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► **To cite this version:**

G Meneghesso, M Meneghini, E Zanoni. Recent results on the degradation of white LEDs for lighting. Journal of Physics D: Applied Physics, 2010, 43 (35), pp.354007. 10.1088/0022-3727/43/35/354007 . hal-00569692

HAL Id: hal-00569692

<https://hal.science/hal-00569692>

Submitted on 25 Feb 2011

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Recent results on the degradation of white LEDs for lighting

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Abstract

Over the last years, GaN-based LEDs have shown to be excellent candidates for the realization of high-efficiency light sources. White LEDs based on phosphor conversion can reach record efficiencies in excess of 150 lm/W, as demonstrated by several manufacturers and research groups. However, the reliability of white LEDs is still limited by a number of issues that must be addressed before these devices can find wide application in the market. This paper gives an overview on the most important physical mechanisms that limit the reliability of GaN-based LEDs for application in solid-state lighting. Starting from general considerations on the reliability of state-of-the-art white LEDs, the following degradation mechanisms are described in detail: (i) the degradation of the active layer of LEDs, due to increased non-radiative recombination and to reverse-bias stress; (ii) the degradation of the package/phosphor system, with subsequent worsening in the chromatic properties of the LEDs; (iii) the failure of GaN-based LEDs submitted to Electrostatic Discharge events. The data presented in this paper are critically compared to those reported in the literature.

1. Introduction

More than 20 % of the electricity generated in the United States is used for lighting [1]; furthermore, worldwide lighting is responsible for the emission of more than 1900 million tons of CO₂ per year. The use and development of highly efficient light sources would decrease more than 50 % the worldwide lighting consumption [2], with subsequent economic and environmental benefits.

Over the last decade, GaN-based LEDs have emerged as good candidates for the realization of high-efficiency light sources for general lighting. Thanks to the continuous optimization of the growth and processing procedures, blue and white LEDs with outstanding performance have been recently demonstrated: blue LEDs have a record wall-plug efficiency in excess of 60 % [3], while white LEDs can reach luminous efficacies in excess of 150 lm/W [4]. These advancements came from the improvement of the following parameters: (i) internal quantum efficiency (IQE); (ii) extraction efficiency; (iii) technology used for the realization of phosphors; (iv) packaging and assembling procedures.

However, efficiency is not the sole parameter that is taken into account by consumers: LEDs are semiconductor-based devices, and for this reason they are expected to have an intrinsically high reliability, compared to conventional light sources (incandescent and fluorescent lamps). Incandescent lamps have a typical lifetime of 1000 hours, and during aging can show a 10-15 % lumen depreciation, due to the condensation of the tungsten contained in the filament on the inner part of the glass bulb. Fluorescent lamps can reach a 10000-hours lifetime, with a limited (10-20 %) lumen decrease, which is due to the degradation of the phosphors used for white light generation, and to the increase in absorption within the lamp. On the other hand, LEDs can have a significantly longer theoretical lifetime (in excess of 50000 h, [5]), making them good candidates for the realization of long-lasting light sources. While the degradation mechanisms of conventional light sources are well known, the origin of the degradation of LEDs is still subject of intense study.

Over the last few years, several authors [6-37] have investigated the origin of the degradation of LEDs submitted to accelerated ageing tests. In particular, it was shown [6, 7, 9, 12, 14, 17, 20] that stress at constant current level can determine a significant decrease in the internal efficiency of the devices: degradation was

attributed to the increase in the non-radiative recombination rate in the active layer of the LEDs, due to the generation/propagation of defects [12, 14, 17, 20], or to the diffusion of dopants or impurities in the quantum well (QW) region [34, 35]. It was also shown that operation at high temperature levels can induce a significant degradation of the optical characteristics of GaN-based LEDs: high-temperature degradation was attributed *(i)* to the worsening of the electrical properties of the ohmic contact and semiconductor material at the p-side of the diodes [21, 23, 31], due to the interaction between hydrogen and the magnesium dopant, and *(ii)* to the thermally-activated darkening of the package and phosphors system, with subsequent worsening of the chromatic properties of white LEDs [22, 24, 25, 26, 29, 33]. Recent studies [14, 36] highlighted that also exposure to reverse-bias can determine the degradation of GaN-based LEDs: when submitted to reverse-bias stress, devices can show a significant increase in reverse current (corresponding to a decrease in breakdown voltage), which was ascribed to the generation of point defects in proximity of pre-existing defective leakage paths. Finally, some authors [10, 27, 32] indicated that also Electrostatic Discharge (ESD) events can represent an issue for GaN-based LEDs: when submitted to ESD events, LEDs can show catastrophic failure, with subsequent shortening of the junction. Failure usually takes place in proximity of a weak region [37], corresponding to the presence of lattice or morphological defects.

In this paper, we give an overview on the most important physical mechanisms that affect the reliability of state-of-the-art white LEDs. Starting from recent results obtained on commercially available power LEDs, we describe in detail the degradation processes that affect *(i)* the electrical and optical properties of InGaN-based LEDs, and *(ii)* the optical efficiency of the package/phosphors system. Finally, we describe the failure of LEDs submitted to ESD events.

2. Physics of LED failure

2.1 Structure of commercially available LEDs

High-power LEDs are complex systems, constituted by several elements: the core of a white LED structure is a blue GaN-based LED chip, with an emission wavelength of 450-460 nm. This chip typically has an area of 1 mm^2 , and is mounted on a thermally-conductive frame in a power LED package, in order to achieve a good heat dissipation. The power LED chip is usually covered with a lens, which has the twofold aim of improving the efficiency of the light extraction process, and of modifying the shape of the emitted light beam. Blue light is converted into white light by means of a phosphorous layer, which can be deposited directly on the chip (Chip Level Conversion, CLC), or incorporated in the encapsulating lens. As an example, in Figure 1 we report a Scanning Electron Microscopy (SEM) image of a commercially available power LED chip: the image was taken after the removal of the encapsulating lens, and is referred to an LED with vertical current conduction path.

Commercially available power LED chips usually have a nominal operating current in the range 350-1000 mA (corresponding to current densities in the range 35-100 A/cm^2 for 1 mm^2 chips), and an operating voltage in the range 3.2-3.4 V. These devices are therefore rated for an electrical power consumption between 1 and 3.5 W.

In their final application, the thermal resistance of power LEDs is in the range between 10 K/W and 20 K/W, depending on the optimization of the heat extracting path. Therefore, under normal operating conditions devices can show a certain self-heating, with a temperature increase (with respect to ambient temperature) ranging between 20 °C and 80 °C. As it will be clear in the following, the current and temperature levels reached by LEDs during ageing time can strongly influence the degradation kinetics of LEDs: for this reason an accurate definition of the operating conditions, and a careful optimization of the heat dissipation process are mandatory steps for the achievement of a long LED lifetime.

