Life tests of Nichia AlGaIn/GaN blue-light-emitting diodes

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ABSTRACT

We report on the results of life testing Nichia NLPB500 blue LEDs. All tests were performed with the LEDs in a temperature controlled chamber, and all equipment operation and data collection was computer automated. The tests began with 18 newer (Nichia batch 4B0001) and two older (Nichia batch S403024, acquired a year earlier) LEDs, operated at 20 mA continuous wave (CW) and 23°C. Light from each LED was coupled to an optical fiber and fed directly to individual photodetectors. The general trend for the 18 newer LEDs was for the output intensity to increase at a faster rate within the first 50 h and then at a slower rate over the remainder of the first test. The output intensity of the two older LEDs increased within the first 50 h then decreased during the remainder of the first 1000 h. All 20 of the LEDs in the first 1000-h test were subjected to a second 1650-h test at 23°C and at currents ranging from 20 mA to 70 mA CW. Only one LED, an older device, suffered a soft failure during this second test. The remaining LEDs underwent a third test at 30°C and a fourth test at 35°C, all at various currents. We will perform failure analysis on all sufficiently degraded devices and report those results elsewhere.

Keywords: Optoelectronics, LED, GaN, Group III Nitrides, Blue, Life Test, Degradation

1. INTRODUCTION

A bright blue LED, if it could be proven reliable with a lifetime on the order of 10,000 h, would be very attractive in applications such as flat panel displays, outdoor traffic signals, or even indoor room lighting^{1,2}. There exists a class of remarkably bright (1.2 mW, 450 nm, 1 cd--as of late 1994) GaN-based blue LEDs, the NLPB 500 series, produced exclusively by Nichia Chemical Industries, Ltd.³. Nichia's brilliant success has shifted the efforts of many optoelectronics researchers, who were searching for the electrically pumped semiconductor blue laser, to the group III-nitride materials. The reliability and, subsequently, the failure analysis of Nichia's GaN-based blue LEDs is of great interest at this time. Data sheets from Nichia, received 10/22/95, showed a sustained relative luminous intensity in the 90 to 98% range for LEDs operated at room temperature and 20 mA DC for 2000 h⁴. As this paper will show, Nichia's estimates of LED performance were conservative.

Only one other published paper was found which included life testing of the Nichia LEDs. John Lindberg at Abbot Laboratories began life testing Nichia GaN blue LEDs in June of 1994. Lindberg operated the LEDs at room temperature and constant currents and was looking for hard failures, the cessation of visible output. Lindberg drove five LEDs each at a given current and found that the degradation of output power was proportional to drive currents of 30, 40, 50, and 60 mA⁵. As of January 1996, after about 15,000 h of testing, Lindberg's study had produced the following results. The LEDs driven at 60 mA all failed after about 11,000 h. Some of the 50-mA LEDs had failed as of the 15,000-hour mark. And all of the 30- and 40-mA LEDs still had acceptable outputs⁶.

The Nichia NLPB 500 blue LED is of considerable interest since this highly efficient LED is considered a step toward a blue semiconductor laser. When a blue semiconductor laser is sufficiently developed to have a lifetime on the order of 10,000 h, it will have many exciting applications⁷. One major contribution will be to increase the density of optically stored information. In December of 1995 Nichia announced they had produced the first nitride-based blue laser diode. It consisted of InGaIn active, GaN guiding, and AlGaIn cladding layers. It was a multi-quantum well (MQW) laser operated in a pulsed mode at room temperature with an output near 410 nm⁸. The next commercial LEDs from Nichia will have a MQW structure and will be life tested by us.

2. GOALS OF PRESENT LIFE TESTING

The goals of the present life testing included control of the environmental temperature and LED drive current to within a few percent. Another goal was the automated *in situ* recording of the voltage across each LED and the relative intensity of each LED⁹. Thus, a meaningful record of the operating history of the LEDs would be obtained.

