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ABSTRACT

During the past few years several manufacturers have introduced white Light Emitting Diodes (LEDs). At the present time these LEDs do not provide sufficient luminous flux for general lighting applications. Many manufacturers are studying the possibility of grouping several LEDs and overdriving them to produce more luminous flux. The impact of higher drive current on long-term performance of LEDs is not well known within the lighting community. Therefore, an experimental study was conducted to investigate the photometric characteristics of white LEDs as a function of time for different drive currents. The LEDs investigated in this study were the 5-millimeter type that uses GaN-based blue LEDs and $Y_3Al_5O_{12}$ (yttrium aluminum garnet) phosphors (YAG phosphors). These LEDs produced 65 percent more light output at 55 mA compared to the light output at 20 mA. Groups of ten LEDs were driven continuously at constant current 20, 30, 50, 70, 90, and 110 mA and their relative light output were monitored at regular intervals for over 4000 hours. The light output degradation rate increased with increasing drive currents. Typically, LED manufacturers do not recommend driving these LEDs above 20 mA. However, it was noticed that the light output of these LEDs degraded to 65% of its initial value around 4000 hours even for those LEDs driven at 20 mA, which is the manufacturer recommended value for drive current. Considering the amount of flux produced by these 5mm type white LEDs and their light output degradation rate, they are not yet suitable for general lighting applications.

Keywords: White light, LED, general lighting, degradation

1.0 INTRODUCTION

In 1993 Gallium Nitride (GaN) based blue Light Emitting Diodes (LEDs) were introduced into the marketplace by Nichia Chemical Company of Japan [1, 2]. Since then the development of GaN-based LEDs has progressed rapidly, and several manufacturers have introduced white LEDs. Architectural lighting is one of the potential applications for this new technology. Although at present, white LEDs do not provide sufficient luminous flux for general lighting applications, experts in the field are optimistic that within the next few years these devices will provide higher luminous flux to make them attractive for architectural lighting applications [3]. Furthermore, researchers around the world are aggressively working on developing LEDs that produce ultra-violet (UV) radiation. These UV LEDs in combination with phosphors may ultimately produce the white light that is needed for architectural lighting applications. In anticipation of this promising application, several third-party manufacturers have introduced white light sources, using the 5-millimeter white LEDs, in a cluster form with screw bases for general lighting applications. Long life and potential for energy savings are two main factors that have captured the attention of the architectural lighting industry. Long life, 50,000 to 100,000 hours, is an advantage that is commonly claimed for LED devices. However, the term life as used in the LED industry may need revision for use in the lighting industry since the "useful life" of LEDs for the target application may be shorter, and will be discussed in this manuscript at a later section.

White LEDs produce higher light output with higher drive current. Some manufacturers exploit this feature to increase light output from the LED. However, the impact of higher drive current on long-term performance of LEDs is not well known within the lighting community. The goal of this study is to understand how the photometric parameters of white LEDs change with different drive currents and with time. A literature survey was conducted to identify what information is available in the public domain. The literature survey showed that during the past few years there have been an enormous number of publications related to GaN technology and devices and there were several publications attempting to identify the degradation mechanisms of GaN devices [3-5]. There were other papers including manufacturers' data sheets, that showed data for light output variation with time for GaN based blue LEDs [6-9]. However, there was no published information available on how the light output of GaN-based white LEDs depreciates over time. Therefore, an experimental study was conducted to understand the photometric characteristics of a sample of white LEDs at different drive currents and how these parameters change over time.

2.0 EXPERIMENT

The white LEDs used in this study were the 5-mm GaN-based blue LEDs with YAG phosphors. A short pilot study was conducted to gain better understanding of the behavior of white LEDs with different drive currents. The goals of this pilot study were to help design the apparatus needed for photometric testing of white LEDs, to help select the appropriate drive currents that would allow us to achieve the desired results, and to develop the necessary testing protocols.

