Reliability Datasheet RD25

LUXEON®
never before possible

LUXEON® Reliability

Introduction

LUXEON® Power Light Sources represent a revolutionary advance over conventional small signal LED light sources. This application note summarizes the reliability performance of the LUXEON family. The application note discusses general reliability concepts, potential failure modes, and aspects of product reliability that are affected by the customer application.

While the reliability of LUXEON Power Light sources is very high, adherence to the device maximum ratings is required. The overall product reliability depends on the customer's drive conditions and adherence to recommended assembly practices. As with any other type of LED, extreme junction temperatures caused either by excessive power dissipation, an abnormally high thermal path, or improper assembly can cause thermal overstress failures. As with any LED, electrical transients can cause electrical overstress failures. These different failure modes are discussed in this application note.

The reliability of the LUXEON light source is different from typical filament light sources. Filament light sources typically wear out after a certain operating time. For LUXEON light sources, assuming that the junction temperature and maximum drive current is within the product maximum ratings, the catastrophic failure rate of the LUXEON can be characterized as a constant, random failure rate as defined by the MTTF equation as described in more detail within this application note.

In addition, similar to other LEDs, the LUXEON light source exhibits a gradual reduction in light output over time. This change in light output, commonly called the lumen maintenance, depends on the drive current and operating temperature and is described in more detail within this application note.

PHILIPS

LUMILEDS
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LUXEON Reliability Information Available from Lumileds

This document covers basic reliability concepts including prediction of catastrophic failures, factors that affect rate of LED degradation, abnormal failure modes for LUXEON, importance of good designs to minimize failures, and importance of adhering to proper assembly processes. This application brief also summarizes reliability improvements of LUXEON versus conventional epoxy-based LEDs and describes Lumileds product qualification process.

General Packaging Considerations

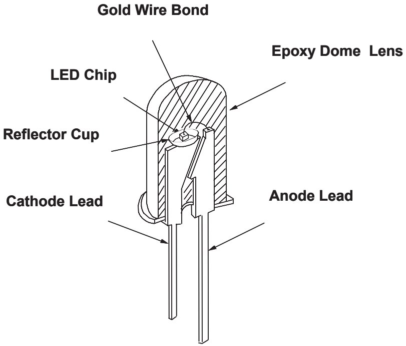
Traditionally, LED light sources have been constructed using a small signal LED chip mounted in an optical-grade epoxy package. LUXEON Power Light Sources differ in many aspects to these small signal LEDs due to the requirements for higher power operation and longer life-time expectations. The overall reliability of any packaged LED is determined by the reliability of the LED chip as well as the mechanical interactions between the LED chip, pins, gold wire, and the surrounding encapsulent.

Variations in ambient temperature and self-heating can cause mechanical stress within the LED package, which may affect the overall product reliability. Due to different thermal coefficients of expansion, the LED package can be subjected to mechanical stress when subjected to extreme ambient temperature conditions. Over time, this mechanical stress can cause cracking, mechanical delamination, or broken bond wires, which may cause catastrophic failures. Since most of the power applied to the LED is dissipated as heat, the junction temperature will always be hotter than ambient temperature, depending on the power dissipated and the resistance to heat-flow. Thus the internal temperature of the LED is determined not only by the ambient temperature, but also by the drive current and thermal resistance in the customer's application. Finally, the package can absorb moisture, which may also adversely affect the product reliability.

Packaging of Small-Signal LEDs

The packaging construction of a typical small signal LED is shown in Figure 1. A small LED chip is attached to one of the metal pins and connected to the other metal pin by use of a small gold wire. Then the LED chip and pins are encapsulated in optical-grade epoxy.

Figure 1



While the optical-grade epoxy provides mechanical strength to the LED package, it is also tends to limit the operating temperature range. Over the operating temperature range the epoxy is very hard. Temperature variations cause the package to expand and contract. As the coefficient of expansion is different for each of the components of the LED package, temperature variations cause mechanical stress to be applied to the gold wire, LED chip, and die attach material. Under normal operating conditions, the epoxy encapsulent operates at temperatures below the glass transition temperature, T_G, of the epoxy in order to control its coefficient of expansion. At temperatures above T_G, the epoxy expands at a much higher rate, which causes much higher mechanical stresses within the package. The gold wire can break after a large number of thermal cycles. In addition, extreme thermal shocks can crack the epoxy, break the gold wire, break the LED die, or cause the LED die to separate from the LED pin. Because most of these reliability issues are caused by the mechanical properties of the epoxy, great care is taken in selecting the best epoxy for a given product. Even so, the upper and lower temperature limits of a given LED package are usually determined by the mechanical properties of this epoxy encapsulent.

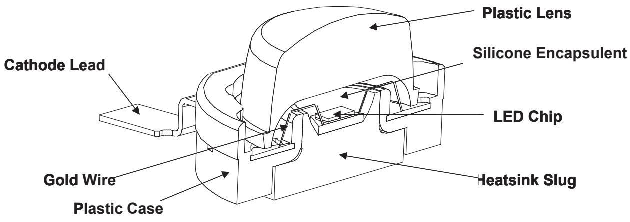
In addition, optical-grade epoxy can turn yellow or brown when subjected to UV exposure from sunlight and high levels of blue light. Several years ago, various UV inhibitors were added to epoxy in order to retard the yellowing of the epoxy in sunlight. However, the spectrum of blue and white LEDs have high levels of near-UV energy, at much higher radiant flux levels than sunlight. Thus, even with UV inhibitors, the lifetime of blue and white small-signal LEDs can be often limited by the light output degradation caused by yellowing/browning of the epoxy encapsulent immediately surrounding the LED die.

LUXEON Packaging

General Packaging Considerations

The LUXEON Power Light Source represents a departure from many of the packaging techniques used in small-signal LEDs. These changes are needed not only to improve the thermal properties needed for high-power operation but also to mitigate some of the limitations of the epoxy encapsulent. The packaging construction of the LUXEON Power Light Source is shown in Figure 2. Note that the thermal and electrical paths are separate. A power LED chip is attached to a metal heat-sink slug, which provides the primary thermal path. Meanwhile, the power LED chip is electrically

Figure 2



connected to the anode and cathode leads. A high temperature plastic lens is attached to the plastic case and the gap between the power LED chip and the lens is filled with a patented proprietary silicone encapsulent. The packaging of LUXEON is discussed in more detail in this application note in section "Internal LUXEON Package Structure."

The LUXEON packaging was developed to provide a much lower thermal resistance than small-signal LEDs. The LUXEON family consists of both AlInGaP LED die technology (i.e. red, red-orange, and amber colors) as well as InGaN LED die technology (i.e. royal blue, blue, cyan, green, and white colors).

Chip Mounting

The AlInGaP LUXEON LED die is soldered directly to the heat-sink slug. The resulting thermal resistance, $R\theta_{J\text{-}SLUG}$, is 15 to 18°C/W for the different AlInGaP LUXEON packages.

The junction of the InGaN LUXEON die is grown on an insulating sapphire substrate and then the die is flipped over and soldered to a silicon chip. The silicon chip is die-attached to the heat-sink slug.

The resulting thermal resistance, $R\theta_{J\text{-}SLUG}$, is 15°C/W for the InGaN LUXEON package, including white, 13°C/W for the InGaN LUXEON III package, and 8°C/W for the InGaN LUXEON V package.

Silicone Encapsulent

The LUXEON package uses a patented proprietary silicone encapsulent instead of optical-grade epoxy that is dramatically more stable than standard optical epoxy in order to get improved mechanical characteristics. Unlike epoxy, which is very hard and brittle, the silicone material is very soft and allows the gold wire to move within the encapsulent. Thus, temperature cycling in silicone encapsulent causes much less mechanical stress to the gold wire than temperature cycling over the same temperature range in epoxy. The patented proprietary silicone encapsulent can also withstand much higher temperatures than optical-grade epoxy.