Because the present study varied two parameters, environmental temperature and drive current, it was not our intention to predict or model LED lifetimes¹⁰. Instead, the intent was to produce soft failures (relative intensity reduced to 50% of its original value) which left the LEDs operational. Failed LEDs would then undergo extensive failure analysis using measurement techniques such as: I-V characteristics, forward resistance, electron beam induced current (EBIC), transmission electron microscopy (TEM), and focused ion beam (FIB) analysis¹¹.

3. DESIGN OF LIFE TESTING SYSTEM

A complete, and very expensive, system for life testing LEDs would include the *in situ* monitoring of output power and light spectrum for each LED as well as full temperature control of all temperature sensitive components (such as drive circuitry) in the test. Because of the cost of the required life testing equipment and the time involved, few commercial companies are able to extract such exhaustive life test data from their optoelectronic products. Gathering this life testing data would not be a cost-effective or timely feedback mechanism for improving the manufacturing process of the devices.

The present life testing system was designed to control and monitor each LED's voltage, current, and intensity; as well as the supply voltage, the time data was recorded, and the chamber temperature. Twenty Nichia GaN blue LEDs were tested, 18 newer LEDs (Nichia batch 4B0001), purchased in 1995, and two older LEDs (Nichia batch S403024), purchased in 1994. The LEDs were placed electrically in parallel, and failed devices were removed from the test for failure analysis.

A block diagram of the life testing system used is shown in Fig. 1. All test control and measurements were fully computer automated across an IEEE-488 bus. The computer used to automate all tasks was a 66-MHz, 486-based PC-compatible computer, running version 3.12 of Hewlett Packard's HP VEE, an iconic programming language for test and measurement. The current status of the test was constantly visible on the computer's monitor.

During the first 1000 h of testing, LED currents were controlled using two methods. An op-amp circuit was designed to provide constant current to one half of the LEDs even if the LED resistances changed. For comparison, we also designed a circuit based on current limiting resistors, designed to prevent excessive current drain in any one LED. The resistor-based circuit relied on the constant voltage from its power supply. In theory, the op-amp circuit was to provide better current regulation. After the first 1000 h of testing, we found that both designs adequately controlled the drive current. In later segments of the life testing, where higher drive currents were required, the resistor-based circuit was more easily adapted to handle the higher currents. The use of a circuit board that supplied approximately constant current to each LED allowed the use of a single power supply (with an ample maximum current rating) to power all 20 LEDs. The power supply was a Keithley model 238, set up as a constant voltage source, with remote voltage sensing at the current distribution circuit board.

All LEDs were operated in a large temperature chamber (a Thermotron, with model 2800 programmer controller). A fiber optic probe was secured to the output end of each LED. A metallic fixture held each fiber-LED pair in a fixed relationship. The fibers traveled outside the temperature chamber, and each was coupled to a PIN-10D silicon photodiode using a fixture that blocked the ambient light. Three switch banks (Wavetek 500 MHz/10 channel switching system, model 601) and two switch controllers (Wavetek switcher control panel, model 603) were used to obtain data from the 20 separate channels. LED intensity was monitored by recording detector currents (at first with a Keithley model 485 autoranging picoameter, and later with a Hewlett Packard 4140B picoameter). LED voltage and current were measured with a Hewlett Packard model 3478A multimeter. LED voltage was monitored at the LED contacts, while LED current was derived from the voltage across the 1- Ω resistors on the current distribution board.

Fig. 1. Block diagram of the life testing system used

4. MONITORING LED OPTICAL OUTPUT

Since only a portion of the LED's output would be monitored during actual testing, a well controlled pre- and post-test power measurement system was incorporated as a check on the *in situ* intensity data. The power measurements utilized a 5-inch diameter Labsphere optical integrating sphere, a Newport optical power meter model 835, and a Newport detector model 818-SL. Forty power readings were taken during a three-minute warm-up of the LED and were computer controlled for consistent timing between measurements. Power data were recorded as the average of 10 readings.