As stated above, LEDs are complex systems, composed by several elements: during device lifetime, each of these components can degrade, leading to a depreciation of emission intensity and chromatic properties. The blue LED chip, if submitted to constant current stress, can show a significant optical power decrease, due to the

increase in non-radiative recombination rate [9, 12, 14, 38, 39]. Furthermore, operation at high current/temperature levels can lead to significant modifications in the chromatic properties of LEDs, due to the darkening of the phosphorous material and to the worsening of the reflective properties of the package [22, 25, 29]. Finally, the lens - usually adopted to improve the efficiency of the light extraction process - can also show a significant darkening as a consequence of device ageing, both due to the high temperatures reached during LED operation, and to the short wavelengths emitted by the device itself [8].

Lifetime tests are usually carried out by submitting LEDs to accelerated ageing, under relatively high current and/or temperature levels. Under these conditions, it is quite difficult to understand whether degradation processes are mainly due to the flow of a relatively high current density through the junction, or to the high temperatures reached by the devices during operation. Furthermore, when the many components of an LED structure degrade simultaneously, it is quite difficult to understand whether degradation is mainly due to the ageing of the blue LED chip, or to processes related to the package/phosphors/lens system. In order to achieve a good understanding of the physical processes that limit the reliability of advanced LED structures, it is therefore necessary to develop specific testing procedures, capable of separately analyzing the degradation of the individual components of an LED during ageing time. In the following we will describe some general results on the reliability of state-of-the-art white LEDs, and more specific data concerning the degradation of the blue LED chip (weaknesses of InGaN-LED technology) and of the package/phosphors system.

2.2 Reliability testing of high-power white LEDs

Ageing tests of high power LEDs are usually carried out under slightly accelerated conditions. A reasonable acceleration can be obtained by ageing the LEDs at the maximum current indicated in the datasheet, with an ambient temperature between room temperature and 85 °C [40-42]. For the stress tests, devices are mounted on proper heat sinks, by means of thermally-conductive adhesive, in order to keep the junction-to-ambient thermal resistance sufficiently low. The thermal resistance of the LEDs can be evaluated by means of the indirect forward-voltage method, proposed by the group of E. F. Schubert and described in detail in [43]. The ageing

current should be applied continuously, except for the time spent for the measuring procedures. Devices are considered to be failed when they show a 10-30 % decrease in the luminous flux, or a certain operating voltage shift (typically 200 mV) (see for instance [42]). In Figure 2 we report typical optical power degradation curves measured on three families of state-of-the-art white LEDs, aged at 100 A/cm^2 , $80 \text{ }^\circ\text{C}$ during a benchmarking test carried out in our laboratories. Analyzed LEDs come from three leading manufacturers, and were acquired in October 2009: as can be noticed, one of the three families of analyzed LEDs showed a significant optical power degradation during the mid-term stress test, demonstrating a high sensitivity to the applied stress conditions. From the results of this - or similar - ageing tests, it is possible to compare different device technologies in terms of reliability. On the other hand, by simply measuring the optical power degradation (or the operating voltage shift) during the stress tests, no significant information on the physical mechanism responsible for degradation can be achieved. In order to analyze the origin of lumen depreciation, specific stress tests must be carried out, on suitable test and device structures. In the following we report the results of a number of stress tests that we have carried out with the aim of analyzing specific degradation mechanisms affecting the efficiency and the optical properties of the InGaN-based LED chip, of the package, and of the phosphors of advanced LED structures.

2.3 Degradation of the InGaN-based LED chip

The degradation of the InGaN-based LED chip can be studied by submitting bare LED samples to specific stress tests. The results described within this section were obtained on LED samples mounted on metallic TO18 package: no phosphors/plastic package/lens was used for these devices. Therefore, the degradation modes described in the following can be ascribed to the ageing of the InGaN LED chip.

In order to describe the degradation of InGaN-based LED chips, we submitted several commercially-available and R&D samples to stress under constant current level. For the stress tests, devices were mounted on Peltier-controlled fixtures, allowing for an accurate control of case temperature. Stress current levels ranged in the interval 20-180 A/cm², while case temperature levels ranged between 15 °C and 85 °C. During the execution of the stress tests, a complete optical and electrical characterization of the devices was carried out, in order to achieve a description of the degradation process.

In Figure 3 we report the optical power vs current density (L-J) characteristics measured on one InGaN-based LED chip submitted to stress under constant current conditions. As can be noticed, stress can induce a decrease in the optical power emitted by the samples. This effect is more prominent at low measuring current levels, as also described by the optical power vs stress time curves reported in Figure 4. This result suggests that stress induced an increase in the non-radiative recombination rate: at low measuring current levels, the non-radiative recombination centers present in the active layer can efficiently trap the carriers flowing through the junction, thus reducing the amount of electrons that undergo radiative recombination. An increase in non-radiative recombination rate therefore results in a decrease in the optical power emitted by the LEDs at low measuring current levels. On the other hand, at high measuring current levels, the injection of a large amount of electrons can lead to the saturation of the non-radiative centers: therefore, the L-J characteristics of LEDs are not significantly modified at high measuring current levels [38, 39].

This kind of degradation process is only slightly thermally activated, at least within the nominal operating range of commercially available samples (maximum temperature is 105-125 °C). Stress tests carried out at different case temperature levels (and with the same stress current level) indicated only a weak dependence of the

degradation kinetics on stress temperature (see Figure 5 for an example). This result suggests that current - rather than temperature - is the main driving force for the degradation of bare LED chips submitted to constant current stress. This hypothesis is supported by recent reports describing the degradation of InGaN-based laser diodes, both in the lasing and sub-threshold operating region [44, 45]. A linear dependence of the degradation rate on the stress current level was found for these devices, which are – in their inner structure – very similar to LED chips [44]: on the other hand, degradation was found to have a weak dependence on temperature, with activation energies in the range 0.25-0.30 eV [44].

A similar degradation process is usually explained by supposing that the injection of charged carriers through the junction leads to the generation/propagation of defects (such as vacancies or impurities), due to the interaction between highly energetic electrons and the lattice [7, 12, 20]. This may determine an increase in the non-radiative recombination rate in the active layer of the devices, a the decrease in the efficiency of the light generation process.

Furthermore, recent reports [20, 34] demonstrated that during constant current stress the distribution of charge in the active region can significantly change: this result was obtained by means of Capacitance-Voltage (C-V) profiling. C-V measurements represent a powerful tool for the analysis of the distribution of charged carriers in the active layer of LEDs: starting from C-V characterization, it is possible to extrapolate the Apparent Charge Distribution (ACD) of free carriers within the junction [20], and to detect possible changes arising as a consequence of stress. In Figure 6 we report the C-V characteristics measured before and during constant current stress on one InGaN-based LED. As can be noticed, stress induced a significant increase in junction capacitance, in the voltage region between -4 and 0 V. For the analyzed devices, when the voltage is varied in this range, the border of the space charge region is located within the quantum-well region, as described in detail in [37]. Therefore, an increase in junction capacitance measured in this voltage region corresponds to significant variations in the charge density in the active layer of the LEDs. By integrating the differential capacitance increase reported in Figure 6, it is possible to quantitatively evaluate the amount of charge increase induced by the constant current stress experiment [34]. The most important result of this analysis is shown in Figure 7. This figure reports on the horizontal axis the variation in the optical power induced by constant current stress, and on