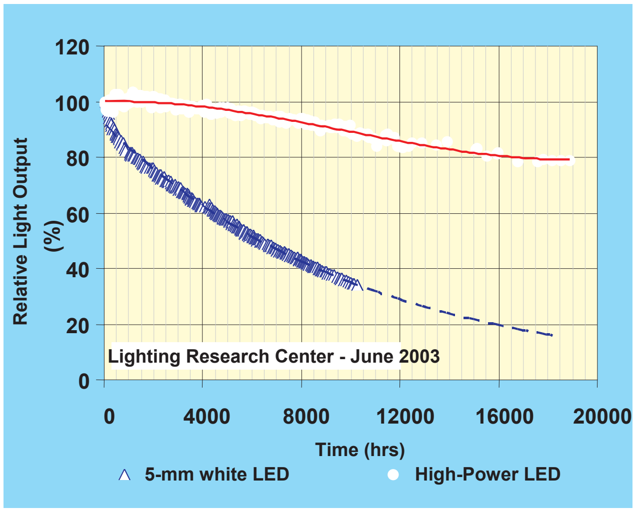


Figure 3. Relative light output from 5-mm indicator lamps and high-power illuminator LEDs, as a function of operating time (Narendran, Deng, Pysar, Gu, and Yu, 2003).[1]

In addition, the patented proprietary silicone encapsulent is more resistant to browning due to UV exposure and high levels of blue light emission. Figure 3 shows the lumen maintenance of conventional epoxy-encapsulated small-signal 5mm white LEDs compared to silicone-encapsulated Power LEDs as measured in an independent study by the Lighting Research Center, Troy, NY. In these tests, the 5-mm white LEDs were driven at 20 mA and the Power LEDs were driven at 350 mA. In both cases, the LEDs were driven at room temperature. While the 5-mm white LEDs have degraded by 65% after 10,000 hours operation, the Power LEDs have only degraded by about 10%.

Lumileds Product Qualification Process

Lumileds conducts extensive reliability stress testing before the introduction of a new product to ensure that the product meets the reliability expectations of the intended market. When the first LUXEON package was developed, an extensive battery of operating life, mechanical, and environmental reliability tests were conducted. These tests are shown in Table 1.

Over the years, the initial LUXEON product offering has been proliferated by the use of new LED die, lens variations, and minor packaging variations. In addition, the maximum operating current has been increased from 280 to 350/385, 700 and 1000 mA. Depending on the nature of the product proliferation and product improvement, only key reliability stress tests, such as operating life tests and temperature cycle tests have been done.

Table 1. Operating life, mechanical, and environmental tests performed on the LUXEON package.

Stress Test	Stress Conditions	Stress Duration	Failure Criteria
High Temperature Operating Life (HTOL)	55C or 85C, I_F = max DC (Note 1)	1000 hours	Note 2
Room Temperature Operating Life (RTOL)	25C or 55C, I_F = max DC (Note 1)	1000 hours	Note 2
Low Temperature Operating Life (LTOL)	-40C, IF = max DC	1000 hours	Note 2
Wet High Temperature Operating Life (WHTOL)	85C/60%RH, I_F = max DC	1000 hours	Note 2
Powered Temperature Cycle (PTMCL)	-40/85C, 18 min dwell, 42 min xfer (2 hour cycle), 5 min ON/5 min OFF, I_F = max DC	200 cycles	Note 2
Non-Operating Temperature Cycle (TMCL)	-40/120C, 30 min dwell/5 min xfer	200 cycles	No catastrophics
High Temperature Storage Life (HTSL)	110C, non-operating	1000 hours	Note 2
Low Temperature Storage Life (LTSL)	-40C, non-operating	1000 hours	Note 2
Non-Operating Thermal Shock (TMSK)	-40/110C, 20 min dwell/<20 sec xfer	200 cycles	No catastrophics
Non-Operating Thermal Shock (TMSK)	-40/120C, 20 min dwell/<20 sec xfer	200 cycles	No catastrophics
Mechanical Shock	1500 G, 0.5 msec pulse, 5 shocks each 6 axis		No catastrophics
Natural Drop	On concrete from 1.2m, 3X		No catastrophics
Variable Vibration Frequency	10-2000-10 Hz, log or linear sweep rate, 20 G about 1 min., 1.5 mm, 3X/axis		No catastrophics
Variable Vibration Frequency	10-55-10 Hz, ± 0.75 mm, 55-2000, 10G, 1 octive/min., 3X/axis		No catastrophics
Random Vibration	6 G RMS from 10 to 2k Hz, 10 min/axis		No catastrophics
Solder Heat Resistance (SHR)	260C ± 5C, 10 sec,		No catastrophics
Solderability	Steam age for 16 hr, then solder dip at 245C for 5 sec		Solder coverage on lead
Lead Strength	1 lb, 30 sec		No catastrophics
Lead Fatigue	1 lb., 3x45° bend		No catastrophics
Salt Atmosphere	35C	48 hours	No catastrophics

Note 1: Depending on the maximum derating curve.

Note 2. Failure criteria includes units with catastrophic failures, or units with greater than 50% Iv degradation at 1000 hours, or an average Iv degradation for the test of greater than 35% at 1000 hours

Catastrophic Failure Rates and MTTF

Definition of a Failure

A failure is defined as a termination of the capability to perform the intended function. LEDs can experience either parametric or catastrophic failures.

Catastrophic Failures

A catastrophic failure occurs when the key electrical or optical data sheet parameters change to a degree that would cause the LED to not light-up. A catastrophic failure in an LED does not have the same implication as a conventional light source, where catastrophic failures could result in explosions or glass breakage. Instead, most LED failures result in the LED not generating light.

The root-cause of the failure, also called the failure mechanism, of catastrophic failures includes both package-related and die-related failure modes. Package-related failure mechanisms include broken bond wires, lifted ball or stitch bonds, delamination within the package that results in an electrical open, and severe discoloration of the lens. Die-related failure mechanisms include severe light output degradation and burned/broken metallization on the die. These failure mechanisms are discussed in more detail in this application note in sections titled “Electrical Overstress Failures” and “Thermal Overstress Failures.”

In most cases, LED catastrophic failures result in open circuits (or a significant increase in the forward voltage). In a few instances, catastrophic failures can also result in short circuits. Catastrophic failures include:

- Opens or Shorts
- Cessation of light output at the normal light-output test condition (i.e. 350 mA for LUXEON)

Parametric Failures

A parametric failure occurs when key electrical or optical data sheet parameters change more than a certain amount from the initial values. Electrical and optical parameters can change slightly over time. Slight changes are normal and typically don’t affect the operation of the LED. These slight changes are not considered failures. However, moderate luminous intensity degradation, moderate changes in forward voltage, or moderate changes in reverse leakage current are examples of possible parametric failure modes. In Lumileds reliability stress testing, Lumileds also counts units with excessive light output degradation as parametric failures. The specific failure criteria are listed on each reliability data sheet.

Failure Rate Versus Time

The failure rate is defined as the percent LED catastrophic failures per unit of time of operation. The operating life of any electronic component can be roughly divided into three time periods each with a different failure rate, as shown in Figure 4.

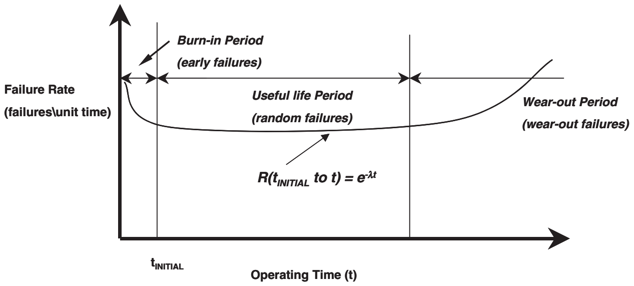


Figure 4. Typical failure rate curve.