In the first experiment of the pilot study, the white LEDs were driven at various constant currents, 20 mA to 120 mA dc, and the corresponding light output were recorded using an illuminance meter at a fixed distance. The light output data was gathered for 600 seconds at regular intervals and the results are illustrated in Figure. 1. It can be seen from Figure 1 that initially it takes about 180 seconds for the LED light out output reach stability. The same data are plotted differently in Figure 2, which shows relative light output as function of drive current at different time intervals. Both figures show that light output degradation rate increases with increasing drive current.

In a second experiment of the pilot study, the spectral power distributions of the LED light output were measured using an integrating sphere and a spectrometer. The LEDs were driven at constant currents, 10 mA to 120 mA dc at 10 mA intervals. Prior to collecting spectral data the LEDs were allowed to stabilize for 180 seconds after changing the drive current. Figure 3 illustrates the relative spectral power distributions (spd) of these white LEDs at 20, 40, 60, 80, 100 and 120 mA. Figure 3 shows partial data to avoid too many data in a single graph and to make it readable. The spectrum plots in Figure 3 are on a relative scale. It is interesting to see that the peak wavelength of the blue LED at 465 nm initially shifts towards shorter wavelength when the current is increased from 20 mA to about 60 mA. After that, the peak wavelength shifts towards longer wavelengths and at the same time the peak starts to broaden. This is different to what P. Schlotter and others have shown for their GaN-type white LED. In their study, the peak wavelength of the blue LED emission remains unchanged approximately at 420 nm for three-drive currents 2 mA, 10 mA, and 40 mA [10]. Similar to what we observed in our study, S. Nakamura, in one of his recent papers, showed blue shift of the emission spectra of a blue InGaN LED at various drive currents from 0.1 mA to 20 mA and mentions that blue LED on sapphire also showed similar behavior [8]. However, Nakamura's paper does not mention what happens when the drive current is increased further. It can be observed from Figure 3 that when the peak wavelength at 465 nm shifts towards higher wavelength and broadens the phosphor conversion efficiency decreases. As an example, comparing two spectral power distributions, at 20 mA and 120 mA, it is evident that the re-emitted portion of the light from the phosphor is higher at 20 mA than at 120 mA, even though the heights of the blue peaks are very similar. Figure 4 illustrates the measured color values plotted on the 1931 CIE chromaticity diagram for the different drive currents. The CIE x,y value of the light output at 10mA is on the blackbody locus. With increasing drive current the chromaticity value shifts towards blue and at 120 mA, LED light output appears distinctly blue. This is mainly due to decrease of phosphor conversion efficiency when the emission peak of the blue LED shifts towards longer wavelength. It was observed during this experiment that the LED returns to its original chromaticity value and appears white when the drive current was reduced back to 10 mA. This was only true for the short term testing.

Figure 5 illustrates how the relative luminous flux changes with different drive currents and the associated changes in relative efficacy. All the values were normalized to the 20 mA value since it is the manufacturer-recommended drive current value for these LEDs. As seen in Figure 5, the relative flux of the LED increases with drive current up to about 55 mA but decreases beyond that value. However, from the beginning, the efficacy of the LED decreases steadily with increasing drive current from 10 to 120 mA. From figure 5, it appears that the maximum light output gain is approximately 65 %, which occurs around 55 mA. At this point the efficacy is below 50 percent of the 20-mA value. From Figure 4 it can be seen that at 55 mA the chromaticity value is very close to the black-body locus and indicates that the color of the light is still white. These data are valid only for the plastic-encapsulated, 5 mm LEDs without additional heat sinks. The next question is what happens to the life of the LED when the drive current is increased to produce more flux. Based on the knowledge gained in the pilot study an experiment was designed to understand the affect of higher drive currents on LED life.