the vertical axis, the variation in the charge concentration detected as a consequence of stress. Results indicate that there is a nearly linear correlation between the amount of optical power decrease and the variation of charge concentration in the quantum-well region. Results can be interpreted by considering that stress induces the propagation of charged defects towards the active layer of the LEDs. The rate of non-radiative recombination is directly correlated to the density of defects located within the active region. Therefore, an increase in charged defect density can lead to a decrease in the optical efficiency of the devices and to an increase in the apparent charge concentration in the quantum-well region (detected by means of C-V characterization). Recent studies indicated that these modifications in the charge distribution can be correlated to the presence of deep levels with activation energies in the range 160-430 meV [20, 46]. However, the origin of the deep levels responsible for the degradation of LEDs was not univocally identified, and several efforts are currently in progress in this direction. Furthermore, investigations carried out by means of Secondary Ion Mass Spectroscopy (SIMS) suggested that also the penetration of dopant towards the active layer of the devices, activated by the stress test, can play a role in determining LED degradation [35]. In particular, it was suggested that the diffusion of acceptor dopant (Magnesium) through dislocations in the quantum well region, might determine a significant increase in non-radiative components, and the subsequent degradation of the efficiency of the devices.

InGaN-based LED chips can degrade also when exposed to reverse-bias, as suggested by some recent reports [14, 36]. In order to investigate the degradation mechanisms activated by reverse-bias, we have submitted a number of InGaN-based LEDs to stress under constant current and constant voltage level. We have used stress voltage levels in the range -20 V / -45 V, and stress current density levels in the range between -0.3 A/cm² and -2.4 A/cm². Results indicated that LEDs can show a remarkable increase in reverse current, when they are submitted to negative-bias stress. As an example, in Figure 8 we report the I-V curves measured in the reverse-bias region on one LED submitted to stress under constant negative current. The measured increase in reverse current corresponds to a significant decrease in the breakdown voltage. On the other hand, reverse-bias stress does not significantly affect the forward-bias electrical characteristics (and the forward-bias operating voltage) of InGaN-based LEDs (see the I-V curves in Figure 9). Experimental data indicated that the optical performance

of LEDs is only slightly affected by the reverse-bias stress: even samples aged under significantly high reverse-current densities (up to -2.4 A/cm^2), showed a limited decrease in optical power (see Figure 10).

The significant degradation of the reverse-bias electrical characteristics of LEDs was explained according to the following interpretation [14, 36]: when LEDs are submitted to reverse-bias stress, current flows by tunneling through localized leakage paths, related to the presence of structural defects [36]. Injected carriers are significantly accelerated by the high electric field present under reverse-bias conditions, and can achieve enough energy to interact with the lattice and induce the generation of point defects. Defect generation takes place close to the pre-existing leakage paths responsible for reverse-current conduction. This mechanism induces a significant increase in the reverse-leakage current of LEDs submitted to negative-bias stress. On the other hand, no significant modification is detected in the forward-bias electrical and optical characteristics of LEDs as a consequence of reverse-bias stress. This can be explained by considering that *(i)* degradation interests nanometer-size regions, which are considerably small with respect to the whole device area; *(ii)* under forward-bias conditions, the impedance of the junction is low compared to that of generated defective leakage paths. For this reason, the forward-bias behavior of LEDs is dominated by the conduction and recombination mechanism of the LED junction, rather than by the presence of defective tunneling paths.

2.4 Degradation of the package and of the phosphors

One of the core elements of a white LED structure is the phosphorous layer used for the conversion of blue light into white light. Furthermore, the external efficiency of white LEDs is maximized if LEDs are placed in reflective packages, with optimized optical properties. Recent reports [22, 25, 29, 33] indicate that the package/phosphors system can significantly degrade during LED lifetime. This can result in a significant decrease in LED efficiency, and in possible modifications of the chromatic properties of the devices. Degradation of the phosphors and of the package is mostly correlated to thermal effects, and is particularly present when heat dissipation is not properly optimized. Phosphors and package usually degrade when they are exposed to temperatures in the range between 100 °C and 200 °C [22, 24, 25, 26, 29, 33]. On the other hand, within this temperature range the efficiency of the blue LED chip is stable over storage time [47]. Therefore, the most convenient way to study the degradation of the package/phosphors system is to carry out “purely thermal” stress tests, by submitting the LEDs to high temperatures without any applied bias. In this way, degradation can be only ascribed to the worsening of the optical properties of the package and of the phosphors.

The Spectral Power Distribution (SPD) of a white LED is constituted by the superposition of a blue emission band, centered around 460 nm, and a broad yellow-green peak, related to the luminescence of the phosphorous material (see the black line in Figure 11, as an example). In general, high temperature storage can determine significant modifications in the spectral output of a white LED. As an example, in Figure 8 we report the SPD of a state-of-the-art white LED, submitted to stress at 140 °C, no bias. Stress was found to induce both a decrease in the external efficiency of the white LED, and modification in the shape of the electroluminescence spectrum. The intensity of the blue and yellow luminescence peak showed a different percentage variation during stress time: in Figure 12 (a) we report – for the same device – the decrease in the intensity of blue and yellow luminescence induced by high temperature treatment. Data are referred to the same sample as in Figure 11. As can be easily understood, besides the overall optical power decrease, stress induced a significant decrease in the intensity of the phosphor-related luminescence with respect to the main blue emission peak (Figure 12 (b)). This corresponds to a shift of the chromatic coordinates of the analyzed LEDs towards bluish light [48].

In most of the cases, the degradation of the spectral output of white LEDs can be ascribed to (i) the browning of the material used for the incorporation of the phosphors, (ii) or to the darkening of the package, with subsequent worsening of its reflective properties. Of course, these degradation modes can take place also when devices are submitted to stress at moderate current levels (i.e. within the nominal operating range), with junction temperatures greater than 100-120 °C. In Figure 13 and 14 we report two examples, obtained on commercially-available devices aged under similar conditions. As a consequence of stress, the device in Figure 13 showed a significant darkening of the package material, without any visible degradation of the phosphorous layer. As described in [26], a similar degradation process can result in a reduced optical output, since after stress the reflective properties of the package are significantly altered. On the other hand, the LED in Figure 14 showed – as a consequence of stress – a significant browning of the phosphorous layer in proximity of the center of the emitting area. This process, related to the high temperatures reached by the junction during operation, can result in a significant quenching of device luminescence, and in the modification of the spectral properties of the LED (see Figure 11 and 12).

Degradation processes related to the phosphors/package system are significantly thermally activated, as reported by a number of authors [25, 26, 48]: typical activation energy values range in the interval 0.47-1.5 eV, depending on the analyzed device technology. Stress tests carried out on moderately-biased devices indicated that the Time-To-Failure (TTF) of white LEDs is significantly dependent on the operating junction temperature, with no significant dependence on the stress current level (at least within the nominal operating range). As an example, in Figure 15 we report the Arrhenius plot for the $TTF_{50\%}$ (time necessary for a 50 % decrease in luminous flux) for a number of white LEDs submitted to stress at different current and junction temperature levels. From the slope of this diagram, the activation energy of the degradation process can be extrapolated (equal to 470 meV for this specific device technology).