Note that a higher failure rate typically occurs during the initial hours of operation. This period is called the burn-in or infant mortality period. During this time, weak or improperly assembled units fail. For LUXEON Power Light Sources, it is critical during assembly that the heat-sink slug on the underside of the emitter be properly attached to an external heat sink so that the junction temperature remains within the recommended operating temperature range. Furthermore, non-adherence to the recommended soldering procedure as discussed later in section “Assembly Related Failures” can thermally overstress the LUXEON package. In both cases, these units can fail prematurely.

The second portion of the failure rate curve is called the useful life period. During this period failures occur at a low, constant rate. In general, the failures that do occur are random and cannot be prevented by additional electrical testing or burn-in of the components.

The third portion of the failure rate curve is called the wear-out period. During this period the failure rate increases until the unit eventually fails. One common example of the wear-out period is the normal failure mode for incandescent bulbs, where the filament fails abruptly after a certain operating time. LEDs do not have the same failure mechanism as just described for incandescent bulbs, but other wear-out mechanisms exist. LEDs also can fail from light output degradation, although in this case the ‘failure’ might be caused by an arbitrary limit on the acceptable percent change in light output. In general, the human eye is sensitive to only large changes in light output of about 50%, and smaller changes are generally not noticeable.

While Figure 4 shows the general trends in failure rates versus time for an LED under normal operating conditions, abnormal failures can still occur which are not properly accounted for in this graph.

For cases of extreme electrical overstress or thermal overstress conditions, the trends shown in Figure 4 may no longer apply. For example, it is possible that failures are caused by electrical transients, which are either generated by the electrical drive circuit or by the electrical mains and which are not eliminated by the electrical drive circuit and can fuse the gold wire. Or, the bond wire can break due to extreme thermal overstress. In either case, the LED immediately ceases to emit light. Thus, it may be useful to perform a detailed failure analysis to determine whether the root cause of the failure was caused by a random failure mechanism or by an externally applied electrical or thermal over-stress.

Mean Time To Failure

Reliability is defined as the probability that a device will operate satisfactorily after a specified period of time. During the useful life period (e.g. the second portion of Figure 4), the failure rate is constant and the reliability is equal to: (Note: this assumes an exponential distribution of failures)

$$R(t) = \exp[-\lambda t]$$

Where:

$R(t)$ = probability that unit will operate at time t
λ = failure rate = 1/MTTF
t = time component is ON

Note that the probability of a catastrophic failure during the useful life period is equal to:

$$P(t) = 1 - R(t)$$

The mean time to failure, MTTF, is the reciprocal of the failure rate during the useful life period and is expressed in hours. The MTTF and failure rate can be determined by operating life testing. The MTTF is simply equal to the total number of devices times the number of operating-hours per device divided by the total number of catastrophic failures (e.g. 100 units operated for 1000 hours, with 2 failures, would have an MTTF of 50,000 hours). If no failures occur during testing, the MTTF is calculated by assuming one failure. For example, if 100 units were operated for 1000 hours with no failures, the MTTF would be calculated to be 100,000 hours, even though the MTTF could potentially be much higher. In general, Lumileds determines the MTTF by operating LEDs under worst-case operating conditions (e.g. at the maximum operating current at the maximum allowable junction temperature). Note that the reciprocal of the MTTF is also called the "point failure rate."

The failure rate can be described in various units of time. Table 2 shows the failure rates for different MTTF's.

	Failure Rates	
MTTF (device hours)	%/1000 hours	FIT (failures/10^9hours)
1M	0.1%	1000 FIT
10M	0.01%	100 FIT
100M	0.001%	10 FIT

Table 2. Commonly used units for failure rates.

The '90% upper confidence limit (abbreviated as UCL) for failure rate' is defined as the failure rate given that there is a 90% probability that the actual failure rate will be as good or better than the value predicted, based on an assumed exponential distribution of failures. In other words, if the tests were repeated multiple times, then 9 out of 10 times, the measured failure rate would be better (lower) than the 90% UCL prediction. Hence, the 90% UCL for failure rate is more of a 'worst-case' failure rate estimate than the point failure rate. The 90% UCL for failure rate is greater than or equal to the reciprocal of the MTTF. Note that the reciprocal of the 90% UCL failure rate is equal to the 10% lower confidence level (abbreviated as LCL) MTTF. Figure 5 shows the relationship between the 90% UCL failure rate and point failure rate, and the relationship between the 10% LCL MTTF and the MTTF. The ratio between the 90% UCL failure rate and the point failure rate depends on the number of failures that occurred in the test. Note for additional information on confidence limits, the reader is directed to the following reference: (Applied Reliability, Tobias and Trindade, 1995).[2]

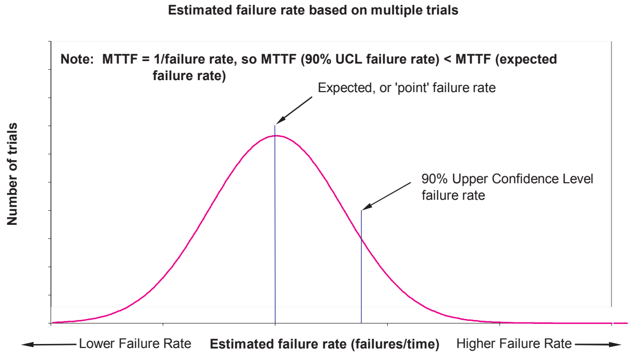


Figure 5a. Relationship between expected or 'point' failure rate and 90% UCL failure rate.

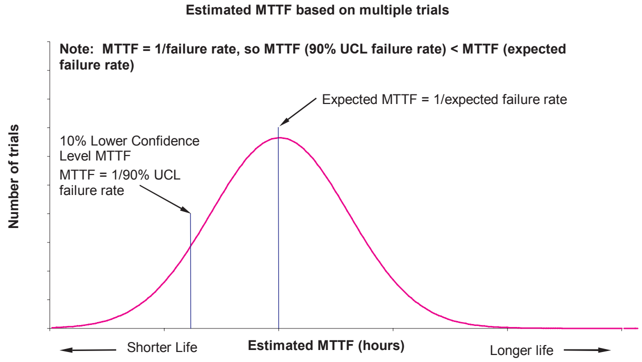


Figure 5b. Relationship between expected MTTF and 10% LCL MTTF estimate.

MTTF Estimate for LUXEON

Arriving at an estimate for MTTF requires conducting operating life tests at a specified drive condition until failures occur. The requirement for running reliability tests to failure is difficult for a highly reliable product like LUXEON, as failure seldom occurs. To accurately determine the MTTF for LUXEON would require tens of thousands of units to be stressed for 10,000 hours.

Since the LUXEON High-Power Light Source was introduced in 1998, it has been used in over 1 million traffic signals, each traffic signal using 12 to 18 LUXEON emitters, which have been installed in traffic intersections around the world. These traffic signal heads are operating continuously 24 hours a day, seven days a week. To date, virtually all traffic signal product returns have had failures due to water intrusion into the plastic case. In a review of product returns of Lumileds-manufactured traffic signal heads, in no case was there an LED failure that was not caused by shorting of the LED array board through water intrusion or due to failure of the electronic drive circuitry. Based on this evidence, the MTTF for LUXEON is very likely to be excess of 100M to 1000M device hours. For the purpose of estimating failure rates it is suggested that a MTTF of 100M device hours at a junction temperature of 80°C be used until further data is available.