2.1 Life Test Experiment

Six drive currents, 20, 30, 50, 70, 90 and 110 mA, were selected for the life test experiment. All LEDs used in this investigation came from a single batch and from a single manufacturer. The LEDs were mounted on printed circuit boards with their current regulating circuits mounted behind the boards. An image of a single printed circuit board is shown in Figure 6, and the schematic of the current regulator circuit is shown in Figure 7. The wire traces on the circuit boards adjacent to the LEDs were 12 mils wide, and all circuit boards had identical dimensions. To study the affect of wire trace dimension, an additional circuit board was made with 50 mil wire traces, and the LEDs in this group were driven at 110 mA. The current in each individual LED is controlled by the LED's own circuit. Altogether, there were seven circuit boards (denoted as bay#1, bay#2, etc. in Figure 9) and each board carried ten LEDs, all driven at the same current.

During this experiment it was noticed that the light output of LEDs is very sensitive to the ambient temperature. Therefore, an imaging type setup as shown in Figure 8 was developed to ensure that the surrounding environment of the LEDs was not disturbed while gathering light output information. All seven circuit boards were mounted on a common mounting plate, and the system was driven by a regulated power supply at 12 Volts dc. The mounting plate with the LED circuit boards was placed vertically in front of an optically diffusive glass plate, and a CCD camera was placed on the opposite side as shown in Figure 8 to capture the luminance images of the LEDs. A sample camera image of the LEDs is shown in Figure 9. A software program associated with the CCD camera system was utilized to obtain the relative luminance of each individual LED. This was accomplished by drawing regions of interest, circular segments of the same diameter, around the LEDs, as shown in Figure 9. The software package automatically determines the total light output within these circular segments. Luminance images were captured at regular intervals with the same exposure time, and the software estimated the relative luminance of each individual LED. This procedure significantly simplified the data collection process. Two thermocouples, one at the middle of the top row and the other at the middle of the bottom row, were mounted to monitor the ambient temperature near the LEDs. The temperature at the bottom row where the 20 mA LEDs were situated remained around 25^{o}C throughout the experiment. The temperature at the top row was initially around 55^{o}C and after the 110 mA LEDs ceased to operate the temperature dropped to around 45^{o}C. Although the test room had a temperature controller, it was not sufficient to maintain the operating temperature of the LEDs to within 0.5^{o}C. There was an overall random temperature swing of about 5^{o}C during the experimental period.

Figure 10 illustrates the mean light output value of the ten LEDs on each board for all seven boards. At the time this manuscript was prepared, the LEDs have continuously operated for over 4000 hours. As expected the light output depreciation increased with increasing drive current. The ambient temperature fluctuation directly impacts light output and is seen in each light output depreciation curve as small oscillation about the average trend.

Of the two boards operated at 110 mA, the one that had thinner wire traces had slightly faster light output depreciation compared to the one that had thicker wire traces. The thinner wired circuit LEDs show slightly higher light output compared to the thicker wired circuit LEDs towards the end when the light output remains unchanged. It appears that with more heat sink the light output depreciation rate can be reduced. More experimentation is needed to confirm this effect and to explain why the LEDs with thinner wires end up at higher light level than the one with thicker wires.

It is interesting to see from Figure 10 that the light output reached 65% of its initial value around 4000 hours for those LEDs driven at 20 mA, which is the manufacturer-recommended drive current. This light output degradation rate seems excessive compared to data published in literature for GaN-based blue LEDs [7]. The authors suspect the increased degradation rate is due to either degrading phosphor [11] or change in transmittance of the encapsulating plastic [9]. However, this cannot be confirmed without additional testing. Currently, the LED industry rates LED life at 50 percent light output. Typically, this is done by gathering data for a limited time and extrapolating it to the necessary light output value. A logarithmic curve fit is commonly used for this extrapolation. Although, this may work for GaN and AlGaP LEDs the same extrapolation may not be valid for white LEDs since they have an additional component, namely the phosphor, which degrades along with the semiconductor device. From the data gathered so far, the life of the LED at 50% light output can be obtained directly for drive currents 110, 90, 70 and 50 mA. However, for drive currents 30 mA and 20 mA, the data points have to be extrapolated. Its appears that these white LEDs would reach 50% light output around 5000 to 6000 hours at these two drive current, which is much shorter than commonly assumed 50,000 to 100,000 hours life.