2.5 ESD Failure of LEDs

Recent reports [10, 27, 32] indicate that advanced LED structures – especially those with high indium content – can be particularly susceptible to ESD events. The ESD stability of LEDs is usually evaluated by means of the Human Body Model (HBM): the human body is modeled as a 100 pF capacitor, that is discharged on the device through a 1.5 k Ω resistance and a switch. The ESD robustness is defined as the maximum voltage a device can withstand before ESD failure. While HBM can be an excellent predictor of the ESD robustness of an electronic device, by means of this method no information on the physical mechanism responsible for failure and on the electrical behavior of LEDs at high current/voltage levels can be extrapolated [49]. For this reason, over the last decades, another method has been widely adopted for a better investigation of the characteristics of electronic devices submitted to ESD events: the Transmission Line Pulse (TLP) method [50]. The TLP method is based on discharging a (pre-charged) transmission line on the LED under test. By the TLP method it is possible to generate ESD-like pulses with increasing voltage amplitude. The length of the pulses (100 ns for the results described in the following) depends on the length of the transmission line used for the tests. The TLP method has the unique advantage of permitting the accurate control and measurement of the characteristics of the devices at extremely high current levels. For this reason, TLP method is adopted in many research laboratories, to study the effect of ESD on the electrical characteristics of electronic devices. In the following we will mainly refer to results on the ESD robustness of LEDs obtained by means of the TLP method.

In Figure 16 we report the pulsed Current-Voltage (I-V) characteristics measured under forward and reverse bias on two InGaN-based LEDs. Measurements were taken by means of a Transmission Line Pulse system, i.e. by applying a series of (100 ns) voltage pulses with increasing amplitude to the devices. In the forward-bias region (Figure 16 (a)), the I-V curve has a linear behavior: at high current levels, the electrical behavior of LEDs is dominated by the series resistance of the junction and of the measuring system (approx. 6 Ω in this case), while the voltage drop on the junction is negligible. Under forward-bias ESD events, devices can withstand a TLP current in excess of 10 A without reaching the failure. On the other hand, under reverse-bias, the pulsed I-V curve of the LED (Figure 16 (b)) has a nearly exponential shape, with a turn-on voltage around -70 V and a

significant series resistance component. LEDs can show a low failure threshold, when submitted to reverse-bias ESD. In the I-V curve in Figure 16 (b), ESD failure can be recognized as a sudden decrease in the impedance of the device, with subsequent snap-back of the electrical characteristics. Device failure under reverse-bias ESD events is usually explained by considering that reverse-current conduction occurs via small-size leakage paths, related to the presence of structural defects, such as dislocations/V-defects or Indium related-defects [37]. The position of these paths can be identified by emission microscopy, as suggested by recent research reports [51].

The injection of reverse current through defective states gives rise to a weak luminescence signal (Figure 17). Reverse-bias luminescence is localized in specific positions, corresponding (i) to the presence of preferential paths responsible for leakage (and ESD) current conduction (related to the presence of structural defects) or (ii) to the presence of morphological defects (pits) that are known to promote light extraction. Under reverse-bias ESD events, an high current density flows through nanometer-size defective paths: this results in a subsequently high power dissipation, that can lead to the localized failure of the junction [37]. After ESD failure, devices behave as short circuits, and failure cannot be recovered. The position of the failed region can be identified by means of Scanning Electron Microscopy (SEM, Figure 18), or by optical microscopy: in many cases the failure point is located in correspondence of pre-existing structural defects [37]. Several methods have been proposed with the aim of improving the ESD robustness of InGaN-based LEDs, including (i) the use of a silicon-based protection circuit in parallel to the LED [27], (ii) the use of optimized growth procedures, capable of reducing the defectiveness of the active layer and the Dislocation Density [52, 53] and (iii) a careful optimization of junction capacitance, that can result in an improved ESD performance [32].

3. Discussion and conclusions

With this paper we have presented an analysis of the physical processes that limit the reliability of GaN-based LEDs. State-of-the-art LEDs are complex devices, constituted by several components. All of these components can degrade during stress time: as a consequence of ageing, LEDs can show a reduction of the total luminous flux and a worsening of the chromatic properties. Degradation may be ascribed to several driving forces, as briefly summarized in the following:

1. Current flow through the active layer of the LEDs may induce the generation/propagation of defects, with subsequent increase in the non-radiative recombination rate. It was recently shown that LED degradation can be correlated to significant modification of the apparent charge distribution in the quantum-well region [20, 34], that may be due to the increase in the concentration of deep levels [20], or to the diffusion of dopant or impurities towards the active layer of the LEDs [35]
2. Temperature can play a significant role in limiting the reliability of white LEDs. When LEDs are exposed to high temperature levels (or operated with non-optimized thermal dissipation) the optical properties of the package and of the material used for the encapsulation of the phosphors can severely degrade [24, 25, 29]. This can result in a significant reduction of the luminous flux emitted by the devices, and in modifications of the spectral characteristics of the LEDs. Degradation of the package and phosphors system is generally thermally activated, with activation energies in the range 0.45-1.5 eV depending on the analyzed device technology
3. Reverse-bias ESD current can represent a critical driving force for catastrophic LED failure [10, 27, 32]. When LEDs are submitted to reverse-bias ESD events, a significantly high reverse current flows through localized leakage paths, related to the presence of structural defects. This may result in an extremely high and localized power dissipation, which determines the catastrophic shortening of the junction. An improvement of the quality of the active layer (reduction of the concentration of defects),

and/or the use of suitable ESD-protection structures can result in a significant improvement of the robustness of LEDs towards ESD events.

The results described within this paper and in the quoted references indicate that, despite the excellent potential of LEDs, a number of factors can limit the reliability of these devices. Some of the degradation mechanisms described above, including the generation of defects in the active layer and the ESD failures, are strongly related to the quality of the heterostructure. A significant increase in the reliability of the devices may be obtained only through an improvement of the growth and processing procedures.

On the other hand, the thermally-activated degradation mechanisms can be avoided (or at least slowed down) through a careful optimization of the thermal management process. Since the activation energies for the degradation processes related to the package and the phosphors can be quite high, a reduction of the operating temperature can make a significant difference in terms of device reliability. In conclusion, if on one hand the manufacturer is responsible for the degradation processes related to the quality of the LED chip, on the other hand the designer of the final LED application/luminaire can play a significant role towards the improvement of the reliability LED-based lamps, through a careful optimization of the operating conditions and of the thermal dissipation process.

Acknowledgments

This work was partially supported by the CARIPARO Foundation, and by the ALADIN project (Italian Ministry of Industry). The authors kindly acknowledge Dr. Berthold Hahn and Dr. Rainer Butendheich (OSRAM OptoSemiconductors Regensburg, Germany), Dr. Nicola Trivellin and Dr. Augusto Tazzoli (University of Padova, Italy), Prof. Massimo Vanzi and Dr. Giovanna Mura (University of Cagliari, Italy) for their fruitful contributions to the research activity.

