Effects of Moist Environments on LED Module Reliability

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***Abstract*—Unless their reliability is no longer a concern, light-emitting diodes (LEDs) will be unable to be used for broader applications. One important factor in the operating environment of LEDs is moisture, which is always present if the packaging is not hermetically sealed. In order to investigate the effects of moisture on the reliability of LEDs, several high-power white LEDs were subjected to extremely moist conditions at different temperature points in this study. Different light-output regression rates were measured. Digital microscopy was used to observe moisture diffusion on the LED module. The results demonstrate that the light output of LEDs decreases as the environmental moisture changes. Moisture diffuses into the interfaces of the packaging material, which not only decreases light output but may also disable the LED module due to electronic failure.**

***Index Terms*—Light-emitting diodes (LEDs), moisture, reliability.**

I. INTRODUCTION

HIGH-POWER light-emitting diodes (LEDs) are generally considered to be the light sources for the next generation of illumination. However, the issue concerning their reliability is one problem that has slowed down LED development and its widespread application. The amount of environmental moisture is one of the most important factors affecting LED reliability [1], [2] and why most commercial companies use various accelerated testing methods which involve moisture, such as 85C/85RH, etc. [3].

The relative humidity (RH) changes frequently, particularly in outdoor conditions. Some LED packaging materials consist of macromolecules that have the ability to absorb moisture. The diffusion of water steam into the packaging structure causes multiple problems, such as stress, corrosion of the metal packaging materials, discoloration of the metal reflectors, and so on. It also affects the performance of phosphor that is deposited or coated around the LED die to create white light and accelerates LED aging. The mismatch in coefficients of moisture expansions will also induce hydromechanical stress in LED packages [4]. Moisture inside LED packaging may also cause thermal resistance to increase, since small defects produced in LED packaging processes would be expanded as LEDs operating in high-moisture-content environments, and this may result in delamination between chips and substrates [5]–[8]. These all contribute to the overall degradation of the LEDs.

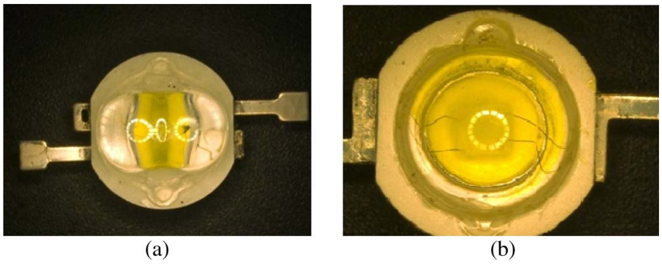
(a) (b)

Fig. 1. Microscope photos of two types of LED module samples. (a) ASP module. (b) Conventional hemisphere lens module.

In this paper, we will investigate some extreme moisture cases to see how moisture enters into the LED packaging and how moisture affects LED light output, which should be of interest to the LED packaging process design and LED reliability community.

II. EXPERIMENT: DEVICES AND PROCESS

The two most common approaches to creating white LEDs are the following: 1) combining a short-wavelength LED with a single phosphor or multiple downconversion phosphors and 2) mixing monochromatic LEDs in appropriate proportions. The phosphor method produces a convenient integrated single LED package. We use the first approach to package ten high-power white LED samples, labeled as sample 1, sample 2, and so on. The LED chips of the samples are from the same vendor. The only difference in the samples is that the first seven samples utilize application-specific packaging (ASP) developed by our group, as shown in Fig. 1(a). The other three samples use conventional hemisphere lens to package, as shown in Fig. 1(b).

ASP is a kind of LED packaging that integrates secondary optics with traditional LED packaging. The optical structure of an ASP includes a LED chip, phosphor layer, silicone, and the PC or silicone freeform lens. During the ASP process, the only change made is fixing a freeform lens instead of a domed lens on the frame, and that is quite compatible with

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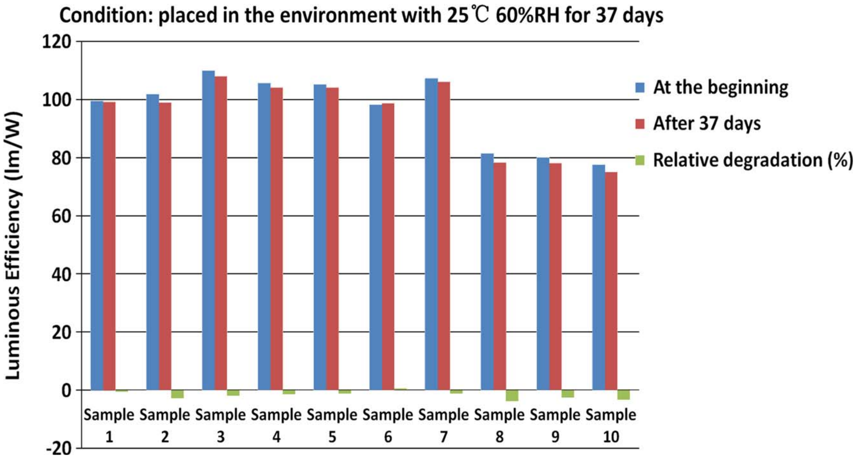