Estimating Failure Rates Over Temperature

In many cases it is desired to estimate the failure rate at a new junction temperature based on the failure rate measured at another junction temperature. For example, Lumileds typically measures the failure rate at the worst-case maximum junction temperature, and the customer may want to estimate the failure rate at a more typical operating condition. This calculation can be done using the Arrhenius Model as shown below:

$$\lambda_2 = \lambda_1 \exp\left[\frac{E_A}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$$

Where:

λ_1 = failure rate at junction temperature T_1
λ_2 = failure rate at junction temperature T_2
E_A = activation energy, in units eV
k = Boltzmann's constant (8.617×10^{-5} eV/°K)
T = junction temperature in °K (°K = °C + 273)

Lumileds has not determined the activation energy for LUXEON, but historically has used a value of 0.43eV for activation energy. 0.43 eV is the activation energy recommended by MIL-HDBK-217C for interconnection failures for hybrid semiconductors. The value of 0.43eV represents our best knowledge of activation energy. Using this model, the failure rate and MTTF get worse at higher junction temperatures. Note for additional information on the Arrhenius Model, the reader is directed to the following reference: (Handbook of Reliability Engineering and Management, Ireson, Coombs, and Moss, 1996).[3]

System Failure Rates

In general, the reliability of a system in which a single component failure leads to system failure can be calculated as shown below. (Note that in many systems multiple LED failures are required before the total light output or system light output radiation pattern is considered to be a failure).

$$R(t) = \exp\left[-\left(\sum_i \lambda_i\right)(t)\right]$$

For a system consisting of *n* identical components, the reliability of a system is equal to:

$$R(t) = \exp[-\lambda n t]$$

In some applications, the system might tolerate one or more failures without causing a system failure. In these cases, the reliability is greatly increased. The general solution in these situations is an application of the binomial distribution. In general, the probability of failure *P* of exactly x failures in n trials with the probability of failure p per trial is equal to: Sample calculations using these formulas are given in Appendix A.

$$P(n_x) = \frac{n!}{(n - x)!x!} p^x (1 - p)^{n-x}$$

General Lumen Maintenance Characteristics

LEDs experience a gradual permanent reduction in light output during operation. This phenomenon is called light output degradation and can either be caused by a reduction in the light-generating efficiency of the LED die or a reduction in the light transmission of the optical path within the LED package. In general for the LED die, the rate of light output degradation is higher during the first few hundred hours of operation and then slows down afterwards. Therefore, the light output degradation of the LED die varies approximately as the logarithm of time. In general, the LUXEON is expected to provide an average of 70% lumen maintenance after 50,000 hours provided that the LUXEON is driven at a dc drive current of 350mA for LUXEON I and 700mA for LUXEON III and the junction temperature is maintained at or below 90°C. In addition, LUXEON III is expected to provide an average of 50% lumen maintenance after 20,000 hours when driven at 1000 mA and the junction temperature is maintained at or below 90°C. Note that the human eye is insensitive to small changes in light output and that a change of about 50% is needed in order to create a noticeable change.

Figure 6 shows lumen maintenance data for the AlInGaP LUXEON stressed at 350 mA at 55°C slug temperature (71°C junction temperature). (Note: in these reliability stress tests, the LUXEON is mounted to a thermally-controlled plate such that the temperature at the underside of the heat-sink slug is maintained at a fixed temperature, which in this text is referred to as the slug temperature). Note that the change in light output is expected to be about –9% after 10,000 hours.

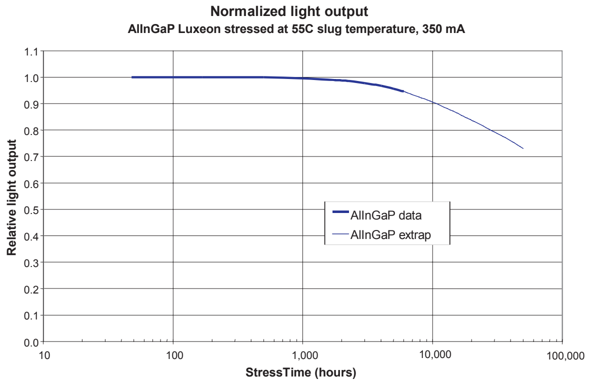


Figure 6.

Figure 7 shows long-term lumen maintenance data for InGaN LUXEON emitters stressed at 350 mA at 55°C slug temperature (72°C junction temperature). Note that the change in light output is expected to be about –6% after 10,000 hours. Driven at the same drive current and junction temperature, generally, the InGaN LUXEON has less light output degradation than the AlInGaP LUXEON.

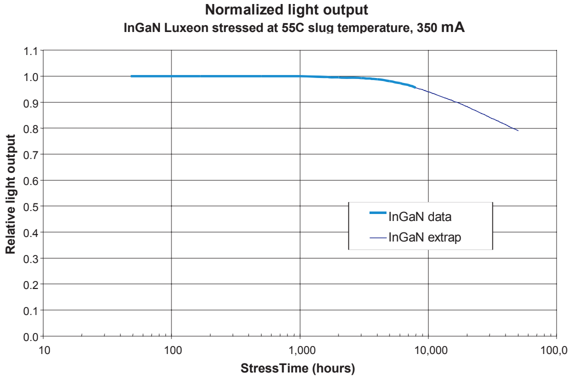


Figure 7.

Affect of Drive Current on Lumen Maintenance

For AlInGaP LEDs, the rate of light output degradation is roughly proportional to the dc drive current when driven at a fixed temperature. Figure 8 shows the lumen maintenance of AlInGaP LUXEONs driven at forward currents of 280 mA, 350 mA, and 500 mA with a 85°C slug temperature (junction temperatures of 97°C, 101°C and 110°C, respectively). Note that the change in light output is expected to increase from –17% to –27% to –45% after 10,000 hours.

Figure 9 shows the lumen maintenance of the InGaN LUXEON driven at 350 mA with a 55°C slug temperature and the InGaN LUXEON III driven at 700 and 1000 mA with a 55°C slug temperature (junction temperatures of 72°C, 87°C, and 103°C, respectively). Note that the change in light output is expected to increase from –6% to –12% to –29% after 10,000 hours. Figures 8 and 9 show that generally the light output degradation of the InGaN LUXEON is less sensitive to drive current than the AlInGaP LUXEON.

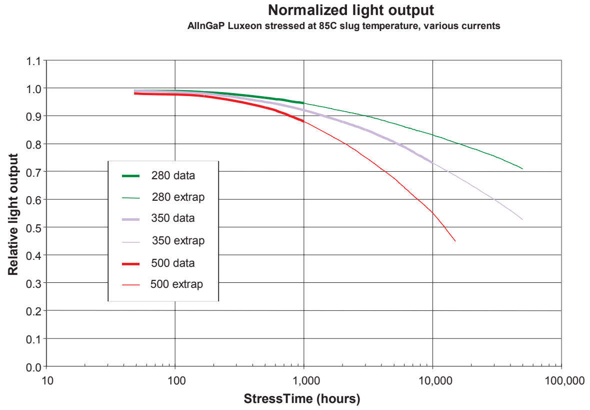


Figure 8.

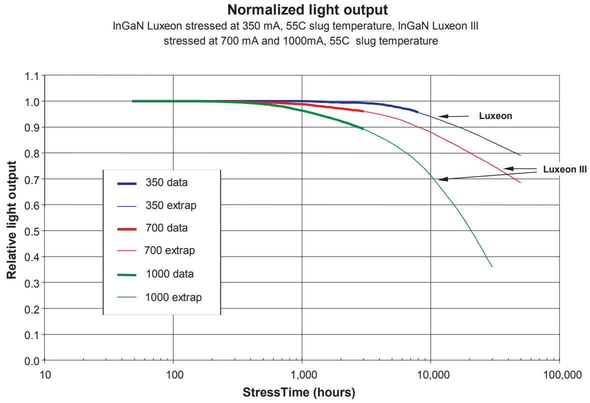


Figure 9.

Affect of Ambient Temperature on Lumen Maintenance

The rate of light output degradation also tends to increase at higher temperatures when driven at a fixed dc current. Figure 10 shows the lumen maintenance of AlInGaP LUXEONS driven at 350 mA at slug temperatures of 55°C, 85°C and 100°C (junction temperatures of 71°C, 101°C, and 116°C, respectively). Note that the change in light output is expected to increase from –9% to –27% to –40% after 10,000 hours.

