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Moisture Resistance Coating for High Power White Leds Using Diamond Like Carbon

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ABSTRACT

Moisture is found to be a major cause of LED lumen degradation along with various other factors. In this work, a method is proposed to prevent moisture from penetrating into the LED's internal structure by having diamond like carbon (DLC) films coated on the LED's encapsulant as a moisture barrier sheet via RF sputtering system at room temperature. However, we found that the DLC coating is not suitable for this role as it underwent structural changes with time that lower its moisture resistance ability. The LED encapsulant expansion is found be the reason for the DLC's structural changes. Consequently, higher lumen degradation is observed for LEDs coated with DLC coating as compared to its non- DLC counterpart.

Keywords: Crack, Flattening, Moisture penetration, Temperature-humidity test, Diamond like carbon

INTRODUCTION

High power white LEDs are now used in various harsh working conditions including extreme temperatures, relative humidity and vibrations to name few [1,2] due to their various advantages over the other light sources such as higher lifetime, energy efficient and eco-friendly nature [3,4]. While many works on the investigation of the effect of temperature on LEDs and the corresponding methods to reduce this effect to its minimum have been reported [5-7], the works on the moisture effect study on LEDs are relatively few. Recent works show that the moisture along with temperature can lead to more severe reliability issues than temperature alone [8,9].

The moisture effect on LEDs is mainly due to the gap between the silicone encapsulant and the molding part created due to their difference in thermal expansion [10,11]. This gap allows rapid moisture penetration into the LED structure which in turn causes degradation at various sites such as die attach, phosphor and molding part [12-14]. Therefore, a possible method to reduce the impact of moisture could be a transparent coating to prevent the moisture from penetrating inside the LED structure. Diamond like carbon (DLC) is chosen in this work because of its higher elongation strength and moisture resistance properties [15,16].

In order to examine if DLC can perform the required role, 2 groups of 5 LEDs each are subjected to 85˚C/ 85% RH conditions under ON condition. Group 1 consists of LEDs with DLC coating, and Group 2 consists of LEDs without any coating and used as reference.

EXPERIMENTATION

Hydrogen-free DLC films were deposited on OSRAM golden dragon LED's encapsulant at room temperature by RF magnetron sputtering system (HUTTINGER PFG-600) with a pure diamond powder (DP) target in an Ar plasma. The diamond powder used in this work was a commercial product (FACT Diamond, Taiwan), which was synthesized using the high-pressure high temperature (HPHT) method [17]. The diamond target fabricated as the RF-magnetron cathode for DLC sputtering was 3 inches in diameter, and it was composed of high-purity diamond powder with a mean particle size of about 1 µm.

The LED's as a substrate were placed at a distance between 9 and 12 cm from the target with a rotation speed of 15 rpm. DLC films were deposited at RF powers ranging from 75 to 200 W at 13.56 MHz, and the film deposition times were in the range from 2 to 3 hours. The DLC film thickness and quality was optimized by varying Argon and methane gas flow rate as well as the RF power and time in order to achieve the most transparent DLC film with maximum light transmission.

The LEDs were tested in 85˚C/ 85% RH conditions under ON condition in an environment controlled chamber (KD-162- FUL from KING DESIGN) with 350 mA constant current passing to them individually using Keithley power supply model 2651A, according to the manufacturing specification. Initial set of measurements for all the LEDs are done to serve as reference baseline for each test sample. These measurements include optical microscope examination, Raman spectroscopy and lumen measurement. The setting for the electrical measurements is done according to Tan et al., to prevent self-heating during measurement. Optical examination is done using Keyence VHX5000 [18].

EXPERIMENTAL RESULTS

Raman spectroscopy was used to verify the growth of DLC films as shown in **Figure 1**. The 2 main peaks at around 1300 and 1500 cm^{-1} were observed which indicate the presence of DLC layer on the LED's encapsulant by its D and G peak [19].

