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Solid State Lighting Reliability from Failure Mechanisms Perspective: A Review of Related Literature

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Abstract

Remarkable long-life makes LED lighting systems a long-term investment, and great energy and maintenance savings easily give good reason for the higher initial cost. LEDs are similar in construction to microelectronics devices, but there are functional requirements, materials, and interfaces in LEDs that make their failure modes and mechanisms distinctive. Over the last few years, considerable effort has gone into the study of the failure mechanisms and reliability of Solid State lighting systems (SSL). Although still very incomplete, our knowledge of the reliability issues relevant to SSL is growing. This paper provides an overview of SSL failure modes and mechanisms that are commonly encountered. It focuses on the reliability issues of LED devices.

KEYWORDS: Solid State Lighting, LED Reliability, SSL reliability, SSL Failure modes, SSL failure mechanisms

Introduction

Remarkable long-life makes LED lighting systems a long-term investment, and great energy and maintenance savings easily give good reason for the higher initial cost. All LED systems do not perform equally over their years of operation. Substandard quality products can prematurely fail or degrade in light output far below initial claims - so much so that they fail to provide the value initially promised. The construction of LEDs is somewhat similar to other semiconductor devices, but their applications and construction make their failure modes and mechanisms distinctive.

Hindrance to the large scale adoption of LEDs in traditional applications is the lack of information available on their reliability. Another obstacle is the lack of worldwide accepted standards, because all commercial properties of an LED lighting system, such as luminous flux output, chromaticity, and lifetime, are functions of the junction temperature. All LED systems do not perform equally over their years of operation. Substandard quality products can prematurely fail or degrade in light output far below initial claims - so much so that they fail to provide the value initially promised. Accelerated Life testing in a short time can predict the life characteristics of LED products under the conditions of normal stress; it is the effective way of the reliability evaluation of LED lighting products for long-term use.

The literature review presented in this paper helps LED lighting designers and LED product manufacturers to understand LED failure mechanisms and reliability thus helping them to design efficient LED lighting products.

LED PRINCIPLE OF WORKING

The LED-chip is the main component of the LED device. This chip is a semiconductor that generates light in a PN-junction by electron p-hole recombination. The active region in the LED-chip is a complex structure of epitaxial layers. For different colours differential material-combinations are used: InAlGaP - red, InGaN - blue, GaAlAs - IR, AlGaN - UV. The material and the quality of the epitaxial layers effectively determine the efficiency factor of the generation of light.

The principal parameters for the function are forward driving current IF and junction temperature Tj within the active layer, influencing both the power consumption and the colour, which significantly determine the lifetime as well. LEDs are commercially available in different technologies. Critical and significant criteria are a stable current path through bonding- solder- and glued connection, an appropriate heat sink for sufficient cooling of the chip by a good thermal and a high extraction of light from the LED by optical elements and areas of reflection. LEDs are encapsulated in general with transparent material like silicone or epoxy.

CAUSES FOR LED FAILURE

LEDs fail as there is a gradual lowering of light output and loss of optical efficiency due to aging. Catastrophic failures, however rare, can occur as well. LED failure modes can be broadly classified as Semiconductor-related and Packaging-related.

SEMICONDUCTOR RELATED FAILURES

Nucleation and growth of dislocations

In this type of failure degradation happens in the active region where the radiative recombination occurs [1]. This type of failure happens, if there is an existing defect in the crystal and this defect is accelerated by heat or high current density or emitted light [2-5]. GaAs and AlGaAs are more susceptible to this mechanism than GaAsP and InP. Due to different properties of the active regions, GaN and InGaN are almost insensitive to this kind of defect [6, 7]. Ionizing radiations are also responsible for defect creation.

Future research should focus on improved internal thermal management handling of thermal resistance from junction to the package to decrease the formation of crystal defects and dislocation movements caused by high-current-induced thermal effects and high ambient temperature [8].

Electromigration

It caused by high current density can move atoms out of the active regions, leading to emergence of dislocations and point defects, acting as nonradiative recombination centers and producing heat instead of light. Improperly designed LEDs may develop areas of uneven thermal resistances leading to current crowding, causing thermal runaway resulting in increasing temperature within LED and reducing the life of LEDs [9].

Under Electromigration, high drive currents or excessive current density can cause contact migration between the electrical contact and the surface of the LED die, which causes short circuit [10].Researchers have reported electromigration of contact metals occurrence along crystalline defects [11]. Proper thermal management and improvement of thermal conductivities of interface materials must be improved. As it is seen that contact resistances of interface materials is responsible for overall thermal resistance [8].

Metal and dopant diffusion

Movement of metal atoms from the electrodes into the active region is caused by high electrical currents or voltages at high temperatures can move metal atoms this is metal diffusion [12, 13]. In some cases, especially with GaN/InGaN diodes, a barrier metal layer is used to hinder the electromigration effects [14]. Some materials, notably indium tin oxide and silver, are subject to electromigration which causes leakage current and non radiative recombination along the chip edges. It is frequently observed in LEDs diffusion of dopants into the active region during operation can cause reduction in light output [15]. The main reason for light degradation is current density, temperature, and current distribution, which causes an increase in series resistance [16-19]. LEDs with low dopant concentration in active region degrade most rapidly. Contaminants like oxygen can be intentionally introduced to form complexes to prevent doping migration [20].