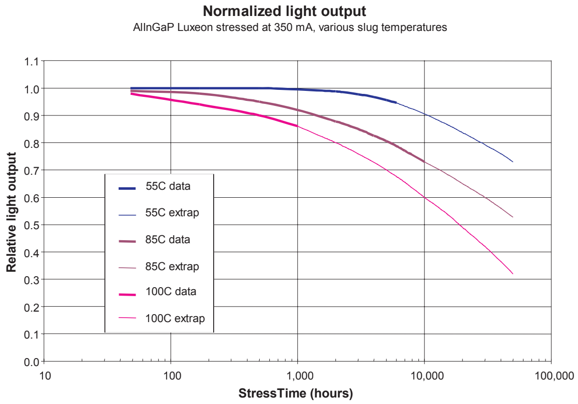


Figure 10.

Figure 11 shows the lumen maintenance of InGaN LUXEONS stressed at 350 mA at slug temperatures of 55°C, 85°C, and 100°C (junction temperatures of 72°C, 102°C, and 117°C, respectively). Note that the light output degradation is expected to increase from –6% to –8% to –19% after 10,000 hours. Figures 10 and 11 show that generally the light output degradation of the InGaN LUXEON is less sensitive to temperature than the AlInGaP LUXEON.

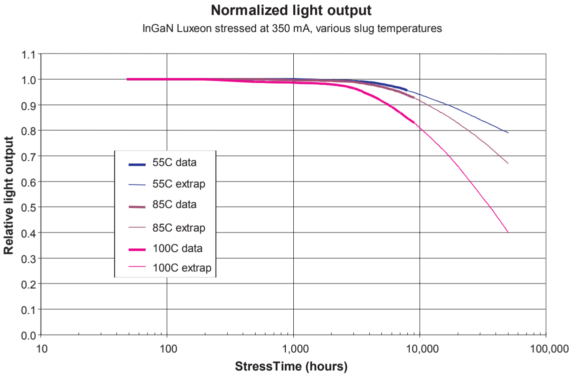


Figure 11.

Internal LUXEON Package Structure

Internal construction

AlInGaP

While a general discussion of the LUXEON package was discussed previously, a detailed understanding of the internal structure of the LUXEON package is important in order to better understand the physical limitations of the LUXEON package.

Figure 12 shows a sketch of the internal construction of the AlInGaP LUXEON. The LED chip is soldered to the heat-sink slug. Then the LED chip and the heat-sink slug are connected to the package pins using gold wires. Note that the ball bond of one gold wire is connected to the bond pad on the top of the LED die and the ball bond for the second gold wire is connected to the heat-sink slug. The other ends of these wires are stitch-bonded to the package pins. Note that the internal structures of the AlInGaP LUXEON die are different. The Batwing AlInGaP LUXEON die has the anode on the top of the die while the Lambertian AlInGaP LUXEON die has the cathode on the top of the die. Thus, the heatsink slug is electrically connected to the cathode of the Batwing AlInGaP LUXEON and the anode of the Lambertian AlInGaP LUXEON.

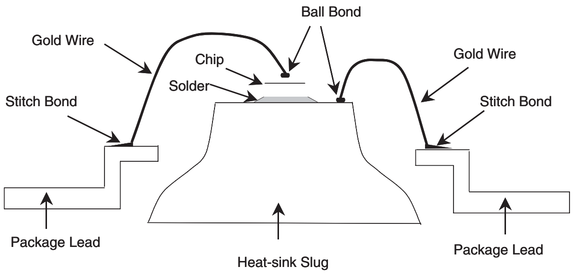


Figure 12. Internal construction of AlInGaP LUXEON.

InGaN

Figure 13 shows a sketch of the internal construction of the InGaN LUXEON. Note that both anode and cathode connections of the InGaN die are on the same side of the die. The LED die is mounted atop a silicon chip. The silicon chip provides both the external electrical connections to the LED chip and protects the InGaN chip against electrostatic discharge (ESD). The InGaN chip is connected to the silicon submount chip with multiple, redundant solder bumps. The silicon submount chip is attached to the heat-sink slug using die-attach epoxy. This die-attach epoxy is electrically and thermally conductive. Then the silicon chip is connected to the package pins using gold wires. Note that both ball bonds are connected to bond pads on the top of the sicon chip and the other ends of these wires are stitch-bonded to the package pins.

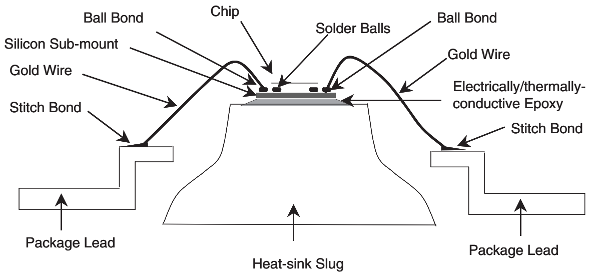


Figure 13. Internal construction of the InGaN LUXEON.

Electrical Characteristics

AlInGaP

The electrical schematic of the AlInGaP LUXEON is summarized in Figure 14. When forward biased, the internal series resistance is very high until the applied voltage exceeds a turn-on voltage of about 2V. Above this voltage, the forward current increases very quickly and the internal series resistance is very low. When reverse biased, the series resistance is very high until sufficient voltage is applied to cause the die to break down and then a reverse current flows though the AlInGaP die. Operation in the reverse direction is not recommended as a reverse current of more than a few µA can permanently damage the LED die.

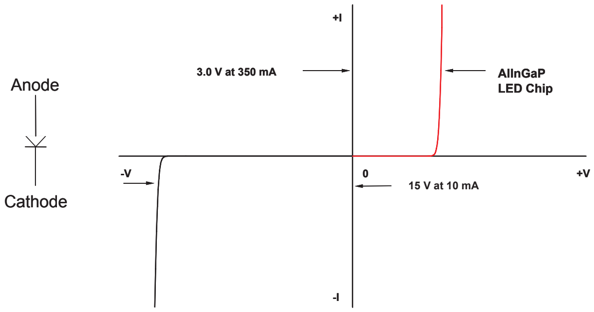


Figure 14. Electrical schematic of the AlInGap LUXEON

InGaN

The electrical schematics of the InGaN LUXEON I and III are summarized in Figure 15. The InGaN die is connected in parallel with two back-to-back silicon zener diodes. These back-to-back silicon zener diodes protect the InGaN die from ESD transients. Under normal forward bias conditions, current flows through the InGaN die since forward voltage of the InGaN die is about 3V while the breakdown voltage of the back-to-back zener diodes is about 7V. When forward biased, the internal series resistance of the InGaN die is about 1 ohm. When reverse biased, the series resistance is very high, until either the back-to-back zener diodes or the InGaN die breaks down. As the reverse breakdown voltage of the InGaN die is in generally in excess of 10V, reverse current flows through the back-to-back zener diodes instead of the InGaN die and protects the InGaN die from electrical overstress. Note that the heat-sink slug is internally connected to the anodes of the two back-to-back zener diodes. It is recommended to keep the heat-sink slug electrically isolated from any external circuitry.

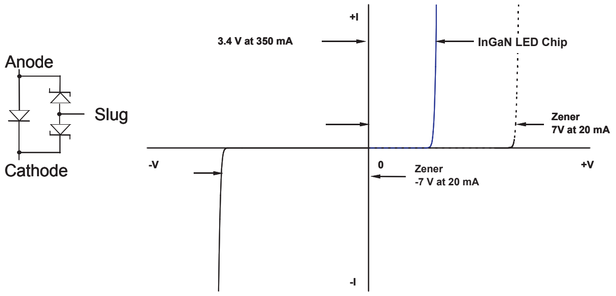


Figure 15. Electrical schematic of the InGaN LUXEON I and LUXEON III.