Fig. 2. Change in the luminous efficiency of samples 1–10 when placed in testing conditions at 25 °C and 60% RH for 37 days.

current LED packaging processes. This makes it easier for LED manufacturers to adopt this new technology with few changes in existing processes. Specific radiation patterns can also be obtained through ASP. For example, an ASP with a subrectangular radiation pattern can be directly used for road lighting. No further secondary optics are needed for LED luminaries to be integrated with ASPs. Compared with traditional LED modules integrated with secondary optics, ASP had advantages in being of much smaller size in volume (∼1/8), higher system luminous efficiency (∼8.1%), lower costs, and more convenience for customers to design and assemble, possibly enabling much wider applications of LED for general lighting [9].

In order to investigate the impact of moisture on LED modules, the samples were subjected to different moisture conditions. The detailed experimental procedures were described as follows. The first step was to place the ten LED modules in a vacuum drying oven under 85 °C for 24 h, which eliminated effects that may have been brought on by the previous packaging process. The second step was to measure the optical parameters of the LED modules, such as luminous flux, luminous efficiency, color rendering indices, etc. The third step was to subject the samples to 25 °C and conditions of 60% RH for 37 days. The fourth step was to repeat the second step. The fifth step was to subject samples 1–3 to purified water at 99 °C for 48 h, while samples 4–10 were placed in purified water at 85 °C for 48 h and then taken out for optical testing as mentioned in the second step. These samples were again placed into purified water at 85 °C for another 72 h. Thus, the total immersion time in pure water for samples 4–10 was about 120 h.

It should be noted that the optical tests before and after 72 h of immersion were conducted as quickly as possible in order to prevent the moisture in the packaging from spreading to the air, which would have potentially caused experimental errors. In addition, all of these LED samples were operated at their rated current of 350 mA at the same ambient temperature during optical tests.

III. ANALYSIS AND DISCUSSION

Fig. 2 shows the luminous-efficiency changes of samples 1–10 when placed in the test environment at 25 °C and 60% RH for 37 days. According to Fig. 2, it was found that the LEDs' luminous flux degrades with time under certain temperature and moisture conditions. With the exception of sample 6, the luminous efficiency of these samples decreased when placed in a test environment of 25 °C and 60% RH for 37 days. However, the degree of degradation found was not that significant, with the maximum relative degradation found to be about 2.75% for sample 2.

It was noted that the optical efficiency of sample 6 increased slightly in such mild moisture conditions, which can be explained by the following. For one, the humidity affected the silicon gel and phosphor of the LED modules, which will result in a decrease in luminous efficiency. On the other hand, the optical power of LED chips will usually increase in the initial stages of aging. Previous studies [10], [11] have reported similar phenomena. It should be emphasized that the increase of optical efficiency exists only during the initial aging period, with the duration depending on individual chips.

Since there are two factors affecting the optical efficiency of LED modules during the initial aging period, there will be two outcomes. For some LED modules, the optical efficiency will increase when the increase in chip optical power is larger than the decrease in optical efficiency from silicon gel and phosphor aging. However, for most of the LED modules, the side effects resulting from silicon gel and phosphor aging have a greater effect on performance than the results produced by an increase in optical power from the LED chips during the initial aging period. Based on the discussions aforementioned, we can understand why the optical efficiency of sample 6 increased slightly when placed in mildly humid conditions; however, in general, the optical efficiency of other samples decreased, as shown in Fig. 2.

Fig. 3 shows the change in the luminous efficiency of samples 4–7 when placed in purified water at 85 °C for 48 h. Fig. 4 shows the change in the luminous efficiency of samples 1–3 when placed in purified water at 99 °C for 48 h. Comparing Figs. 3 and 4 with Fig. 2, we can see that the higher the temperature and RH of the surrounding area, the faster the light efficiency of the LED samples decreases. From Figs. 3 and 4, it was noted that the regression rate of the LED luminous flux is higher at high temperatures under the same moisture