Cracking of Die

Severe thermal shocks can cause breaking of dies of LEDs. Due to differences in material properties, LED packages can be subjected to mechanical stress when a high drive current is applied or when high ambient temperature conditions are suddenly applied. The high electrical stress and extreme thermal shock are the causes of die cracking [21]. It is necessary to control die cracking by fine-tuning thermal expansion coefficients between the substrate and epitaxial layers. The growth of the optimal medium layer between the substrate and the epitaxial layer is a important breakthrough to prevent cracking of die [22]. It is reported that cases light output and electrical degradation were due to die cracking. The way in which die are made has a very critical impact on their cracking. Early defects caused by the sawing or grinding process may act as a starting point for die cracking [23, 24].

PACKAGE RELATED FAILURES

Epoxy / Encapsulant degradation

Prolonged exposure to light from LEDs can cause epoxy materials to be degraded [25, 26]. Yellowing of epoxies is due to prolonged exposure to UV light. This type of discoloration results in a reduction in the transparency of the encapsulant and causes a decrease in LED light output [27]. Further, it has been demonstrated that degradation and the associated yellowing increases exponentially with exposure energy. The thermal effects associated with excessive junction temperature also play a role in encapsulant yellowing [27, 28].

Yellowing is also due to a combination of ambient temperature and LED self-heating. It is found that that a temperature of around 150^{o}C was sufficient to change the transparency of the epoxy, causing the attenuation of the light output of LEDs [29]. While phosphors are a necessary component for producing white light, their presence causes a decrease in reliability [28].

Thermal stress

Sudden failures are most often caused by thermal stresses and shocks [21]. Researchers have found number of cracks introduced from thermal expansion in the centre of the lens surface and on the inside of the polymer encapsulation when high power LED samples aged at different temperatures [30].Prolonged exposure to high condensing moisture causes cloudiness of the epoxy lenses in LEDs due to hygro-mechanical stresses [31].

Phosphor degradation

The different phosphors used in white LEDs tend to degrade with heat and age, but at different rates causing changes in the produced light colour. The driving forces are high drive current and excessive junction temperature, which are attributed to increases in temperature of the inside of the package [10] there by efficiency of the phosphor is degraded when the temperature rises.

Encapsulant carbonization

Studies indicate that carbonization of the plastic encapsulation material on the diode surface leads to the formation of a conductive path across the LED and subsequently to the destruction of the diode itself [10, 35]. Carbonisation is responsible for light output degradation. Carbonization of the encapsulant decreases the encapsulant's insulation resistance, significantly inhibiting its ability to provide electrical insulation between adjacent bond wires and leads [35]. The loss in insulation resistance at temperatures above threshold temperature can initiate a thermal runaway process leading to carbonization of the encapsulant. In this process, the fusing of the bond wires at high current causes the current to be shunted through the plastic, leading to joule heating of the plastic [36]. Under carbonization of the encapsulant there will be light output degradation.

Other failures

Further reliability of solder interconnects in a LED package is influenced by environmental loads, solder material properties, and the intermetallics formed within the solder and the metal surfaces where the solder is bonded [32, 33]. The reliability of the interconnects between packages and circuit boards connections depends on the magnitude of the temperature swing, electrical power of LED packages and board design [34]. Higher electrical power in LEDs accelerated the rate of interconnect failures at solder joints. Using an active cooling device improved the cycles to failure and made them longer than did passive cooling methods [34].

Delamination happens when repeated cyclic stresses can cause the material layers of LED packages to separate, causing significant loss of mechanical toughness. Delamination can either occur between the die and silicone encapsulant, between the encapsulant and packaging lead frame, or between the LED die and die attach [8]. Delamination causes decreased light output. Delamination increases the thermal resistance of the delamination layer leading to increased junction temperature, which also affects many other types of failures and eventually decreasing the life of LEDs. Interface contamination during the LED manufacturing can result in poor bonding of interfaces, which can initiate delamination.

CONCLUSIONS

As LED prices fall, designers are increasingly using them in their product designs, especially for lighting. LEDs have a reputation for being tireless workers that that never need replacing and require little payment in terms of power consumption. The main LED failure mechanisms are mechanical and thermal in nature. They involve thermal cycles, thermal shock, and LEDs operating at high temperatures so the wire bond ages. As the metal oxidizes and becomes brittle over time, the likelihood of an LED failure increases. Another cause of LED open circuits is electrostatic discharges.

Better understanding of the causes responsible for failures in LEDs with respect to improving material properties and fabrication technology is the need of the hour. A deeper understanding of various process variables and associated environments critical for LED quality must form part of LED reliability studies. Failure analysis of LEDs has been performed through conventional microelectronics failure analysis approaches and off-line analysis techniques. There is a need to develop advanced failure analysis techniques for LEDs.

Collaboration between standards bodies and professional societies is required to arrive at internationally accepted standards to ensure a fair comparison of published performance and reliability data. Reliability study of complete LED luminaires is the need of the hour.

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