Figure captions

Figure 1: SEM image of a power LED chip, mounted in its package. The image was taken after the removal of the plastic lens, and is referred to a 1 mm² LED chip

Figure 2: optical power degradation curves measured on three different families of commercially-available white LEDs. Devices were stressed at a constant current level of 100 A/cm², with an ambient temperature of 80 °C. Each data point is the average obtained by measuring 4 identical samples (measuring current level is 70 A/cm²)

Figure 3: optical power vs current density characteristics measured on a bare InGaN-based LED chip submitted to stress under constant current conditions

Figure 4: optical power degradation measured during stress at constant current level on one of the bare InGaN-based LEDs analyzed within this work

Figure 5: optical power degradation measured during stress at different case temperature levels

Figure 6: capacitance-voltage characteristics measured during stress at constant current level on one of the InGaN-based LEDs analyzed within this work (f=1 MHz)

Figure 7: variation of charge concentration in the quantum well region, plotted as a function of the optical power decrease measured on one InGaN-based LED submitted to constant current stress

Figure 8: current density vs voltage characteristics measured (in the reverse-bias region) on an InGaN-based LED submitted to negative-bias stress (stress conditions are -0.3 A/cm², room temperature)

Figure 9: current density vs voltage characteristics measured (in the forward-bias region) on an InGaN-based LED submitted to negative-bias stress (stress conditions are -0.3 A/cm², room temperature)

Figure 10: optical power decrease measured on two InGaN-based LEDs submitted to negative-bias stress (stress conditions are -1.2 A/cm² and -2.4 A/cm² room temperature)

Figure 11: spectral power distribution of a white LED submitted to stress at 140 °C, no bias. Measurement were taken at 48 A/cm²

Figure 12: (a) variation of the integral of the blue and yellow luminescence for a white LED submitted to stress at 140 °C, no bias. (b) Variation of the ration between the intensity of the yellow and blue peak measured on a white LED submitted to stress at 140 °C, no bias. Data are referred to the same LED as in Figure 11

Figure 13: micrograph of a white LEDs. Left: before stress. Right: after stress at 100 A/cm², 100 °C

Figure 14: micrograph of two white LEDs. Top: untreated sample. Bottom: after stress at 100 A/cm², 120 °C

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Figure 18: Scanning Electron Microscopy image taken after catastrophic ESD failure on one InGaN-based LED. The position of the failed region (junction shortening) is indicated by a label

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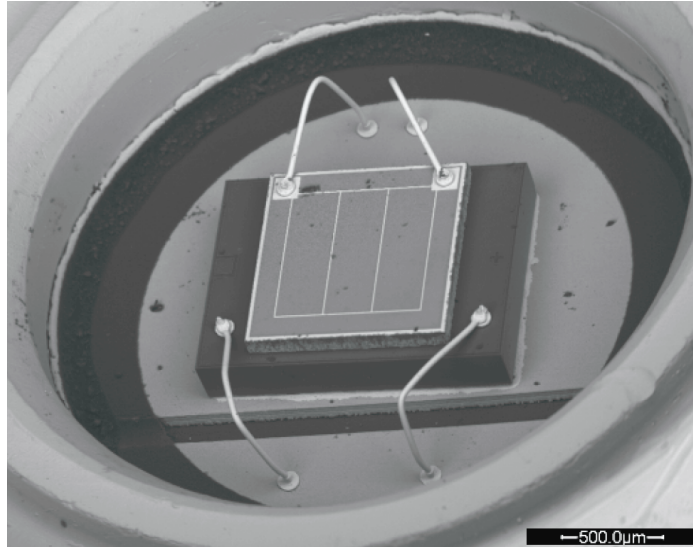


Figure 1: SEM image of a power LED chip, mounted in its package. The image was taken after the removal of the plastic lens, and is referred to a 1 mm² LED chip

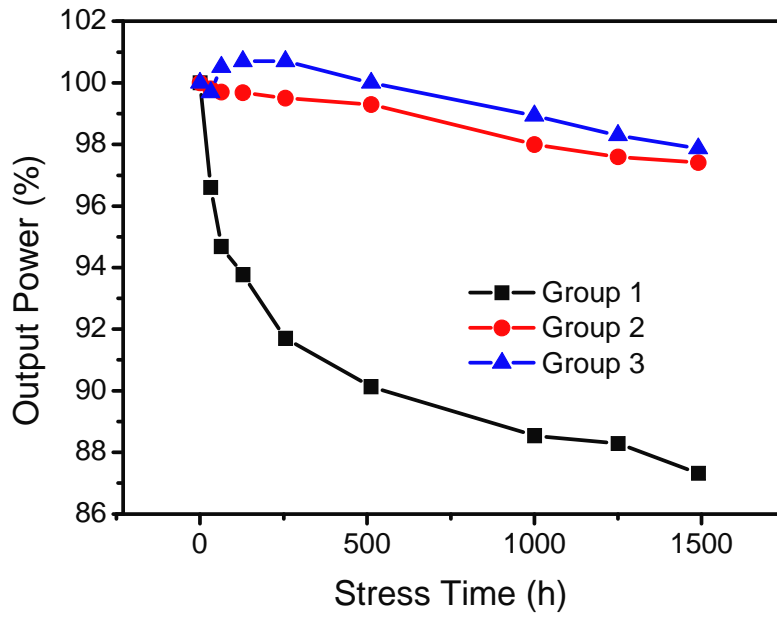


Figure 2: optical power degradation curves measured on three different families of commercially-available white LEDs. Devices were stressed at a constant current level of 100 A/cm^2 , with an ambient temperature of $80 \text{ }^\circ\text{C}$. Each data point is the average obtained by measuring 4 identical samples (measuring current level is 70 A/cm^2)

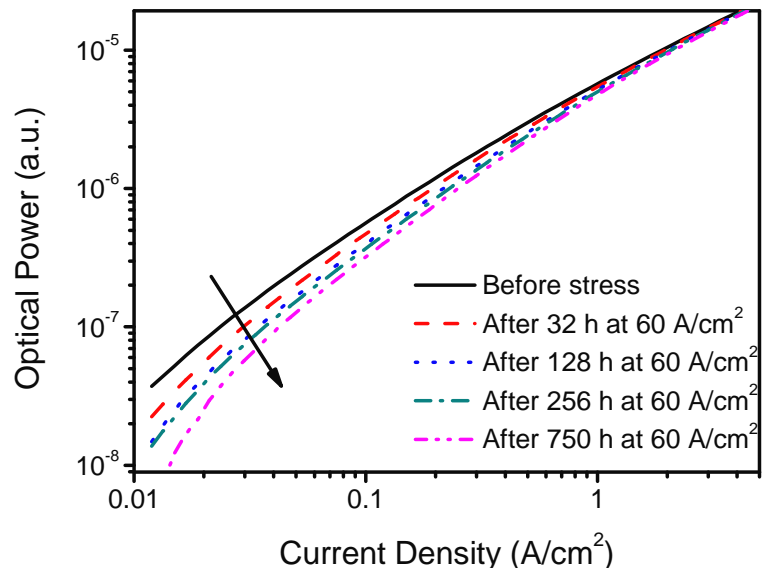


Figure 3: optical power vs current density characteristics measured on a bare InGaN-based LED chip submitted to stress under constant current conditions

