Life Tests and Failure Mechanisms of GaN/AlGaN/InGaN Light Emitting Diodes

Daniel L. Barton, Marek Osinski*, Piotr Perlin*, Christopher J. Helms, and Niel H. Berg

Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-1081, USA
Tel: (505)844-7085, Fax: (505)844-2991
e-mail: bartondl@smtplink.mld.sandia.gov

*Center for High Technology Materials
University of New Mexico
Albuquerque, New Mexico 87131-6081, USA

PURPOSE

Our studies of device lifetime and the main degradation mechanisms in Nichia blue LEDs date back to Spring 1994. Following the initial studies of rapid failures under high current electrical pulses, where metal migration was identified as the cause of degradation, we have placed a number of Nichia NLPB-500 LEDs on a series of life tests. The first test ran for 1000 hours under normal operating conditions (20 mA at 23 °C). As no noticeable degradation was observed, the second room temperature test was performed with the same devices but with a range of currents between 20 and 70 mA. After 1600 hours, some degradation in output intensity was observed in devices driven at 60 and 70 mA, but it was still less than 20%. The subsequent tests included stepping up the temperature by 10 °C in 500 h intervals up to a final temperature of 85 °C using the same currents applied in the second test. This work reviews the failure analysis that was performed on the degraded devices and the degradation mechanisms that were identified.

INTRODUCTION

Until very recently efforts to develop short-wavelength visible light sources concentrated on either II-VI materials, or second harmonic frequency doubling of GaAs/AlGaAs lasers. The situation has changed dramatically following the commercial introduction by Nichia Chemical Industries of high-brightness blue and green LEDs, based on gallium nitride and related compounds (InGaN/AlGaN) with either bulk or quantum-well active region [1-10]. These materials combine a wide, direct bandgap with refractory properties and high physical strength. By controlling the active region composition, group-III nitrides can emit light from deep UV to orange.

A major problem encountered in epitaxial growth of group-III nitrides is the lack of suitable substrates that would match the nitrides in lattice constant and in thermal expansion coefficient. Large lattice mismatch between GaN and sapphire, used as a substrate in Nichia LEDs, raises concern about possible negative impact of defects on device lifetime.

LIFE TEST SETUP

In order to investigate the lifetime of the Nichia LEDs, 20 devices were mounted inside a large environmental chamber which could be maintained at a constant temperature. The light output of each LED was sampled by an optical fiber which was connected to its own photovoltaic detector located outside the chamber. The LED-to-fiber connection was both mechanically stable and light tight, eliminating intensity variations due to mechanical misalignments and ambient light. The system used a switching device to select a single detector’s current, which was fed to a meter for automated reading of each LED’s output.

Two separate driving circuits were used in this first life test, one based on op-amps, the other on current-limiting resistors. Each circuit was powered by a supply which maintained a constant output voltage. Currents were held approximately constant through each LED by two different methods. In the op-amp circuit, there was a current feedback loop for each LED which regulated LED drive current. In the resistor circuit, a current limiting resistor was placed in each parallel leg of the circuit to prevent excessive current through any one LED should any legs become short circuited. Since life testing of the LEDs relies on the consistent performance of each circuit component during the test, using two different drive circuits allows for a life test comparison of the simple resistor circuit and the more complicated op-amp circuit. The op-amp circuit theoretically provides better current regulation, but it may prove to be less reliable during sustained life testing. The test was fully computer controlled, with data automatically gathered every 12 hours or at the operator’s request.

For the test, eighteen Nichia NLPB-500 LEDs (numbered 1-18 for the test) were selected from a new lot (4B0001), acquired in April 1995. The test also used two devices (numbered 19 and 20) from batch 40308, acquired a year earlier. Two devices from lot 4B0001 (labeled A and B) were left unstressed to serve as controls. The LEDs were placed in cw operation after pre-test power measurements were taken on all 20 devices. Ten LEDs were stressed in the resistor circuit and ten in the op-amp circuit.

TEST RESULTS TO DATE

Figure 1 shows the relative luminous intensity from all 20 devices tested, normalized to their initial readings. Table 1 shows a summary of the various test times, shown in cumulative hours from the start of the life test, and the temperature at which each test was run. The general trend for the first 1000 hours was for the 18 newer LEDs was for the output intensity to increase at a faster rate within the first 50-100 h, then at a slower rate over the remainder of the test. The output intensity of the two older LEDs increased within the first 50 h, and then decreased during the remainder of the first test.