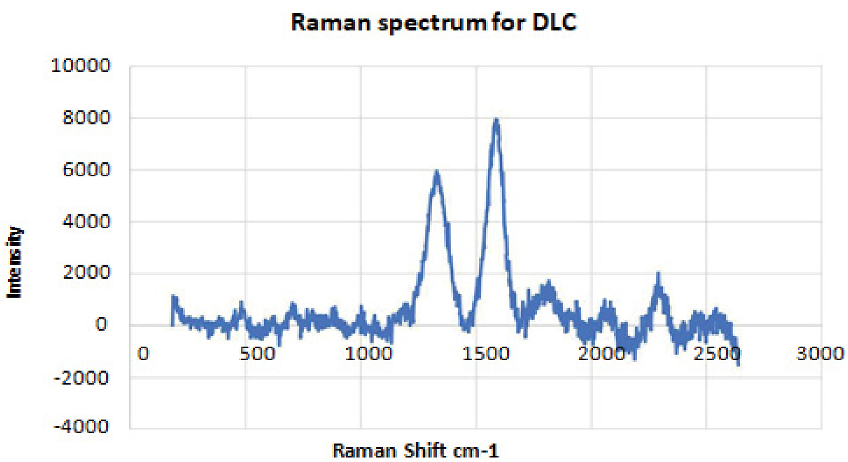

Figure 1: Raman spectrum of the DLC fabricated on the LED encapsulant.

Figure 2 shows the optical microscopic examinations on the LED molding discoloration on LED's with and without DLC coating on the top. It was clearly observed that the LED with DLC coating experienced higher discoloration when compared with the LED without DLC coating, which is unexpected. Besides the LED packaging discoloration, we also examined the LED's luminous intensity which is an important characteristic for the comparison.

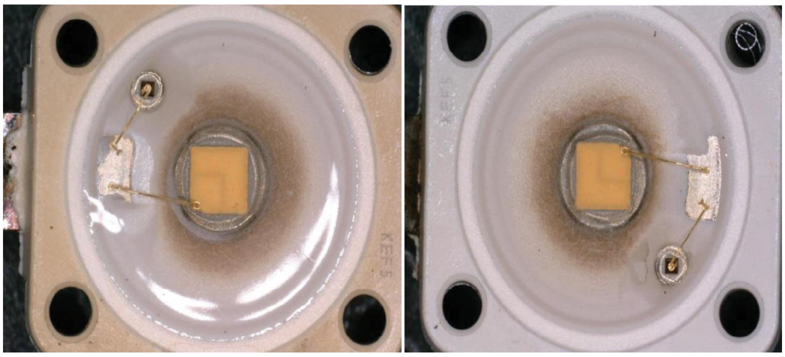

Figure 2: LEDs discoloration comparison with (left) and without (right) DLC coating

Figure 3 shows the average percentage lumen degradation for LEDs with and without DLC coating with time, and it was observed that the percentage lumen degradation is slightly lower for LEDs with DLC during the initial few hours of testing. After 268 hours, the percentage lumen degradation increases for DLC coated LEDs, and the lumen degradation for both groups became similar.

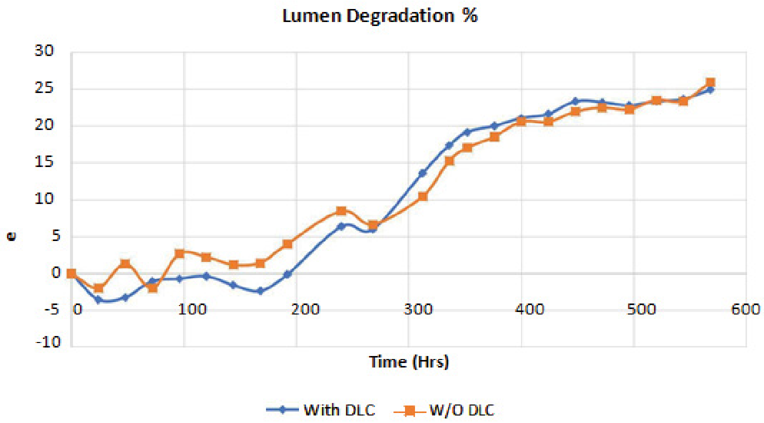

Figure 3: Comparison of average lumen degradation for the 2 group of LEDs with and without DLC coating with the stress time.