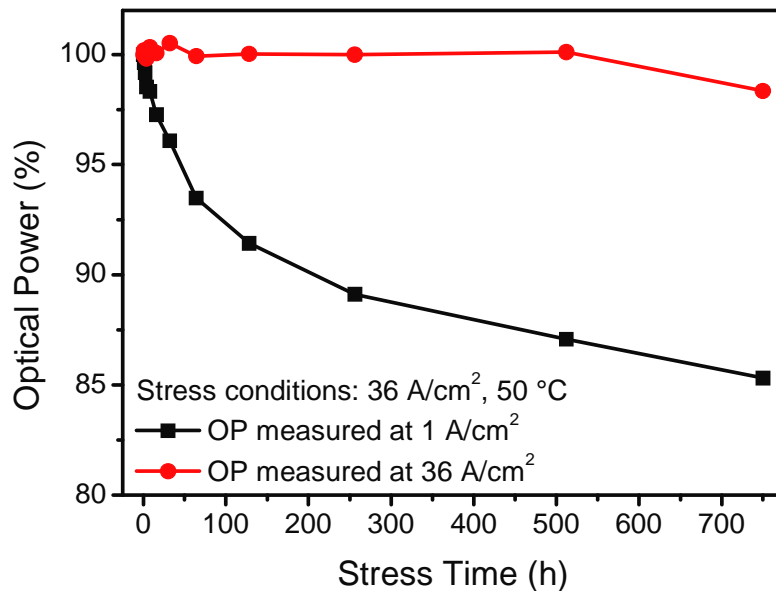


Figure 4: optical power degradation measured during stress at constant current level on one of the bare InGaN-based LEDs analyzed within this work

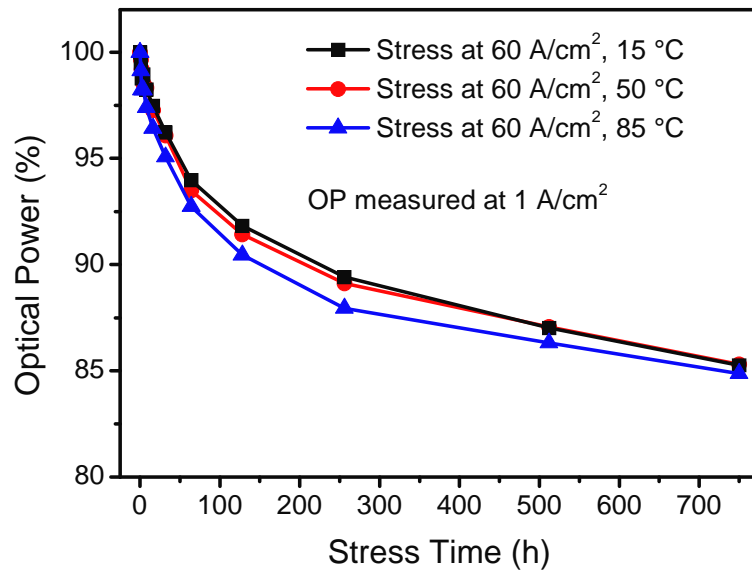


Figure 5: optical power degradation measured during stress at different case temperature levels

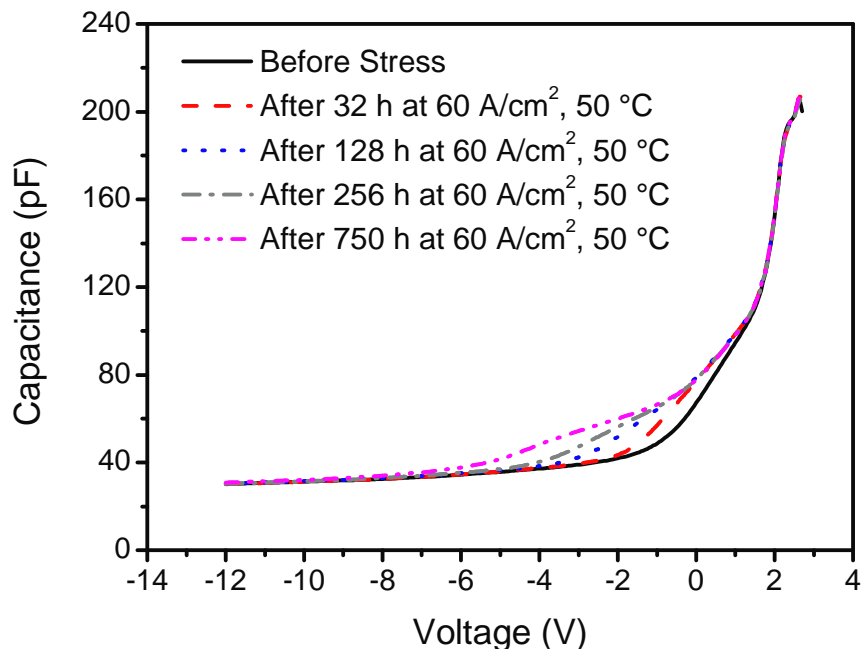


Figure 6: capacitance-voltage characteristics measured during stress at constant current level on one of the InGaN-based LEDs analyzed within this work ($f=1$ MHz)

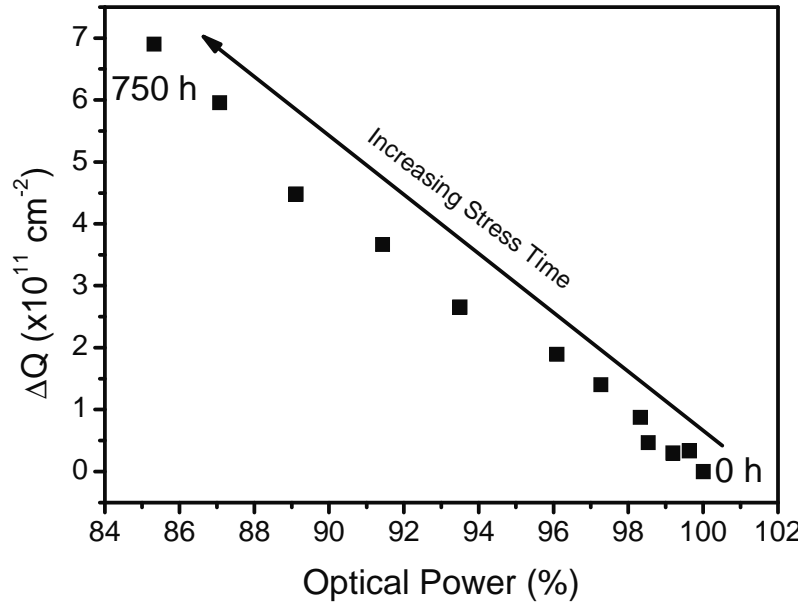


Figure 7: variation of charge concentration in the quantum well region, plotted as a function of the optical power decrease measured on one InGaN-based LED submitted to constant current stress