After the first 1000 hours, the drive currents of the LEDs were increased to try to accelerate the degradation process in some of the devices under test. The previously tested eighteen devices from the new batch were divided into six groups of three. Each group was driven at one of six currents: 20, 30, 40, 50, 60, or 70 mA. Of the two older devices, one (#19) was subjected to a high current of 70 mA, and the other (#20) remained driven at 20 mA. Table 2 shows a summary of the biasing conditions for each LED for tests two
through ten. The maximum current level of 70 mA is close to the condition producing a maximum CW output power from the LEDs. From a measurement of the output intensity as a function of drive current, the onset of thermal rollover was observed at 80 mA with slightly decreased output. A current of 70 mA was thus expected to be sufficiently high to cause measurable degradation after a few hundred hours.

The relative intensity of one of the older-generation LEDs (#19) dropped to about half of its initial value (a 50% decrease in output was the initial failure criterion) after approximately 1200 h and the device was removed from the test. In this case, the high current (70 mA) had indeed caused a rapid failure. The remaining devices driven at the same current level performed much better. After a relatively fast drop in their output (10-15% over the first 750 h), their degradation rate slowed as shown in Figure 1.

Table 2 - LED numbers and associated drive currents.
Note that all devices were biased at 20 mA for test 1 and LEDs 19 and 20 are “older” generation devices.

<table>
<thead>
<tr>
<th>Current (mA)</th>
<th>Device Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1,2,3,20</td>
</tr>
<tr>
<td>30</td>
<td>4,5,6</td>
</tr>
<tr>
<td>40</td>
<td>7,8,9</td>
</tr>
<tr>
<td>50</td>
<td>10,11,12</td>
</tr>
<tr>
<td>60</td>
<td>13,14,15</td>
</tr>
<tr>
<td>70</td>
<td>16,17,18,19</td>
</tr>
</tbody>
</table>

The remaining LEDs were returned to life testing where the temperature was subsequently increased by 5 °C after each 500 hours of testing. The output from one of the newer LEDs driven at 70 mA (LED #16) degraded to 55% of its original value after 3600 hours and a second newer LED (LED #17) degraded by a similar amount after 4400 hours. The LED #16, did not exhibit a significant change in its I-V characteristics indicating that a change in the package transparency could be a likely cause for the observed degradation. LED #17, did show a noticeable change in its I-V characteristics. This device was subsequently returned to life testing where the degradation process was monitored for further changes.

Degradation rates extracted from life test data

The data shown in Figure 1 was used to estimate device lifetimes and the effects of bias current on degradation acceleration. The data in Figure 1 was re-plotted as a function of the square root of time in to allow a linear fit to be made to estimate the time to a 50% loss in output intensity. This is a common method [11] for the prediction of LED lifetimes under accelerated aging, especially under the
conditions of a small sample size and limited acceleration capabilities due to device constraints.

From this analysis, device lifetimes under drive currents from 30 to 70 mA were obtained. The average relative intensity changes from each of the groups of three LEDs driven at the same currents over the first 2654 hours of testing at 23 °C were used. The results are shown in Table 3.

<table>
<thead>
<tr>
<th>Drive Current (mA)</th>
<th>Estimated lifetime (hours to 50%)</th>
<th>Current acceleration factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>no degradation</td>
<td>N/A</td>
</tr>
<tr>
<td>30</td>
<td>5.080x10^4</td>
<td>1.0</td>
</tr>
<tr>
<td>40</td>
<td>2.967x10^4</td>
<td>1.71</td>
</tr>
<tr>
<td>50</td>
<td>1.854x10^4</td>
<td>27.40</td>
</tr>
<tr>
<td>60</td>
<td>4.808x10^4</td>
<td>105.66</td>
</tr>
<tr>
<td>70</td>
<td>3.622x10^2</td>
<td>140.25</td>
</tr>
</tbody>
</table>

In order to investigate the effect of temperature on light output of these LEDs a series of measurements were made at various currents and temperatures. From these measurements it was apparent that increases in temperature will reduce the light output and thus slow any optically induced degradation mechanisms.

The results presented in this section clearly illustrate that there is a severe limitation imposed on accelerated life testing by the current and temperature performance of these LEDs. The current limitations are imposed by the onset of thermal rollover at approximately 80 mA limiting the acceleration factors to those shown in Table 3. The decrease in output intensity with temperature indicates that room temperature (or low temperatures) will provide the fastest degradation due to optically induced mechanisms.

**Analysis of LED #19**

In order to determine the cause of the degradation for device #19, a series of I-V measurements were made. The measurements indicated that the junction leakage had increased during the life testing and that the light output degradation was not due to a change in contact resistance or a change in the optical transmission of the plastic encapsulation. This data is significant in that the degradation mechanism could be similar to the one identified in the high pulsed current testing done earlier [12]. Figure 2 shows the I-V characteristics of the degraded device #19 and an unstressed LED (#52) for comparison. The figure shows that the degraded device has an ohmic leakage path across the junction of about 600 MΩ.