The graphs shown in Figure 10 raises an interesting question regarding the definition of life for these LEDs, especially if they are to be used for general illumination applications. Unlike other light sources used in the illumination industry that fail to produce light after a period of time due to failed electrodes or filaments, LEDs in general do not fail catastrophically. However, the light output slowly depreciates over time. Therefore, the key question is what is the useful life of a white LED for general illumination applications? Some of the characteristics of LEDs resemble the characteristics of certain metal halide lamps used in general illumination applications. Similar to these types of metal halide lamps, the 5-mm white LEDs also have significant color variation between similar LEDs. Also, the light output depreciation curves for these LEDs look very similar to those for some metal halide lamps. Although, the term life for metal halide lamps denote the time at which 50 percent of lamps survive and 50 percent have ceased to operate, their useful life is about 60 to 70 percent of their rated life. This is mainly due to the fact that metal halide lamps have high lumen depreciation rates and undergo color shift. As an example, a metal halide lamp rated at 10,000 hours has about 6000 hours of useful life. At this point the metal halide lamp produces about 70 percent of its initial light output. Usually, manufacturers recommend the useful life as the time for group relamping of metal halide lamps in certain applications [12]. The LED light sources intended for use in the illumination industry also need a similar useful life definition based on light output and color shift.

3.0 SUMMARY

An experimental study was conducted to investigate the photometric characteristics of white LEDs over time for different drive currents. The LEDs were characterized for light output and color shift when they were driven at constant currents, ranging from 10 mA to 120mA. With increasing current, light output increased; however, the rate of light output degradation also increased. The color of the light output shifted towards blue with increased current and at 120mA it appeared distinctly blue.

To understand how drive currents affect the light output of LEDs over time, groups of ten LEDs were driven continuously at constant current, 20, 30, 50, 70, 90, and 110mA, and their relative light output were monitored at regular intervals for over 4000 hours. As expected, the light output degradation rate increased with increasing drive currents. It was noticed from the experimental results that the light output reached 65% of its initial value around 4000 hours even for those LEDs driven at 20 mA, which is the manufacturer-recommended drive current value. Its appears from the data that these white LEDs would reach 50% light output around 5000 to 6000 hours which is much shorter than commonly claimed 50,000 to 100,000 hours life. This light output degradation rate seems excessive. Therefore, the authors suspect the increased degradation rate is due to either degradation of phosphor and/or change in transmittance of the encapsulating plastic. All LEDs used in the initial investigation came from a single batch and from a single manufacturer. A second group of LEDs, bought from two different manufacturers at a later time, was subjected to similar testing. These LEDs have, to date, lasted 2000 hours, and the light output degradation curves look very similar to the ones observed from the first test. The results of the second test will be published elsewhere once sufficient data are collected to confirm their performance. An important lesson learned in this study is that the LED sources intended for use in the illumination industry need a useful life definition based on light output and color shift to better represent the life time of LED light sources.

The authors of this paper wish to point out that the progress of white LEDs has been rapid over the past year, and therefore the absolute values for light output degradation and color shift may be different for some of the newer products. In addition, the usefulness of the source will depend very much on how the LEDs are packaged to form the light source. Although, at the present time original equipment manufacturers (OEMs) are using these 5-mm white LEDs to form white light sources, they are not yet suitable for general illumination applications, since they produce very little light and they have short useful life. LED device manufacturers are working on devices that produce more light from a single LED and are in the process of improving their overall performance by providing improved heat sinks to meet the needs of the target applications.