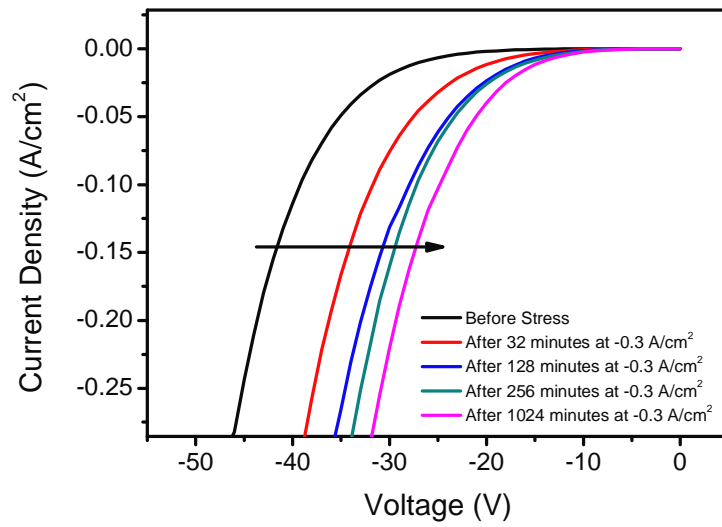


Figure 8: current density vs voltage characteristics measured (in the reverse-bias region) on an InGaN-based LED submitted to negative-bias stress (stress conditions are -0.3 A/cm^2 , room temperature)

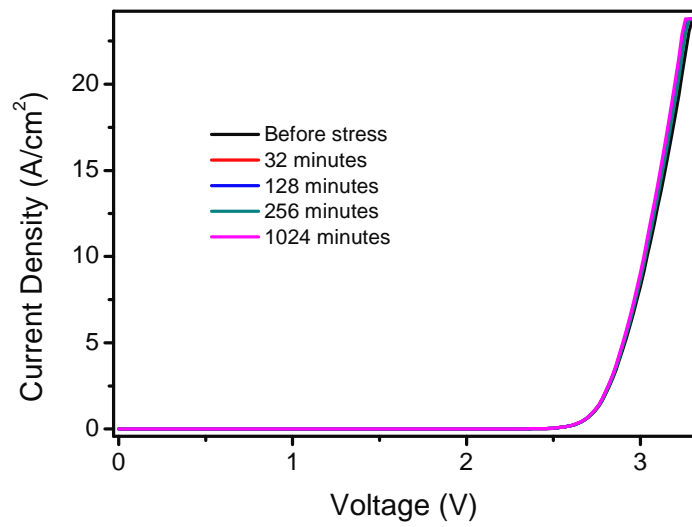


Figure 9: current density vs voltage characteristics measured (in the forward-bias region) on an InGaN-based LED submitted to negative-bias stress (stress conditions are -0.3 A/cm^2 , room temperature)

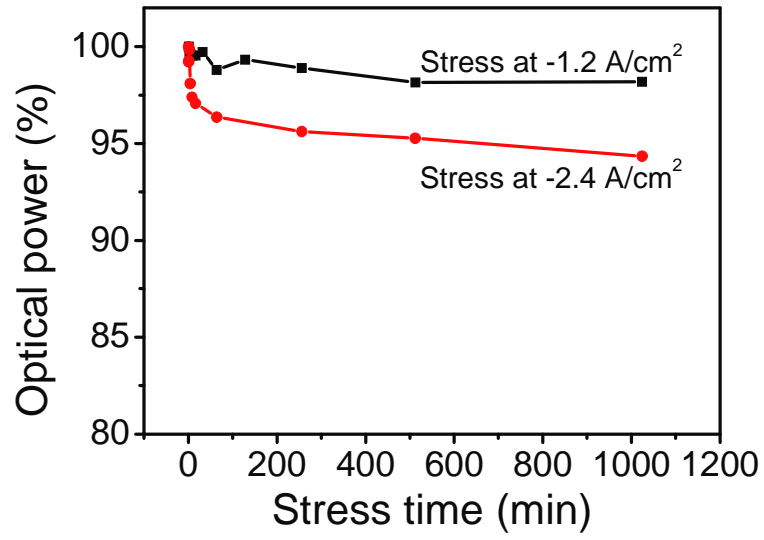


Figure 10: optical power decrease measured on two InGaN-based LEDs submitted to negative-bias stress (stress conditions are -1.2 A/cm^2 and -2.4 A/cm^2 room temperature)

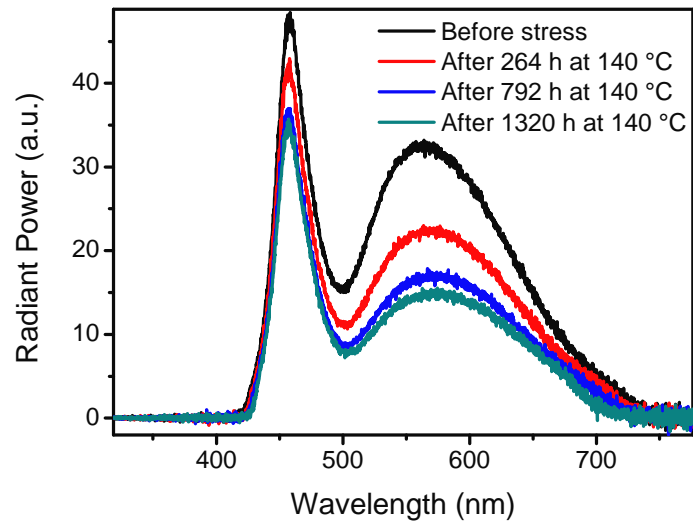


Figure 11: spectral power distribution of a white LED submitted to stress at 140 °C, no bias.

Measurements were taken at 48 A/cm²

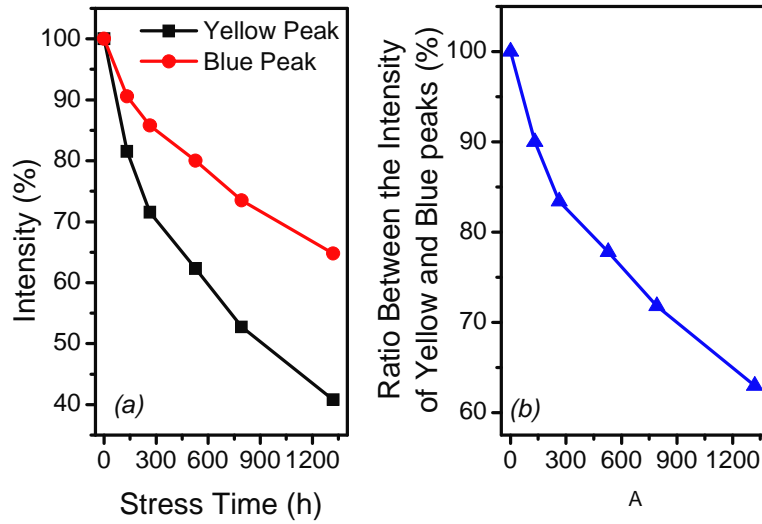


Figure 12: (a) variation of the integral of the blue and yellow luminescence for a white LED submitted to stress at 140 °C, no bias. (b) Variation of the ration between the intensity of the yellow and blue peak measured on a white LED submitted to stress at 140 °C, no bias. Data are referred to the same LED as in Figure 11