To identify the cause of the degradation, device #19 was de-encapsulated and prepared for electron beam-induced voltage (EBIV) analysis. EBIV analysis differs slightly from the more common EBIC analysis in that the voltage variations created across the junction by the incident electron beam is used to create the image instead of the current collected across the junction. The EBIV analysis quickly identified that the cause of the light output degradation was a crack in the LED which isolated part of the junction area from the p-contact. With an electron beam energy of 5 keV, the beam interaction volume did not penetrate down to the n-contact. The EBIV image (Figure 3) clearly shows that the crack has propagated through the p-contact and the active layer thus isolating part of the LED from the electrical stimulus and reducing its light output accordingly. We therefore concluded that LED #19 did not degrade in a manner that would be considered typical for operation under normal conditions.

**Analysis of LEDs #16 and 17:**

In order to identify the process responsible for the degradation in light output measured on LEDs #16 and 17, the first task was to carefully measure the current-voltage characteristics of each device and compare the results to a control LED of the same type. Figures 4-5 show some of the measurements made on the two degraded LEDs along with a control LED. The figures indicate that LED #16 has not undergone a significant change in its I-V characteristics. In fact the I-V data indicates that LED #16 has a lower forward series resistance than the unstressed control device, #120. None of the I-V data leads us to a degradation mechanism that involves the electrical performance of the LED. The only possibilities for degradation are limited to a change in the radiative versus non-radiative recombination rate or a change in the optical properties of the plastic encapsulation. The former process would involve a 45% loss in radiation from the LED. A careful inspection of LED #16 under a low forward bias (just above the LED's turn-on voltage) revealed no significant non-radiative areas that could account for the loss in light output. The LED showed almost perfectly uniform illumination distribution which is unlike LED #19. The results leave the plastic encapsulation material as the most likely cause for output degradation.
parts per million sensitivity. The PDS technique involves immersing the samples in an organic medium which has a refractive index which is sensitive to temperature. A highly stable HeNe laser beam is placed parallel to and near the surface of the sample while a chopped heating light is incident on the sample surface. With this method, any heating of the sample caused by absorption of the heating beam will bend the HeNe laser beam. Deflection of the HeNe laser beam is detected using lock-in techniques.

Samples from an unstressed LED were first exposed to light at 3.25 eV which is approximately equal to the direct bandgap of GaN for about 5 hours with no noticeable increase in absorbance. In order to speed up the test, energies of 3.9, 3.8, 3.7, and 3.6 eV were used to set a basis for extrapolation to 3.25 eV. Figure 7 shows typical absorbed energy data (measured by the in-phase PDS signal) for exposures at 3.9 eV for 11 hours. The upper curve was obtained after the 11 hour curve and demonstrates that even an exposure as short as a few minutes to light above the fundamental π-π* molecular transition causes a large increase in absorption at lower energies. The absorption coefficient can be obtained from the PDS data by using the relation, \( \alpha(E) = (1.62X_{	ext{PDS}}/E_0)^{1/2} \), assuming that the absorption is reasonably uniform as is the case for these measurements. The parameter, \( E_0 \), is the polymer thermal length and is estimated to be 50 μm for this material. The in-phase PDS signal is \( X_{	ext{PDS}} \) and is the measured parameter in this equation.

To determine the effects from exposure to light at 3.25 eV, absorption coefficients were calculated from the data in Figure 7 at energies from 3.6 to 3.9 eV and a linear relationship was used to calculate the change in absorption coefficient at 2.76 eV (the blue emission from these LEDs) based on the absorption coefficients measured at higher energies (which is valid from the data collected). The proportionality constant in this case is proportional to the light intensity and, hence, the emission from the LED as a function of energy. The data suggest that the absorption coefficient at 2.76 eV will grow exponentially with time. The results are plotted in Figure 8 which shows the prefactors obtained from parabolic fits (a \( t^{1/2} \) dependence) to the absorption coefficients measured at different energies. The data shows that the degradation rate is exponentially dependent on exposure energy and that the degradation at 3.25 eV proceeds a decade more slowly than the lowest exposure energy used in this study.