The electrical schematic of the LUXEON V is summarized in Figure 16. Similar to the LUXEON I and III, the InGaN die is connected in parallel with two back-to-back silicon zener diodes. These back-to-back silicon zener diodes protect the InGaN die from ESD transients. Electrically, the LUXEON V looks like two LEDs connected in series, such that the forward voltage of the LUXEON V is roughly twice the forward voltage of the LUXEON I and III. For this reason, the reverse breakdown voltage for the back-to-back zener diodes is somewhat higher for the LUXEON V, nominally about 8V. Note that the heat-sink slug is internally connected to the anodes of the two back-to-back zener diodes. It is recommended to keep the heat-sink slug electrically isolated from any external circuitry.

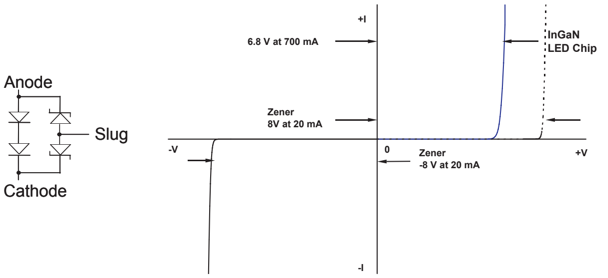


Figure 16. Electrical schematic of the InGaN LUXEON V.

Electrical Overstress Failures

In addition to accelerating the rate of light output degradation; exposure of the LUXEON to forward currents above the data sheet limits or to high peak transient currents can cause catastrophic failures. The type of catastrophic failure depends on the type of electrical overstress as well as the type of LUXEON emitter. Electrical transients can destroy the gold wires within the LUXEON package. In addition, the different LUXEON die types respond differently to electrical transients.

Fused Wire Failures

High-energy electrical transients/currents can also damage the LUXEON package. Under extreme high currents, the gold wire acts as a fuse. Figure 17 shows a typical fused-wire catastrophic failure.

Figure 17. Fused wire failure.

Note that the fusing current depends on the amplitude and duration of the electrical transient as well as the diameter of the gold wire. Finally, note that electrical transients with very long pulse duration as well as excessive dc forward current can also cause various types of thermal overstress failures, which are covered in the thermal overstress section.

Die/Chip Failures due to Electrical Overstress

The different types of LED die used in LUXEON respond differently to electrical transients.

AlInGaP

The AlInGaP LUXEON is generally resistant to positive electrical transients. The metal contacts on the top of the die cause the current to spread equally over the junction area. The internal series resistance of the die is quite low, less than 1 ohm, so without external current limiting, relatively small peak transient voltages can cause high peak currents to be conducted through the LED. Protection against positive electrical transients can be greatly improved either with external current limiting (i.e. with much higher resistance than the internal series resistance of the LUXEON) or for better protection, by the use of an active drive circuit that absorbs electrical transients.

On the other hand, negative electrical transients can permanently damage AlInGaP LUXEON. When a reverse voltage higher than the reverse breakdown voltage is applied to the die, the internal p-n junction breaks down and a reverse current flows through the die. However, reverse currents of more than a few uA cause localized heating within the LED die and can cause permanent damage. Damage from negative transients can be eliminated with the use of a single high-voltage silicon diode connected in series with the LUXEON array, as silicon diodes are available with reverse breakdown voltages exceeding several hundred volts.

The AlInGaP LUXEON is resistant to ESD electrical transients and passes the 16kV Human Body Model.

InGaN

The InGaN LUXEON is generally resistant to positive electrical transients. The metal contacts on the top of the die cause the current to spread equally over the junction area. However, the internal series resistance of the die is quite low, less than 1 ohm, so without external current limiting, relatively small peak transient voltages can cause high peak currents to be conducted through the LED. Protection against positive electrical transients can be greatly improved either with external current limiting (i.e. with much higher resistance than the internal series resistance of the LUXEON) or for better protection, by the use of an active drive circuit that absorbs electrical transients.

The InGaN LUXEON is resistant to low-energy negative electrical transients as the back-to-back zener diodes helps to protect the InGaN die. However, it is recommended that negative transients be eliminated with the use of a single high-voltage silicon diode connected in series with the LUXEON array, as silicon diodes are available with reverse breakdown voltages exceeding several hundred volts.

The InGaN LUXEON is also resistant to ESD electrical transients and passes the 16kV Human Body Model.

Thermal Overstress Failures

Due to differences in the thermal coefficient of expansion within the LUXEON package, exposure to high internal temperatures beyond the maximum ratings or repeated thermal cycling can potentially cause different types of catastrophic failures. As outlined earlier, the silicone encapsulent is generally more resistant to extreme temperatures than epoxy encapsulent due to its soft nature. Note that excessive internal temperatures can arise either due to excessive ambient temperature as well as excessive self-heating, which could be caused by either excessive forward currents or excessive thermal resistance (i.e. due to improper thermal contact to the external heat-sink).

Bond Wire Failures Due to Thermal Overstress

The LUXEON package can withstand greater than 1000 non-operating temperature cycles from –40°/120°C. This temperature range roughly approximates the automotive operating temperature range of –40°/85°C, allowing for self-heating. However, catastrophic failures can occur more quickly at higher/lower temperature excursions. The most common type of failure due to thermal overstress is a broken gold wire. Note that broken wires are a normal wear-out mechanism for LEDs, however the number of cycles to failure is accelerated by the magnitude of the temperature excursion.

While wire failures are rare, the most common type of thermal overstress bond wire failure is a broken stitch bond, where the wire breaks immediately above the stitch.

Delamination Due to Thermal Overstress

Excessive temperatures can cause delamination between the LED die and the encapsulent, which causes a thin chip-air-silicone interface within the package. Figure 18 shows a sketch of delamination between the LED die and the patented proprietary silicone encapsulent. Generally, this problem does not cause a catastrophic failure, but can cause a permanent reduction in light output. In white LUXEON, delamination can either occur between the phosphor coating and the patented proprietary silicone encapsulent or between the InGaN die and the phosphor coating.

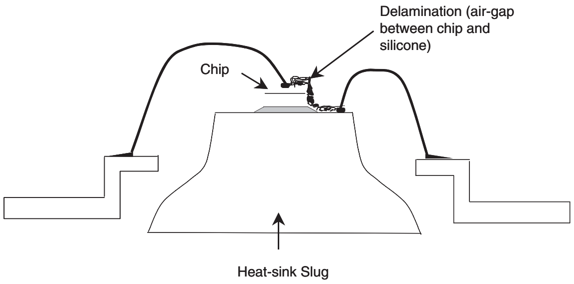


Figure 18. Delamination beween the LED die and encapsulent.

Lens Yellowing

Exposure to excessive ambient temperatures, especially in the presence of high amounts of moisture for a long period of time can also cause the lens to yellow. While this doesn't affect the light output from the LED die, it does result in light output degradation of the LUXEON package due to the absorption of the LUXEON lens.

Internal Solder Joint Detachment

AlInGaP

Exposure to extreme internal temperatures can cause a reflow of the solder used to attach the AlInGaP die to the heat-sink slug. Figure 19 shows a sketch of normal solder die attach between the AlInGaP die and the heatsink slug. The melting point of this solder is well above the maximum junction temperature limit. However, if the junction temperature exceeds the melting point, the LUXEON can fail open catastrophically. Figure 19 shows a sketch of a lifted AlInGaP die caused by the reflow of the solder die attach due to extreme thermal overstress.