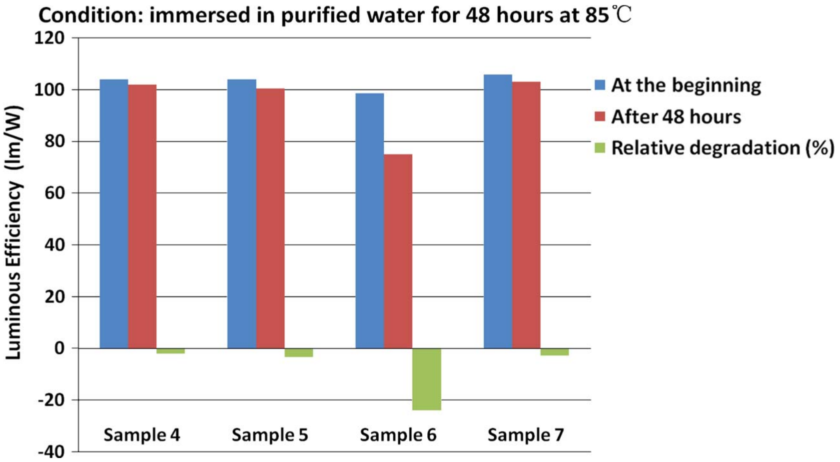


Fig. 3. Change in the luminous efficiency of samples 4–7 when placed in purified water at 85 °C for 48 h.

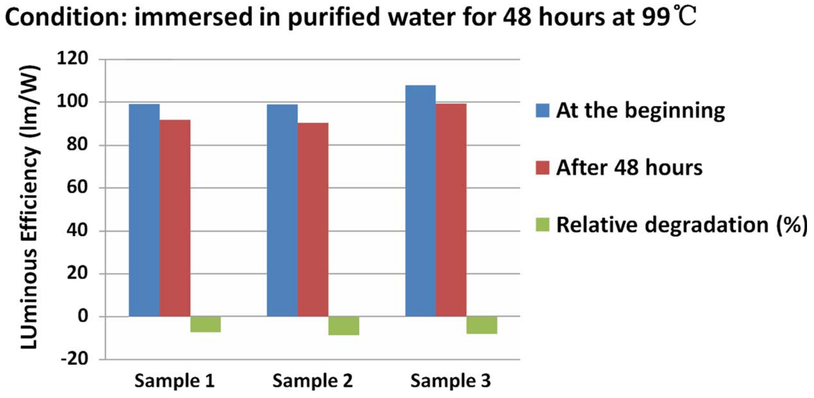


Fig. 4. Change in luminous efficiency of samples 1–3 when placed in purified water at 99 °C for 48 h.

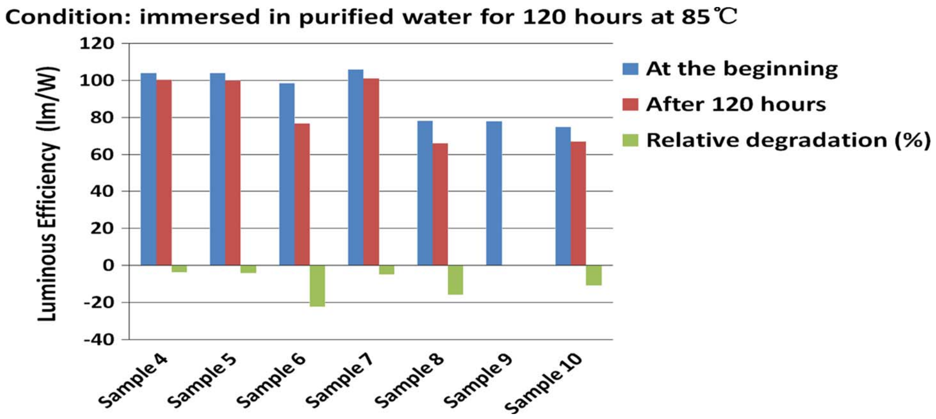
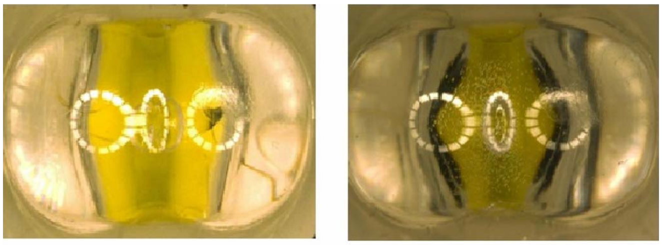


Fig. 5. Change in the luminous efficiency of samples 4–10 when placed in purified water at 85 °C for 120 h.

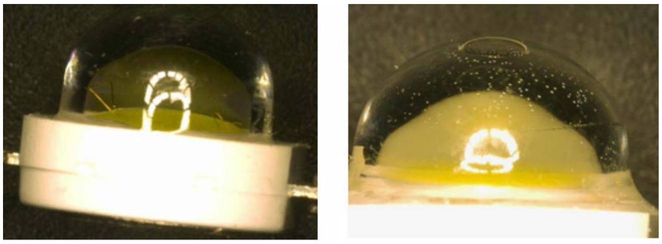
conditions. This may be mainly attributed to the following reasons. The first is that higher temperatures will result in a decrease of phosphor conversion efficiency. The second is that moisture at high temperatures will more easily enter into LED modules through the PC lens and the interface between the PC lens and the packaging frame.

