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White Paper

Factors that Drive LED Reliability

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Introduction

Semiconductor-based light emitting diode (LED) devices first appeared in the 1960s. Today, with the advances in materials, design and manufacture of LED devices, DfR is seeing a wide spectrum of LEDs that are cheaper, more colorful, more efficient, more intense, and more reliable. LED applications include signs and indicators, sensors, communication devices, displays, and increasingly solid state lighting and backlighting for TVs and monitors. The supply chain for LEDs can include producers of LED chips, packaging houses, LED driver chips and system integrators (e.g., LED light bulb). Large players in LED chip manufacture include Nichia, Philips, Osram and Cree.

LEDs provide unique advantages in solid state lighting due to their power efficiency and reliability. As an example, the Pharox 500 equivalent to a 60-watt conventional bulb from Lemnis Lighting (Figure 1) consumes 7 watts and lasts for ~25 years [1]. The cost is currently projected to be under \$40 and can go down to \$10 in five years driven by demand and improvements in the electronics. Philips predicts that LEDs will make up 80% of the general illumination market by 2020.

Figure 1: Pharox LED light bulb from Lemnis Lighting

The exciting market developments will in turn pose new reliability challenges. For example, solid state lighting depends on high power LEDs which generate much heat and they can be used in uncontrolled environment such as outdoors. In this white paper, we'll discuss the driving factors affecting LED reliability.

How do LEDs Fail?

At device level, an LED is a forward-biased diode that enables radiative carrier recombination providing light output. LEDs can be classified according to the light colors or power intensities. Or they can be distinguished based on the base materials systems such as GaAs, InGaP, GaN, ZnSe, Si and even organic compounds. They can also be differentiated based on the device and package designs, e.g., quantum dot LEDs, top emitting and side-emitting LEDs.

LEDs typically display a wearout failure mode due to long term drift of critical output characteristics, e.g., light intensity or color shifts. LEDs can also fail in a more catastrophic manner due to flaws in component materials/structures and assembly related stresses.

LED component suppliers often use 50% light intensity degradation as the LED failure criteria, though the actual end usage scenario can drive application-specific requirements such as those related to the color correctness, intensity, and uniformity of the LED light output. There is a difference in measuring the radiometric vs. photometric light intensity, with the latter weighted by human eye sensitivity to visible light. For example, a sensor application in a machine vision system would depend on radiometric intensity changes rather than the photometric changes. LEDs do not always decrease monotonically in their light output; certain LEDs can display a temporary reverse-degradation behavior with increased light output after ageing, which could pose risks for eye-safety sensitive applications.

In addition to determining failures based on LED output characteristics changes, one can also monitor the operational parameters of the LED such as when the forward voltage shift, forward or reverse leakage currents exceed a pre-defined limit.

LED Reliability

LED reliability will be determined by all its constitutive parts and their interactions upon environmental or operational stresses. DfR discusses the primary drivers from the perspective of the LED die and package below.

LED Die

From the semiconductor die perspective, the two dominant stresses affecting LED reliability are the LED forward drive current and operation temperature.

Atomic defects such as dislocations contribute to the reduced probability of photon generation thus the degradation of the LED. These defects serve as non-radiative recombination centers and generate heat instead of light. In many materials systems such as GaAs/AlGaAs, high forward drive current density causes electro-migration, which is responsible for the nucleation and growth of dislocations and other defects in the region where the radiative recombination occurs. The speed at which these lattice defects increase depends on the magnitude of the forward current density.

Apart from high current density driving bulk crystal defects, ionizing radiations can also lead to the creation of atomic defects. Along the chip edges, high electrical currents or voltages at elevated temperatures may result in electrode metal (e.g., ITO, Ag) diffusing into the active region, resulting in leakage current and non-radiative recombination.

The atomic defect generation and growth can be accelerated at higher temperatures. The semiconductor-based temperature acceleration factor is often modeled by an Arrhenius equation. There can be interactions between the drive current density and temperature. For example, in case a simple bias resistor is used to control LED forward current, drive current may increase at higher temperatures. Most of the electron-hole combinations that don't result in photons create heat, and LEDs generate less light as they get hotter. These two factors can not only accelerate the atomic defect growth, they can also lead to thermal runaway especially for high power LEDs. In addition to reliability concerns, the emitted light intensity as well as wavelength may shift as the junction temperature rises.

As discussed in an earlier DfR Solutions publication [2], another type of defects affecting LED performance and reliability is the threading dislocations (TD). Threading dislocations form in highest densities on sapphire based GaN LEDs, where there can be migration of contact metal through the hollow center of the dislocation, creating an Ohmic resistive path between the P and N regions of the die, disabling the LED.