Initially we expected the measurement of the real-time intensity to correlate with pre- and post-test power measurements. We found the two sets of measurements to be in quantitative disagreement, and for good reasons. Real-time intensity data showed the gradual changes in LED output over long continuous test periods and often revealed warm-up or burn-in periods of 50 to 100 h, during which the output intensity would increase. The *in situ* monitoring of LED intensities also helped avoid catastrophic failures. Intensities were monitored once per hour for the first 10 h then once each 12 h for the remainder of each test. In contrast, the optical power data represented measurements on LEDs running for only a few minutes after a long rest period. The post-test power readings proved very useful in confirming the degree of degradation in LED which suffered soft failures.

5. TEST CONDITIONS

Table 1 shows the parameters used for each of the four phases of the life testing. Forward currents varied from 20 to 70 mA, with 20 mA being the rated operating current and 70 mA being a reasonable maximum before a roll-off in output intensity occurred. Test chamber temperatures ranged from 23°C to 35°C to simulate room temperature and warm ambient operating temperatures of LEDs in display applications. Temperatures much higher than 35°C were also deemed unnecessary since constant, gradual degradation in LED output was seen at 30°C and because soft failures were the aim of this testing. Test duration varied from 500 to 1650 h. Tests 3 and 4 ran for 500 h to represent the time that most LEDs would need to undergo any possible increases in intensity and then stabilize.

	Test 1 1000 h 23°C	Test 2 1650 h 23°C	Test 3 500 h 30°C	Test 4 500 h 35°C
Newer LEDs	18 @ 20 mA	3 @ 20 mA 3 @ 30 mA 3 @ 40 mA 3 @ 50 mA 3 @ 60 mA 3 @ 70 mA	3 @ 20 mA 3 @ 30 mA 3 @ 40 mA 3 @ 50 mA 3 @ 60 mA 2 @ 70 mA	3 @ 20 mA 3 @ 30 mA 3 @ 40 mA 3 @ 50 mA 3 @ 60 mA 2 @ 70 mA 1 SOFT FAILURE
Older LEDs	2 @ 20 mA	1 @ 70 mA SOFT FAILURE 1 @ 20 mA	1 @ 20 mA	1 @ 20 mA

Table 1. Life test conditions for the four phases of testing

6. DISCUSSION OF DATA

The most concise and meaningful representation of LED performance was given by a graph of relative intensity versus elapsed time. To present the relative changes in an LED's intensity over all of the tests, discontinuities were removed by adjusting intensity data. The discontinuities in the intensity data which were accounted for were:

- Temporary rises in temperature to 28°C for 48 h and to 31°C for 72 h during Test 1. These rises caused only temporary changes (mostly decreases) in the output intensities of the LEDs.
- Temporary loss of electrical contact to an LED near the end of Test 1.
- Known physical misalignment of five LEDs and their fibers when DUT #19 was removed from Test 2 with testing in progress.
- Some erroneous detector currents for two of the LEDs, caused by a failure of a Keithley 485 autoranging picoameter. The Keithley 485 was removed from the test and replaced.

- Discontinuities due to system restarts following two weather related power disruptions.
- Discontinuities from one test segment (Test 1, 2, etc.) to another.

The continuous graph of percentage change in relative intensity values is shown in Fig. 2. The intensity values are averaged over all LEDs operating under the same conditions (usually three LEDs per group). By referring to Table 1, the number of LEDs used to obtain these average intensities can be seen.

Fig. 2. Percentage change in relative intensity for the LEDs tested, averaged according to drive current

Because there were typically only three newer LEDs per drive-current group, taking an average of the intensity values did little to smooth out the effects of atypical LEDs. There were two specific examples of this. Only one LED out of three in the 30-mA group showed an increase in intensity of 10 to 15% over the first 100 to 200 h of Tests 1 through 4. Thus, the LED with the unusually high intensity dominated the average of the 30-mA group. The second occurrence of an outlying LED occurred during Test 2; one of the three LEDs in the 50-mA group did not degrade. These two instances may be the reason that the 30-mA data exceeds the 20-mA data and the 50-mA data exceeds the 40-mA data in Fig. 2.