Average Blue to yellow light intensity ratio (BYR) was also compared to observe the effect of DLC coating on the health of the phosphor used to convert the blue to yellow light. BYR is found increasing for all the samples. **Figure 4** shows the percentage increase in Blue to yellow ratio for the two groups of LEDs tested in this work. It was vividly observed from Figure 4 that the phosphor degradation is higher for DLC coated LEDs when compared with non DLC LEDs. Another important observation from Figure 4 is that the rate of increase in the percentage change in the blue to yellow ratio for both group of LEDs become the same after 268 hours of testing, in agreement with the lumen degradation as observed in Figure 3.

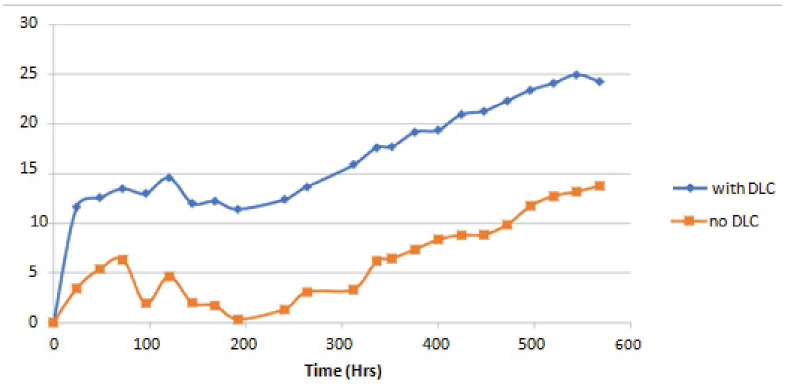

Figure 4: Comparison of the average Blue to yellow light intensity ratio change for LED's with and without DLC coating.

DISCUSSION

It was observed from the experimental results that the DLC coating is not providing the protection as expected. The packaging discoloration and phosphor degradation was found to be higher for DLC coated LEDs in comparison with non-DLC coated LEDs. Although the lumen degradation for the DLC coated LEDs are slightly lower initially, the gain quickly disappears after 268 hours.

In order to understand the ineffectiveness of the DLC coating, high magnification optical microscopic examination at 2000x was employed to observe the DLC coating. The surface topology of DLC is found to change with time as shown in **Figure 5**.

It was clearly observed from Figure 5 that the DLC surface comprises of ripples initially which suggest the coating either has a particular set of quantum states as observed by others as well or could be in a compression state and get folded on silicone substrate. These ripples were found to disappear and the surface becomes flat subsequently [20]. At a later stage, the DLC coating developed cracks over the entire DLC surface as shown in Figure 5(c).