4.0 ACKNOWLEDGMENTS

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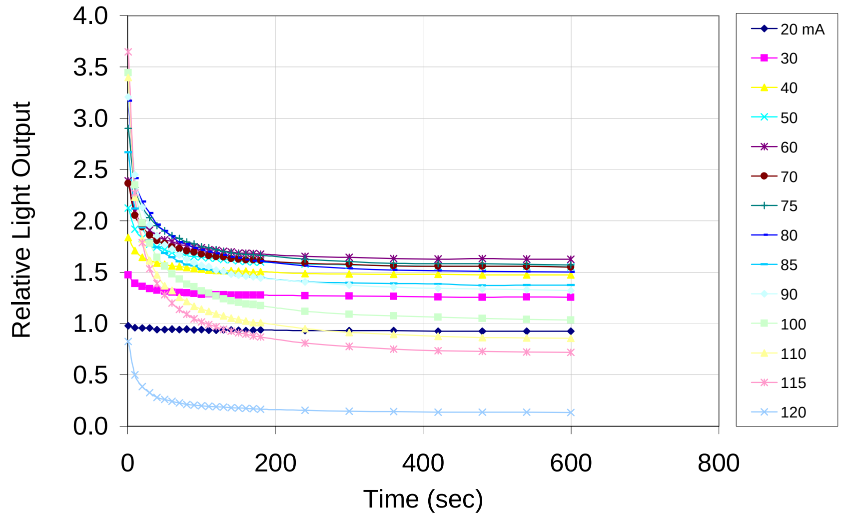

Figure 1: Relative light output as a function time for different

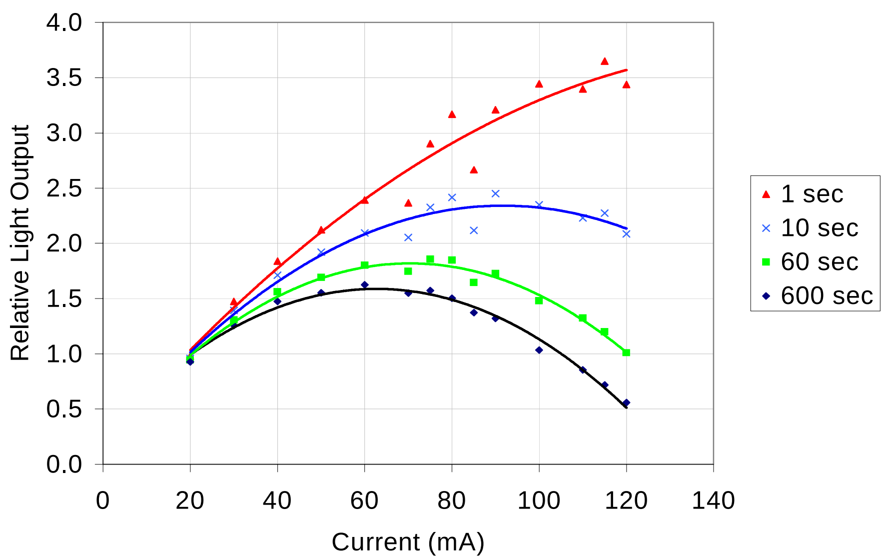

Figure 2: Light output variation as a function of drive currents at different time intervals