In Test 1 the general trend for all LEDs was for output intensity to increase more quickly over the first 50 to 100 h. The newer LEDs then continued to slowly increase in intensity, while the older LEDs began to decrease.

In Test 2 the LEDs were separated into groups of different drive currents. The older LED at 20 mA continued its gradual decline in output intensity. The older LED at 70 mA suffered a catastrophic decline in intensity to 50% of its original value and was removed from Test 2 after about 250 h. The newer LEDs were divided into groups of three, and a group was driven at 20, 30, 40, 50, 60, or 70 mA. The intensity of the newer 20-mA LEDs continued to slowly increase then leveled out at 10% above the initial value. The intensities of the 30-, 40-, 50-, 60-, and 70-mA groups all began to decline, with the decline being proportional to drive current. This proportionality did not apply to the 50-mA group, which contained one LED of unusually high intensity.

In Test 3 the temperature was increased to 30°C. The intensity of the older LED, now at 20 mA, showed a slight increase, possibly indicating that a temperature above 23°C had reversed some of the ill effects of Test 1. The newer LEDs at 20 mA maintained their performance at 10% above their initial average intensity value. Newer LEDs driven above 20 mA continued to decline in intensity, but at a greater rate than they did during Test 1. The temperature increase to 30°C appeared to be increasing the activity of the degradation mechanisms occurring within these LEDs.

In Test 4 the temperature was increased to 35°C. The intensity of the older 20-mA LED continued its increase. During Test 4 the newer LEDs driven at 20 mA continued to hold an intensity 10% above their initial average value. The newer LEDs at higher currents all continued to decline in intensity, with no noticeable change in slope relative to their performances at 30°C (as in Test 3).

7. CONCLUSIONS

Soft failures of Nichia AlGaIn/InGaIn/GaN blue LEDs were more difficult to produce than expected.

These LEDs showed lifetimes well in excess of 4000 h at their recommended operating current of 20 mA. A burn-in period for these 20-mA LEDs was evident, with their average intensity increasing to 110% of initial intensity. No degradation in output intensity was seen for the 20-mA LEDs after 3600 h of testing, even with 1000 h of the test being run at 30 to 35°C.

According to Nichia's own data sheets, the maximum allowable forward current for these LEDs is 30 mA. During the present testing, LEDs driven at 30 mA showed a slight increase in intensity after 3600 h.

The final intensity values for the 18 newer LEDs were as follows:

<u>Drive Current (mA)</u>	<u>Final Relative Intensity (%)</u>
20	110
30	104
40	97
50	96
60	88
70	61

There were only two soft failures seen (relative intensity dropped to 50% of the original value). The older-generation LED, which failed after 1000 h at 20 mA and 250 h at 70 mA, had a diagonal crack across the semiconductor chip. The one newer LED which failed had sustained 1000 h at 20 mA, 2650 h at 70 mA, with 1000 h at 30°C and above. Failure analysis on this device is pending.

Current control circuitry was designed specifically for this life testing. The two circuits used in the first phase of testing, an op-amp circuit and a resistor circuit, performed equally well. No correlation was found between LED performance and the type of circuit used.

Detailed studies were conducted to uncover any correlation which may have existed between operating conditions (LED voltage, current, or resistance) and LED performance. No such correlation was found. For instance, the drive current for each LED was adjusted using a potentiometer to within +/-4% of the target values. Thus, all of the LEDs being driven at "20 mA" had slightly different drive currents. The drive current also varied slightly (by approximately +/-1.5%) during any one phase

of life testing. But neither the variations in initial current settings nor the minor current variations during tests had any correlation to the overall trends of LED intensities.

8. ACKNOWLEDGMENTS

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