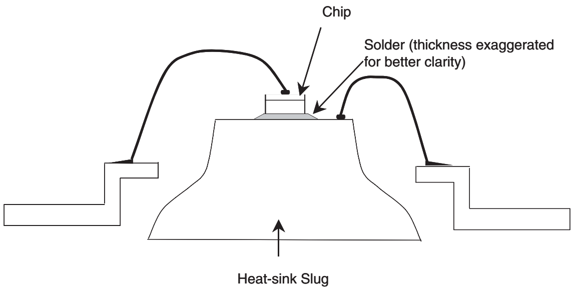


Figure 19a. Normal solder die attach.

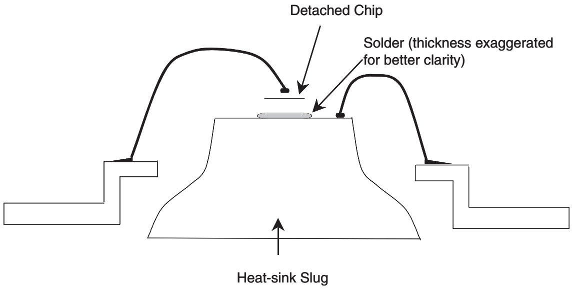


Figure 19b. Lifted AlInGaP die caused by reflow of solder die attach.

InGaN

The InGaN LUXEON uses small redundant solder bumps to attach the InGaN die to the silicon submount chip. The melting point of this solder is well above the maximum junction temperature limit. However, if the junction temperature exceeds the melting point, the InGaN die can become electrically disconnected from the back-to-back zeners, or shorting could occur between adjacent solder connections. Figure 20 shows a sketch of normal solder bumps between the InGaN die and the silicon submount chip. Note that there are redundant anode and cathode connections. Figure 20 shows malformed solder bumps on the silicon submount chip caused by reflow of the solder connections due to extreme thermal overstress.

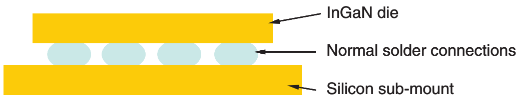


Figure 20a. Normal solder bumps.

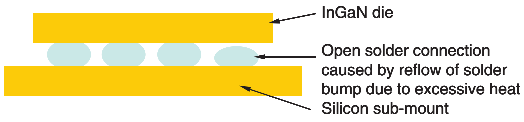
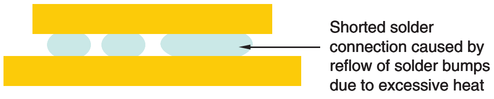


Figure 20b and 20c. Malformed solder connections on silicon submount chip caused by reflow due to extreme thermal overstress.



Shorted solder connection

Assembly Related Failures

The LUXEON is available from Lumileds in both emitter form as well as pre-assembled onto metal-core-printed circuit boards (mcpcb's), such as the LUXEON Star, LUXEON Line, LUXEON Ring, or LUXEON Flood. In cases where customers purchase LUXEON emitters and then assemble them onto their own mcpcb's, sometimes referred to as "level 2 assembly", the reliability of the finished LUXEON product is dependent on the customer following the recommended assembly procedure as outlined in Lumileds Application Brief AB10 "LUXEON Emitter Assembly Information." Premature failures of LUXEON can occur due to poor level 2 customer assembly processes (e.g. improper attachment of the LUXEON emitter to a metal core printed circuit board or to an external heat-sink). Areas of special attention include applying the proper volume of heat-sink glue, minimizing the heating of the LUXEON heat-sink slug during soldering of the package leads, and ensuring that the heat-sink slug is electrically insulated from the circuit ground or other electrically active components.

Heat-sink glue failures

Operation of the LUXEON within the recommended operating junction temperature range relies on consistent internal self-heating, which, in turn, is determined by the internal power dissipation and the thermal resistance path, junction to air. During assembly, the heat-sink slug is mechanically and thermally attached to the metal core printed circuit board (mcpcb) by use of thermally conductive glue. The resulting thermal resistance of the heat-sink glue can be adversely affected if the heat-sink glue does not cover the entire heat-sink slug area, is too thick, or especially if an air-gap exists between the heat-sink slug and the heat-sink glue layer. Thus, it is important that the proper amount of heat-sink glue (as outlined in AB10) is dispensed and a consistent force (as outlined in AB10) be applied to squeeze the glue into the proper thickness. Note that if an insufficient volume of glue is dispensed or the emitter is misaligned then the glue may not cover the entire surface area of the heat-sink slug, which can increase the thermal resistance. Too much glue can result in a very thick glue layer, which also can adversely affect the thermal resistance. Insufficient force (as outlined in AB10) to press the LUXEON emitter into the uncured heat-sink glue might allow a thin layer of air to be under the heat-sink slug, which would significantly increase the thermal resistance.

Improper application of heat-sink glue can cause the thermal resistance of the interface to increase dramatically from less than 1°C/W to over 100°C/W. This significant increase in thermal resistance can cause any of the thermal overstress failures described in the previous section including broken bond wires, delamination, lens yellowing, or reflow of the internal solder connections.

As discussed previously, it is important that the LUXEON emitter is mounted to the mcpcb with the proper amount and thickness of heat-sink glue. The consistency of the customer's LUXEON level 2 assembly process can be monitored using different types of in-process quality tests. LUXEONS that are not attached to the mcpcb can be identified by applying a small force to the LUXEON package after glue has been cured as the unattached units will move with applied force. The thickness of the heat-sink glue and the presence of voids in the heat-sink glue layer can be measured by cross-sectioning LUXEON units attached to the mcpcb. The best method is to measure the thermal resistance junction to air by use a thermal analysis system.

Excessive Soldering Temperatures

During Level 2 assembly, the LUXEON leads are connected to the mcpcb by the application of a solder paste and solder flux and the use a hot-bar soldering tool. The LUXEON emitter is not designed to be reflow solderable. It is important that the user adhere to the recommended assembly procedure as outlined in Lumileds Application Brief AB10 "LUXEON Emitter Assembly Information." Excessive soldering temperatures or dwell time can cause severe expansion of the silicone encapsulent, which can be squeezed out of the LUXEON package and cause air-bubbles, delamination, and in severe cases can cause a reflow of the internal solder connections, stitch bond failures, or damage to the mcpcb. In cases where the customer is soldering wires to the LUXEON Star, Line, Ring or Flood mcpcbs, it is recommended that the customer solder wires to the solder pads, not directly to the LUXEON emitter leads and to preheat the mcpcb to 50°C prior to soldering.

Improper Isolation Between the LUXEON Heat-Sink Slug and the Metal Core Printed Circuit Board (MCPCB)

The LUXEON heat-sink slug is electrically connected to the LED die. If the heat-sink slug is inadvertently connected to ground, than the resulting shortage path, can cause electrical overstress failures. The mcpcb consists of an aluminum core, a thin epoxy resin dielectric, and then a thin copper layer as defined in AB10. This copper layer is then etched into copper traces. Finally, a solder resist layer covers portions of the mcpcb. The epoxy dielectric can withstand 2000V provided that it is not damaged due to excessive soldering temperatures or due to mechanical damage. Thus in the design of the mcpcb, it is important that this epoxy dielectric layer properly electrically insulates the copper layer which is underneath the heat-sink slug without excessively compromising thermal resistance.

The epoxy dielectric layer can be damaged by taking short-cuts in mcpcb fabrication. As an example how things can go wrong, in one of Lumileds' internal LUXEON evaluation mcpcb's, the mcpcb was cut into strips by shearing through the copper layer/traces. Unfortunately, the shearing tool caused thin copper burrs to make electrical contact with the aluminum core layer. As might be expected, these copper burrs caused shorting to the grounded heat-sink which, in turn, caused characteristic electrical overstress failures. Note that this problem could have been avoided by shearing the mcpcb through a section that did not have a top copper layer (i.e. by etching away the copper layer in the vicinity to the shear) or by careful removal of the copper burrs before assembly (i.e. by using a high-pot test to arc-off the metal burrs).