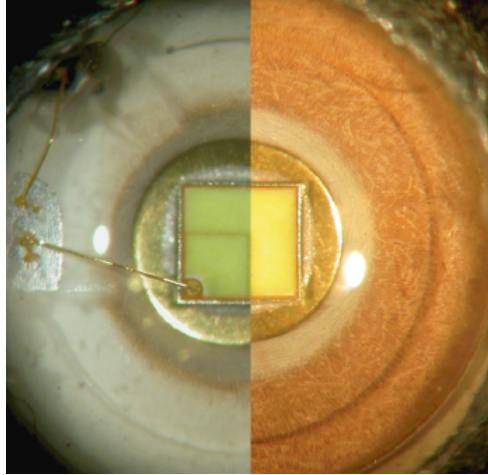


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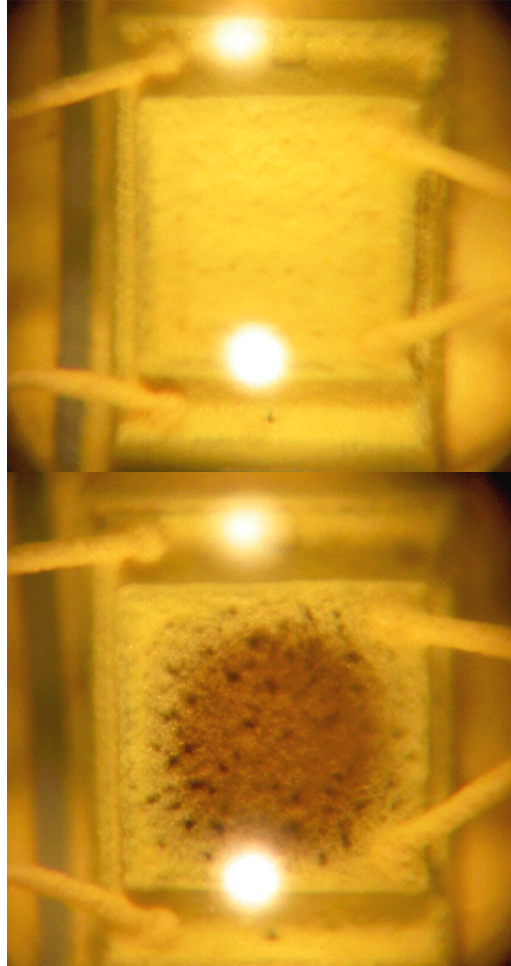


Figure 14: micrograph of two white LEDs. Top: untreated sample. Bottom: after stress at 100 A/cm², 120 °C

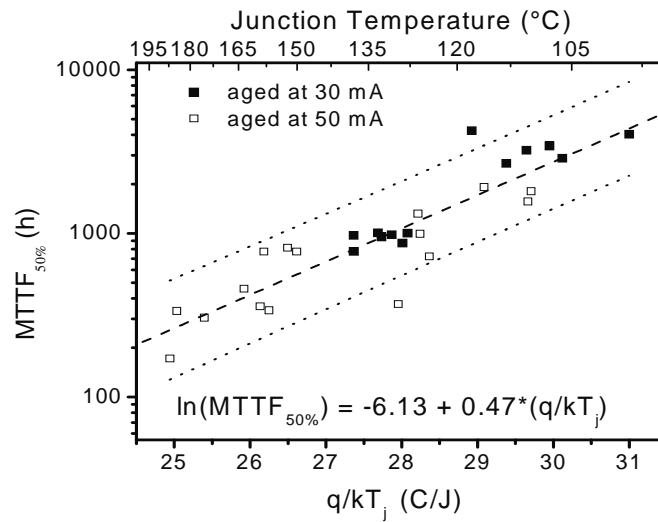


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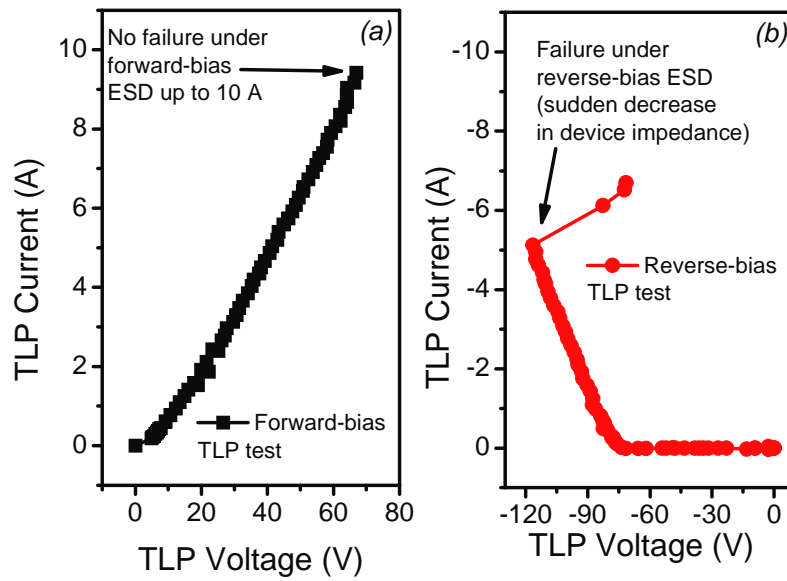


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Measurements were carried out by the TLP method (100 ns voltage pulses)

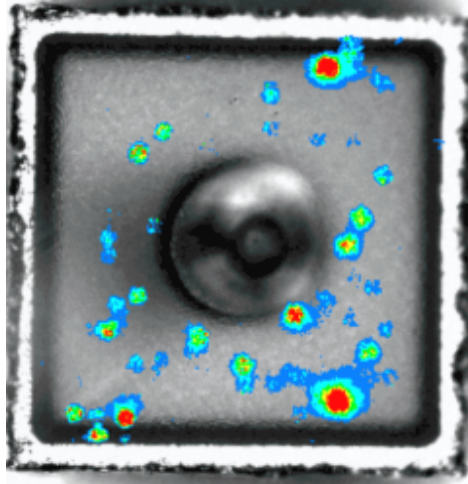


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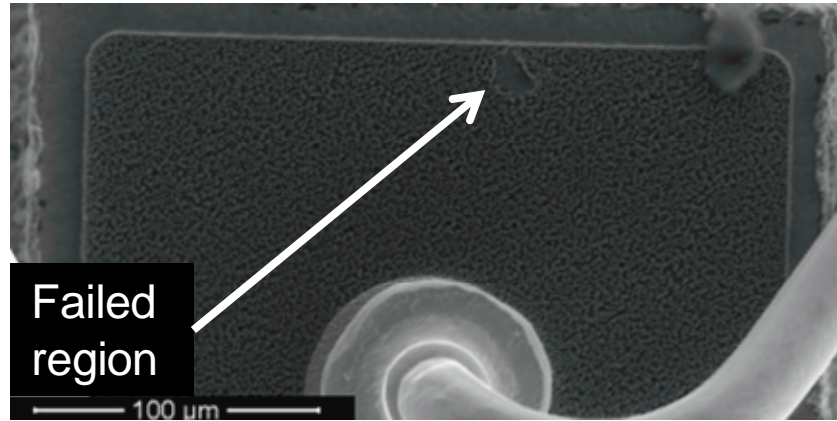


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