LED Package

In addition to protecting the semiconductor die from direct environmental exposures and facilitating the interconnection of the LED to the system; the LED package also play an essential role for the LED optical, thermal, mechanical and electrical performance and reliability requirements. They are discussed below:

Optical: Package optical properties can be affected by epoxy and phosphor degradations when exposed to temperature, moisture, or UV radiation. Optical performance is also affected when air gap forms, e.g., due to delamination, or when the materials optical property/geometry changes. Such changes can modify the optical path, reflectivity and index of refraction matching across the device layers before photons can be emitted efficiently.

Thermal: Thermally, low power LEDs dissipate heat primarily through their leads whereas high power LEDs depend more on the package. For example, most high power LEDs are SMT types that can be directly mounted onto a heat sink. In some cases, package degradation can contribute more to the light output degradation than the LED die itself, as silicone and epoxy may deteriorate faster over time. Packages for state-of-the-art high power LEDs are much more sophisticated than early LEDs. High power LEDs may be mounted on metal-core PCBs to provide efficient heat transfer. However, one should not simply be satisfied with an acceptable “macro” junction temperature. LEDs with design or manufacture package flaws may result in non-uniform heat conduction across the die active region, resulting in current crowding and local heating, posing risks of thermal runaway. Heat can also degrade the different phosphors used in white LEDs. The degradation rates for these phosphors may vary, causing changes in the eventual output light color. For example, purple and pink LEDs with an organic phosphor formulation may degrade after just a few hours of operation resulting in output color shifts.

In addition to high temperatures and high humidity operation degradations, LED packages are susceptible to failures during temperature cycling or when the package is exposed to low temperatures. Thermal cycling can cause thermal fatigue failures related to wirebonding, die attach and die-package delamination. This can be traced to the incompatibility of package structures/materials and the environmental/operational stress experienced. The presence of manufacturing defects such as poor intermetallic formation at the ballbond or inadequate die attach can be particularly susceptible in these scenarios. In addition to issues exposed at high temperature or temperature cycling, LED packages exposed to very low temperature may exert mechanical stress on the LED die, to the extent of causing die cracks.

Mechanical: Mechanical integrity of the LED is another critical aspect that demands attention throughout the package design, assembly and system integration. The compound semiconductor used in LEDs possesses different mechanical strength when compared to, e.g., Si. The wirebonding process parameters need to be carefully designed and controlled in order to form a quality bond without, for example, generating bonding or die weaknesses. In LED assembly to PCBAs, package stress can be introduced due to lead bending or soldering actions, which can introduce package and die defects resulting in early failures.

Electrical: As a semiconductor device, LEDs will be susceptible to electrostatic discharge (ESD) and electrical overstress (EOS). ESD may cause immediate failure at the diode junction, or a shift in its parameters, or latent defect causing later functional failures. As EOS examples, power-line coupled transients and surges can degrade LEDs. And the reverse-breakdown mode for some LED types can occur at very low voltages where any excess reverse bias may cause immediate degradation [2].

Conclusions

In integrating LED devices into a system, the first order business is to carefully evaluate the environmental and operational stress conditions in order to select the LEDs with the proper strengths. For example, thermal and moisture environment exposures and controls, voltage/current fluctuations including the likelihood of ESD/EOS incidents, UV light intensities, etc. are to be examined. Don't forget details such as soldering temperature exposure, mechanical stress on the package due to specific mounting methods can all influence LED reliability. Based on this, suppliers' reliability data should be carefully evaluated and analyzed for differences in test conditions, failure criteria. As an example, manufacturers may specify and test the LEDs at room temperature using pulse rather than continuous current. In this case, the LED junction temperature can stay at room temperature, demonstrating much better reliability than in actual applications.

When it comes to predicting the life of LEDs, the typical long life of the components makes it impractical to obtain meaningful experimental data relevant to real applications, as it is hard to extrapolate future behaviors across populations based on limited testing. For solid state lighting, Philips prescribed a simplified approach that helps lighting designers define operation conditions related to the so-called "B50/L70" lifetime [3], i.e., when 50% of the products have at least 70% lumen maintenance for the projected operating hours. The statistics are based on Philips' extensive internal testing data and is graphically presented with reference to driving current and junction temperature. It is unknown what design margins are provided based on this approach and one can expect variations across vendor bases, technology platforms, production processes, and specific system design and deployment. Frequently, a quality LED that is properly integrated into a system can experience much longer life than the rest of the system and may be the last concern when evaluating the overall system reliability.

References:

[1]: http://news.cnet.com/8301-11128_3-20004760-54.html?tag=newsEditorsPicksArea.0

[2] http://www.dfrsolutions.com/uploads/white-papers/LED_Failures.pdf

[3] http://www.philipslumileds.com/pdfs/WP12.pdf

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