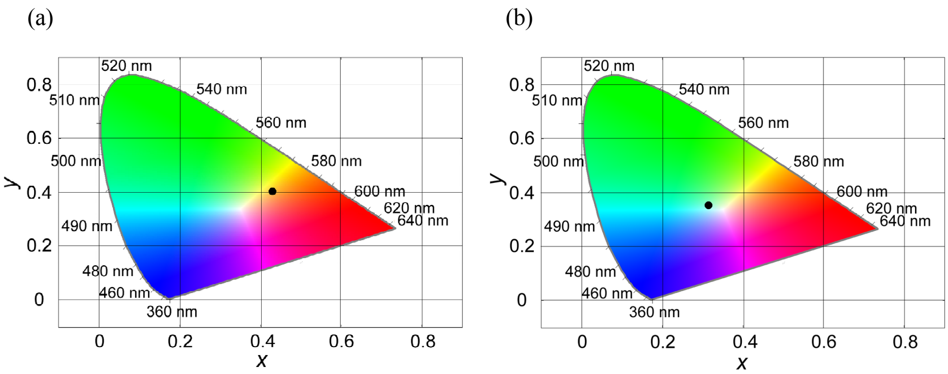

Fig. 7. Colour coordinates in the CIE 1931 colour space chromaticity diagram: (a) Cree PowerLEDs; (b) Optek PowerLEDs.

4. CONCLUSIONS

This research was initiated by the discussions between Prof. Toomas Rang and Prof. Marta Rencz about three years ago. The Thomas Johann Seebeck department of Electronics had just obtained the LED measurement equipment and for introductory research activities the measurement of 5 mm and high-power LEDs was planned. The results of these experiments are presented in this paper. Today the next step has been taken, namely, the improvement of a mathematical model of LEDs is under development as well as the continuation of ageing measurements using the so-called on-line technique.

The results of this particular research are simplified, because the ageing test was interrupted during the measurement acts. Thus, additional switchings on and off of the measured LEDs was included. For this reason, an additional on-line measurement of high-power LEDs is taking place and the comparison of the results will be available in autumn 2011.

This particular experiment gave us the following new information about the ageing information of LEDs.

- Almost all the 5 mm LEDs have a so-called run-in time, which is clearly seen on the light output characteristics. During this time, the lighting parameters of LEDs are improving and afterwards a relatively strong decrease in light output can follow. This behaviour cannot be lead back to material properties of the LEDs, but with a great probability the construction, housing and definitely the phosphor-based passivators or colour lenses are behind this phenomenon.
- The high-power LEDs have much higher quality as can be observed from the measurement results. In spite of the fact that both producers, Cree and Optek, are using the same material (SiC) produced by Cree, the light output behaviour during the ageing has a qualitatively different character. When Cree's samples keep the light output characteristics during the ageing time perfectly constant, the Optek PowerLEDs behave more similar to low-power LEDs, as we have seen by the 5 mm LEDs. This again seems to indicate that the Cree high-power LEDs have a better designed construction and side materials with improved lifetime parameters compared to LEDs, manufactured by Optek.

The results, obtained during this research, clearly encourage us to continue with the experiments and to start the development of exact mathematical models for LEDs. If possible, we shall also include the ageing phenomenon of the LED devices into the model.

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LED-dioodide eluea iseloomustamine

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Artikli eesmärk on kirjeldada ja analüüsida valgusdioodide (LED-ide) parameetreid ja karakteristikuid, kasutades eksperimentide läbiviimisel TERALED-mõõtesüsteemi. On esitatud lühike ülevaade LED-ide arengu olulisematest etappidest ja kirjeldatud kasutatud mõõtemetoodikat. Uurimise all oli neli komplekti 5 mm LED-e ja kaks komplekti suure võimsusega LED-e (PowerLEDs). Eksperimentaalsed uuringud näitasid, et mõnede tootjate LED-ide mõõdetud parameetrid ei lange kokku andmelehtedes esitatud andmetega. Lisaks kõrvalekalletele täheldasime peaaegu kõikide valgusdioodide puhul nn sissetöötamise perioodi olemasolu. See on aeg sisselülitamise järel, mille jooksul valgusparameetrid paranevad. Alles teatud aja möödudes hakkab toimima tegelik vananemisprotsess, mille jooksul hakkavad valgusparameetrid halvenema. Põhjused selliseks käitumiseks ei ole veel selged, kuid autorite arvates on tegemist konstruktsioonimaterjalide degradeerumisega, mitte muutustega pooljuhtmaterjalis endas.