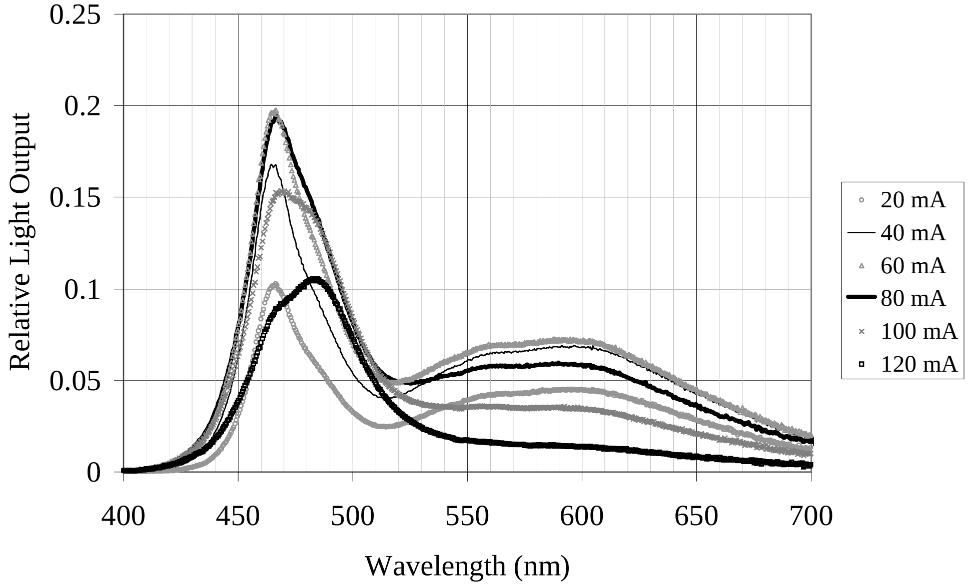

Figure 3: The measured spectral power distribution at various drive currents

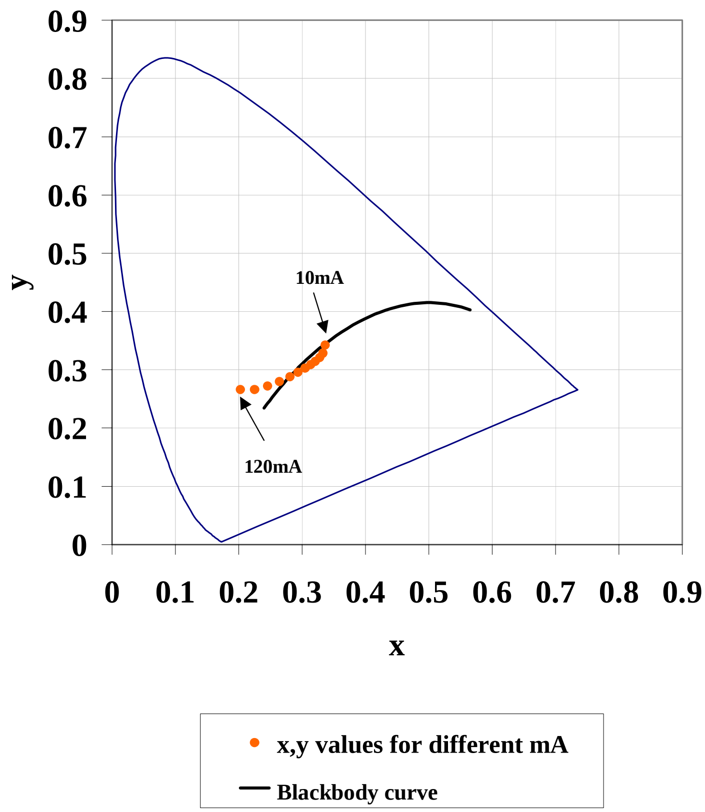

Figure 4: The measured CIE x,y values for different drive currents

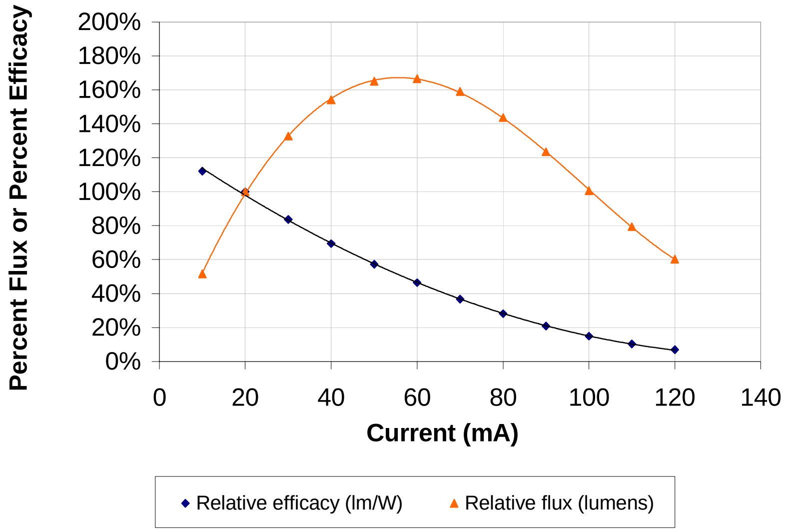

Figure 5: Plot of relative flux output of a white LED as a function of drive current and the corresponding relative efficacy values.