This data can be used to predict the LED lifetime based on a 50% loss in blue light output failure criterion. By calculating the light output and the plastic area exposed, the lifetime can be bounded by using either a linear or parabolic dependence of \( \alpha(t) \). Figure 9

It is commonly known that prolonged exposure to ultraviolet radiation can reduce the optical transparency of many types of plastics. Since band-to-band recombination in the GaN system can produce ultraviolet radiation, a degradation mechanism of this type is reasonable. Figure 6 shows the output spectra for both the older generation, double heterojunction Nichia LED and a newer generation Nichia LED. The spectra were measured at room temperature (295 K) at a forward voltage of 3.5 V. The band-to-band recombination found in the older LED has been suppressed in the newer LED by an increase in the Zn doping concentration in the active InGaN layer [13]. We also know from our earlier work [12] that the band-to-band emission component does increase significantly with forward bias indicating that the newer generation LEDs should have a long lifetime at currents less than the 20 mA cw limit in the data sheet, but may show significant degradation by this mechanism at elevated currents.

In order to study the effects of high energy radiation on the optical transparency of the encapsulation material used on the NLPB-500 series LEDs, sections from the plastic from both degraded and un-degraded LEDs were removed. The sections were polished and were 0.05 to 0.08 cm thick. Since conventional optical transmission techniques are limited to an accuracy of approximately 0.005 absorbance units, a Sandia-developed technique called photothermal deflection spectroscopy (PDS) was used which has
shows the final result from these calculations using the spectral information for the older generation LED in Figure 6. A comparison of the life test data collected and the calculated plastic degradation for these LEDs yields a measured lifetime that is around the mean of these two bounds.

![Graph showing in-phase PDS signal from exposure to light at 3.9 eV up to 11 hours.](image)

**Figure 7 - In-phase PDS signal from exposure to light at 3.9 eV up to 11 hours.**

![Graph showing prefactors from parabolic fits to data in Figure 7.](image)

**Figure 8 - Prefactors from parabolic fits to data in Figure 7.**

**LED #17 after test 8 (5578 hours)**

The I-V data in Figures 4-5 show a different degradation mechanism for LED #17. This LED shows a significant difference in its characteristic when compared to both the unstressed and the other degraded LED. Figure 4 indicates that #17 has about an order of magnitude more leakage current across the junction than #120 and #16. From Figure 5, calculations of the ohmic leakage paths across the junctions of the three LEDs showed that LED #17 had an order of magnitude lower resistance across the junction (18 GΩ for #17 versus 113 GΩ for #120). Since the degradation of #17 was noticeable but subtle, this LED was subsequently returned to life testing to continue the degradation process until its output reached a relative decrease in output power of 80%.

The I-V characteristics of LED #17 were measured again after the conclusion of tests 8 and 10 where it was found to have a cumulative loss in relative intensity of over 80% from its initial value. At this point, the LED was removed from the life test and subjected to failure analysis. The I-V characteristics of this LED were carefully measured and compared to earlier measurements. The results shown in Figure 10 indicate that no further degradation had occurred in the diode which would account for the additional loss in output intensity. This analysis indicates that the degradation may be again tied to the transparency of the plastic encapsulation and not to changes in the semiconductor materials themselves. Analysis of this LED will be further pursued and reported when completed.

![Graph showing LED lifetime based on PDS measurements.](image)

**Figure 9 - LED lifetime based on PDS measurements.**

![Graph showing I-V measurements of LED #17 after tests 6, 8, and 10.](image)

**Figure 10 - I-V measurements of LED #17 after tests 6, 8, and 10.**

**CONCLUSIONS**

The life tests of Nichia blue LEDs completed to date have not produced significant degradation on any of the devices operated at currents less than 60 mA. These results indicate that Nichia devices enjoy a remarkable longevity in spite of their high density of defects [12]. As of this report, one of the older technology, double heterostructure Nichia LEDs showed a greater than 50% light output degradation after 1200 hours. Subsequent failure analysis of this LED revealed that a crack had isolated part of the junction and was the cause of the light output degradation. Two of the newer generation LEDs showed a greater than 40% loss in output intensity after 3600 and 4400 hours. Of these LEDs, the earlier failure did not exhibit any significant change in its I-V characteristics indicating that the failure mechanism may be related to the plastic encapsulation material. An analysis of the degradation characteristics of the plastic packaging material demonstrated that a degradation in light output could indeed be caused by the ultraviolet light emitted by the LED. The other LED did show a difference in its I-V characteristics when compared to an un-stressed LED, but without having a pre-stress I-V characteristic for this LED the only data available was the changes at the life test points where it was measured. This device was returned to life testing to allow the observed degradation process to continue. Analysis of this LED
after 5578 hours of testing did not show further changes in the I-V characteristics indicating that the packaging material may again be responsible for the additional loss in output intensity.

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