Summary

While the reliability of LUXEON Power Light Sources is very high, it does require adherence to the device maximum ratings. In reality, the overall product reliability depends on the customer's drive conditions. For customers purchasing LUXEON emitters and doing their own assembly, it is also important to adhere to the recommended assembly practices as outlined in AB10. For best results the customer needs to provide proper control of the thermal path, protect against electrical overstress conditions, and ensure that LUXEON emitters are properly attached to the mcpcb/heatsink.

The reliability of the LUXEON light source is different from typical filament light sources. Filament light sources typically wear out after a certain operating time, called the rated life. For LUXEON light sources, assuming that the junction temperature and maximum drive current is within the product maximum ratings, the reliability of the LUXEON can be characterized as a low, random failure rate as defined by the MTTF equation. Since 1998, LUXEON has been installed in over 1,000,000 traffic signal heads, each with 12 to 18 LUXEON emitters per head. Based on the number of LUXEONS installed in traffic signals, and the lack of field returns, it is suggested that a MTTF of 100M device hours at a junction temperature of 80°C be used until further data is available.

LEDs experience a gradual permanent reduction in light output during operation. This phenomenon is called light output degradation, or lumen maintenance, and can either be caused by a reduction in the light-generating efficiency of the LED die or a reduction in the light transmission of the optical path within the LED package. In general, the change in lumen maintenance is higher during the first few hundred hours of operation and then slows down afterwards. In most cases, the lumen maintenance of the LED die varies approximately as the logarithm of time. In general, the LUXEON is expected to provide an average of 70% lumen maintenance after 50,000 hours provided that the LUXEON is driven at a dc drive current of 350mA for LUXEON I and 700mA for LUXEON III and the junction temperature is maintained at or below 90°C. In addition, LUXEON III is expected to provide an average of 50% lumen maintenance after 20,000 hours when driven at 1000 mA and the junction temperature is maintained at or below 90°C. The lumen maintenance is a function of drive current, a higher drive current causes a higher rate of light degradation. The lumen maintenance is also worse at higher junction temperatures. Operation at junction temperatures above the maximum rating can cause lens yellowing or delamination inside the package, which can result in a permanent reduction in light output.

Appendix A. System Failure Rate Example

Example of estimated failure rate for individual LED

Based on the number of LUXEONS installed in traffic signal heads, the MTTF is expected to be about 100M device hours at an 80°C junction temperature. The examples below show the expected reliability for a LUXEON system using an expected value of MTTF of 100M device hours, estimated from traffic signal head reliability results.

For example, what is the probability of operation after 10,000 hours, if the MTTF is 100,000,000 hours? (Then the failure rate is 1/100,000,000, = 0.001%/1Khrs).

$$R(t) = \exp[-\lambda t]$$

Where:
R (t) = probability that unit will operate at time t
λ = failure rate = 1/MTTF
t = time component is ON

$$\begin{aligned} R(t) &= \exp\left[-\left(\frac{10{,}000}{100{,}000{,}000}\right)\right] \\ &= \exp[-0.0001] \\ &= 99.99\% \end{aligned}$$

Conversely, the probability of failure is:

$$\begin{aligned} P(t) &= 1 - R(t) \\ &= 1 - 0.9999 \\ &= 0.01\%, \text{ or } 100\,\text{ppm} \end{aligned}$$

Example of estimated failure rate for LED array

For example, if a system uses 10 equal components, then what is the probability of operation without any component failures after 10,000 hours, if the component MTTF is 100,000,000 hours?

For a system consisting of *n* identical components, the reliability of a system is equal to:

$$R(t) = \exp[-\lambda n t]$$

$$\begin{aligned} R(t) &= \exp\left[-\left(\frac{(10)(10{,}000)}{100{,}000{,}000}\right)\right] \\ &= \exp[-0.001] \\ &= 99.90\% \end{aligned}$$

And conversely, the probability of failure is:

$$\begin{aligned} P(t) &= 1 - R(t) \\ &= 1 - 0.9990 \\ &= 0.10\%, \text{ or } 1000\,\text{ppm} \end{aligned}$$

From the previous example, suppose that 10 identical components are used in a system operating for 10,000 hours, with the MTTF of a single component equal to 100,000,000 hours. Also suppose that a single failure can be accommodated without failure of the system. Then what is the probability of failure of two or more components?

This problem is an application of the binomial distribution equation. In general, the probability of failure P of exactly x failures in n trials with the probability of failure p per trial is equal to:

$$P(n_x) = \frac{n!}{(n - x)!x!} p^x (1 - p)^{n-x}$$

Where p in the previous equation is equal to:

$$\begin{aligned} p(t = 10{,}000\text{hrs}) &= 1 - R(t) \\ &= 1 - \exp[-\lambda t] \\ &= 1 - \exp\left[-\left(\frac{10{,}000}{100{,}000{,}000}\right)\right] \\ &= 0.000100 \end{aligned}$$

Then the probability of zero failures after 10,000 hours is equal to:

$$\begin{aligned} P(10_0) &= \frac{(10!)}{(10!)(0!)} (0.0001)^0 (1 - 0.0001)^{10} \\ &= (0.9999)^{10} \\ &= 99.90\% \end{aligned}$$

And the probability of one failure after 10,000 hours is equal to:

$$\begin{aligned} P(10_1) &= \frac{(10!)}{(9!)(1!)} (0.0001)^1 (0.9999)^9 \\ &= 10(0.0001)(0.9999)^9 \\ &= 0.10\%, \text{ or } 1000\,\text{ppm} \end{aligned}$$

And the probability of two failures after 10,000 hours is equal to:

$$\begin{aligned} P(10_2) &= \frac{(10!)}{(8!)(2!)} (0.0001)^2 (0.9999)^8 \\ &= 45(0.0001)^2 (0.9999)^8 \\ &= 0.00004\%, \text{ or } 0.4\,\text{ppm} \end{aligned}$$

So, the probability of failure of two or more components:

$$\begin{aligned} P &= 1 - P(10_0) - P(10_1) \\ &= 1 - 0.99900050 - 0.00099905 \\ &= 0.00004\%, \text{ or } 0.4 \text{ ppm} \end{aligned}$$

Thus, the reliability of the system, where a failure is defined as two or more components is equal to:

$$\begin{aligned} R(t) &= 1 - P \\ &= 1 - 0.0000004 \\ &= 99.99996\% \end{aligned}$$

Example Summary

Mission time of 10,000 hours

	Emitter	Systems			
	Single LUXEON	LUXEON array of 10 emitters			
	Probability of Failure	Systems with 0 failures	Systems with 1 failure	Systems with 2 failures	Systems with 3 or more failures
Expected estimate of MTTF (100M device hours)	0.01% 100 ppm	99.90%	0.10% 1000 ppm	<0.0001% 0.4ppm	

Mission time of 50,000 hours

	Emitter	Systems			
	Single LUXEON	LUXEON array of 10 emitters			
	Probability of Failure	Systems with 0 failures	Systems with 1 failure	Systems with 2 failures	Systems with 3 or more failures
Expected estimate of MTTF (100M device hours)	0.05% 500 ppm	99.50%	0.50% 5000 ppm	0.001% 11 ppm	<0.0001% 0.02ppm

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Light From Silicon Valley

Company Information

LUXEON® is developed, manufactured and marketed by Philips Lumileds Lighting Company. Philips Lumileds is a world-class supplier of Light Emitting Diodes (LEDs) producing billions of LEDs annually. Philips Lumileds is a fully integrated supplier, producing core LED material in all three base colors (Red, Green, Blue) and White. Philips Lumileds has R&D centers in San Jose, California and in The Netherlands and production capabilities in San Jose and Penang, Malaysia. Founded in 1999, Philips Lumileds is the high-flux LED technology leader and is dedicated to bridging the gap between solid-state LED technology and the lighting world. Philips Lumileds technology, LEDs and systems are enabling new applications and markets in the lighting world.

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