Fig. 5 shows the change in the luminous efficiency of samples 4–10 when placed in purified water at 85 °C for 120 h. In Figs. 3 and 5, we note that the decrease in the light efficiency of sample 6 is more than 20% with the optical efficiency of sample 6 dropping significantly. This creates an obvious contrast compared with the slight increase in luminous efficiency of the same module in the conditions of mild humidity, as shown in Fig. 2. The phenomenon can be attributed to the delamination or amplification of the defects produced in the packaging process. In the case shown in Fig. 3, the humidity and temperature conditions are significantly different compared with those seen in Fig. 2. In the mildly humid environment shown in Fig. 2, the temperature was also relatively low. The defects present were not amplified in this case, and delamination did not occur.



(a) (b)

Fig. 6. Microscope photos of samples 4 and 6. (a) Sample 4 after 120 h at 85 °C of water. (b) Sample 6 after 120 h at 85 °C of water.



(a) (b)

Fig. 7. Microscope photos of sample 8. (a) Sample 8 before immersion. (b) Sample 8 after 120 h in 85 °C of water.

However, in the conditions shown in Fig. 3, both the temperature and humidity conditions are extreme. Moisture enters into the LED packaging through the interface between the PC lens and LED packaging frame if the bonding between the PC lens and LED substrate frame is not perfect or the attachment is loose. In this case, as shown in the microscopy results shown in Fig. 6(b), the bubbles enter into the interface between the silicon gel and PC lens, which will significantly decrease the optical efficiency of the LED module because of the refractive index changes among too many interfaces. Therefore, we can see totally different results between mild and extreme moisture conditions. This is why sample 6 has such variations in different conditions, as shown in Figs. 2, 3, and 5.

In Fig. 6(b), it is clear that there are many small bubbles in the interface layer between the silica gel and ASP lens in sample 6. These bubbles change the original optical path, which is optimally designed since the refractive index of the steam bubbles is different from other materials of the packaging. Compared with sample 6, there are no obvious bubbles in sample 4, as shown in Fig. 6(a); therefore, its optical efficiency is not significantly changed, which is shown by Fig. 5. The same phenomenon exists in sample 8, as shown in Fig. 7. Under a digital microscope, we also observed the presence of many steam bubbles existing in the YAG phosphor layer after 120 h in 85 °C of water.

There is another sample that should be noted. In Fig. 5, it clearly shows that sample 9 became disabled and electronic failure was found after testing this sample. This was caused by the moisture spreading after 120 h of water immersion at 85 °C.

From Fig. 5, we can see that different packaging types of LED modules also have an obvious effect on reliability in such an environment of extreme moisture. Compared with conventional packaging, the ASP type is more reliable. In Fig. 5, the optical efficiency for ASP modules 4–7 is much higher than that of conventional packaging samples 8–10 before and after immersion. Meanwhile, the degradation rates of these samples were much lower than those of the conventional packaging samples.

The differences in performance between ASP modules and conventional packaging modules are perceived to be mainly due to the strong bonding between the PC lens and packaging frame for ASP, which prevents moisture from entering into the LED packaging body. As discussed before, moisture has two ways to enter into the packaging module. The first is through the PC lens through moisture diffusion. The second is through the interface between the PC lens and packaging lead frame. Our other experiments have demonstrated that the moisture absorption ability of the PC lens is not strong. Therefore, the second method outlined previously would be the primary way for moisture to enter into the LED module. Since the material of the PC lens in the two kinds of packaging is the same, the rate of moisture diffusion through the PC lens in two kinds of packaging should be the same. However, because the shape of the ASP lens is different from the dome shape of the LED lens in conventional packaging, its bond to the LED packaging lead frame is much stronger. Therefore, its ability to prevent moisture entering into the packaging module is also much stronger. For example, in the extreme moisture tests shown in Figs. 3–5, the ASP exhibited significantly better reliability compared with conventional packaging.

Based on the aforementioned phenomena, it can be concluded that moisture not only diffuses into the silica gel and lens but also diffuses into the interfaces of the packaging materials. This will surely weaken the interfacial strength in the LED package structure. This is one of the most important reasons behind delamination that occurs in LEDs and contributes to the degradation of the LEDs' optical efficiency and reliability. Therefore, it is important to study how to improve the strength of interface adhesion.

IV. CONCLUSION

Through the experiments on reliability in mild and extreme conditions, we found that moisture diffuses into the interfaces of packaging material, not only causing a decrease in light output but also increasing the potential for a LED module to become disabled through electronic failure. These results provide an understanding of decreases in reliability and failure mechanisms for high-power LEDs. In order to improve the capacity for antimoisture diffusion and the overall reliability of LED modules, methods to improve the adhesion strength of the interfaces existing in current LED packaging structures should be a part of ongoing research work for LED packaging processes and structures.

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