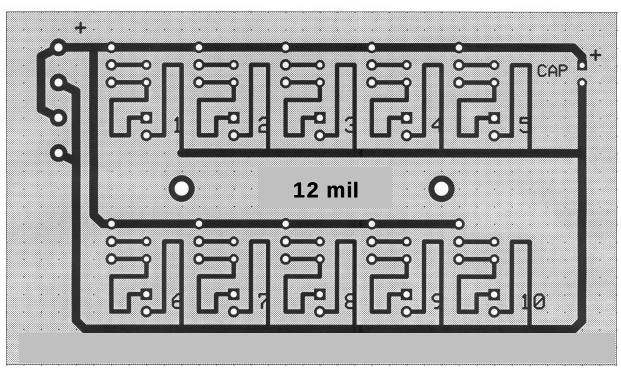

Figure 6: Layout of the printed circuit board.

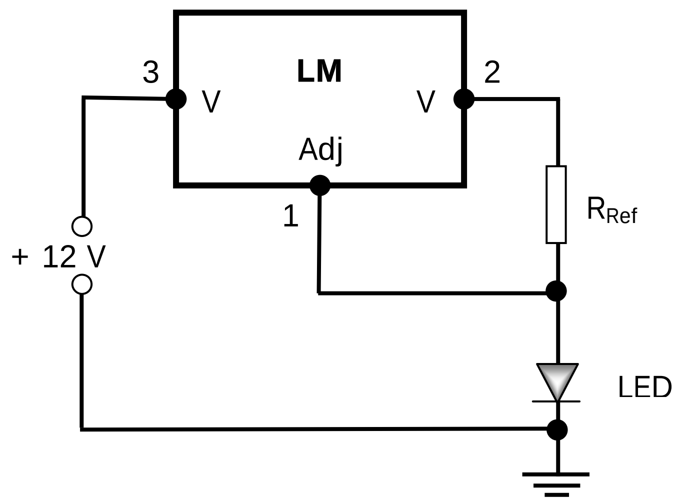

Figure 7. The regulator circuit used for controlling the current through the LED.

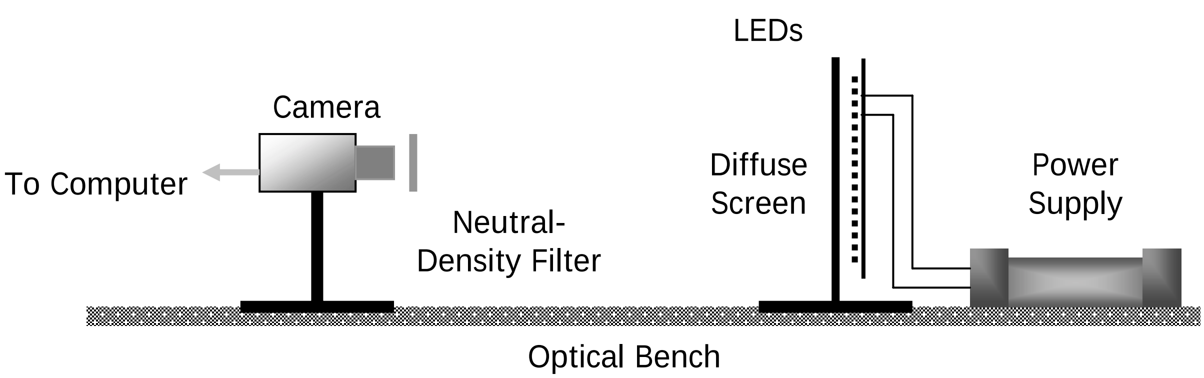

Figure 8. Life test experimental setup.

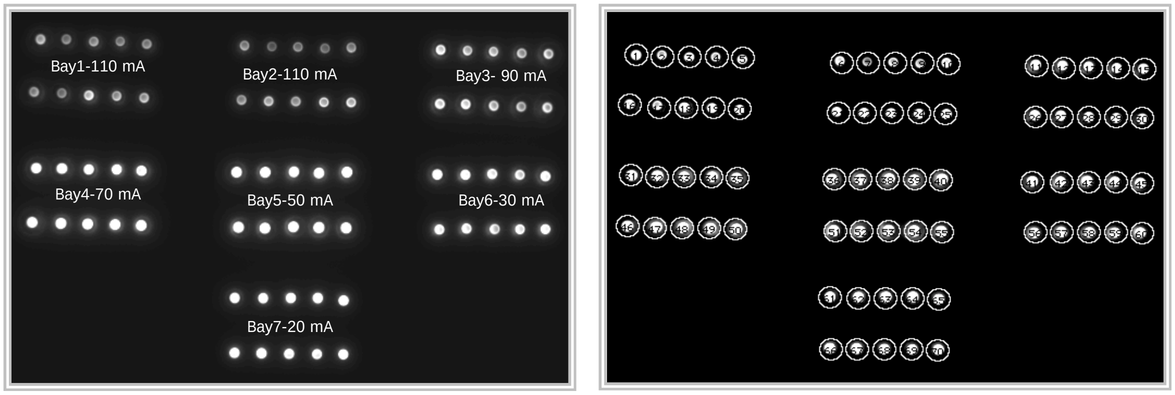

Figure 9. Sample intensity images captured using the digital camera. (a) Image of the board layout with corresponding drive-current for each bay. (b) The same image with circular segments drawn around each LED.

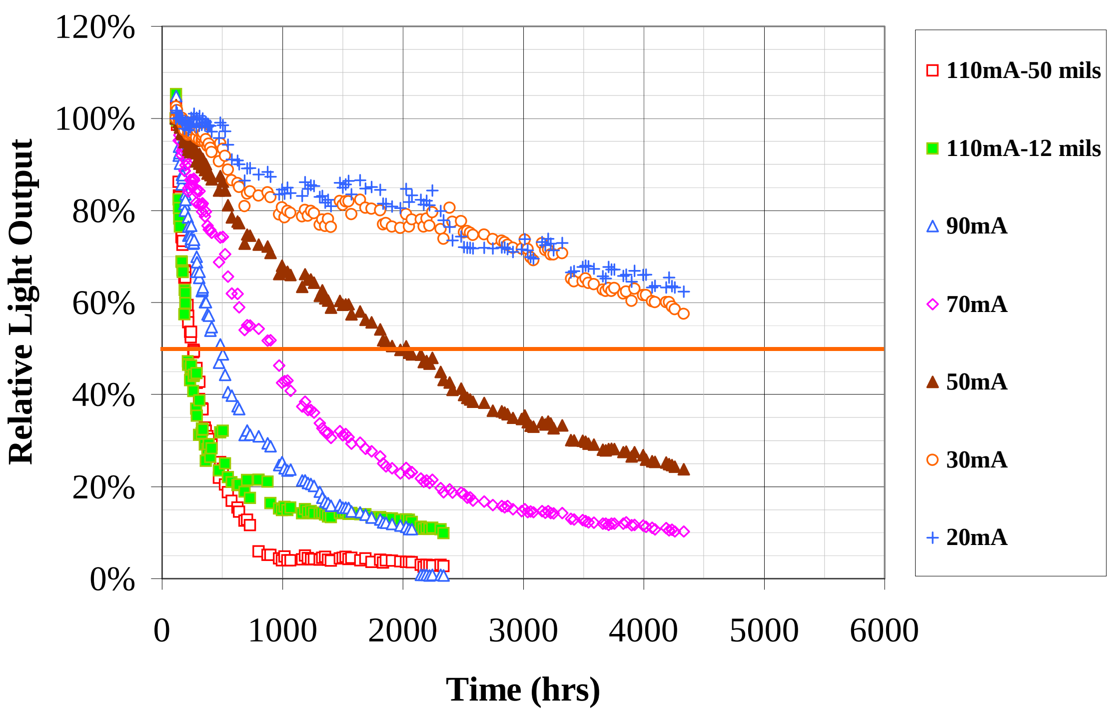

Figure 10: Light output data as a function time and drive current.