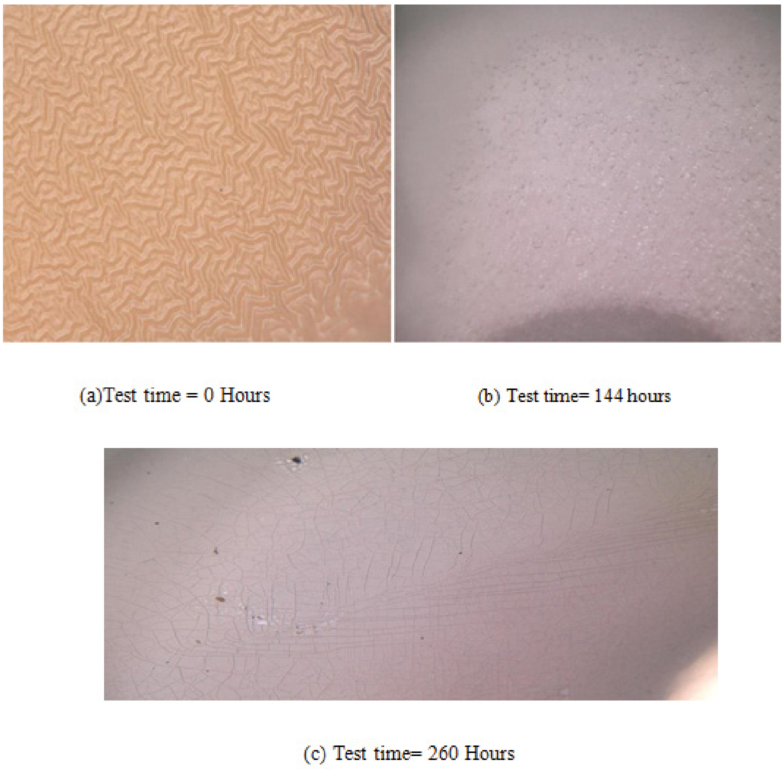

Figure 5: DLC surface topology variation with varying test time as indicated.

The LED encapsulant is silicone rubber in our case, and it experiences expansion and contraction during the turning ON and OFF (as LEDs are tested for 24 hours and then taken out of environmental chamber for testing in 3 hours), due to the high temperature generated inside the white high power LEDs when they are turned on [10,11]. Since the silicone acts as a substrate for the DLC coating, its expansion and contraction stretch the DLC coating and can lead to the flattening of DLC coating from its ripple state initially (Figure 5b) and cracks on the surface due to excessive stretching later on Figure 5c. These cracks can lead to the moisture penetration into the silicone encapsulant as shown in Singh and Tan work [10,11].

The higher heat generation inside the high power white LEDs acts as a heat source to evaporate the moisture away from the LED internal structure which consists of LED chip and phosphor [21]. However, the DLC coating is preventing the moisture to evaporate towards ambient when compared to the case of non DLC coating. This result in moisture accumulation inside the LED, and it can also lead to the DLC coating flattening as observed.

The moisture accumulation can also reach the phosphor surface and renders higher phosphor degradation as was observed for DLC coated LEDs in **Figure 5**. Another possible cause for the phosphor degradation could be due to the rise in LED chip temperature because of the moisture penetration at the LED chip and die attach interface, causing an increase in the thermal resistance of the LEDs as reported by many researchers [22].

To verify if the die attach does degrade, percentage change in forward voltage, V_f was examined for samples with and without DLC coating, and V_f was indeed found to decrease as shown in **Figure 6**. The percentage decrease was found to be higher for DLC coated samples, indicating that the degradation of die attach is more severe for DLC coated LED as expected, and thus leading to higher junction temperature which is another cause for phosphor degradation [12].

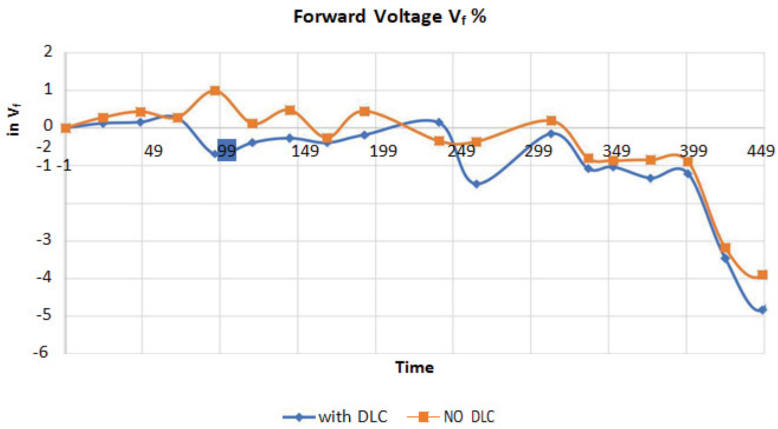

Figure 6: Percentage decrease in forward voltage of DLC coated and non- coated LEDs

From the above experimental results and analysis, we can see that DLC is not a good candidate to protect LED package from moisture. The reasons for its inability is due to its lower elastic modulus when stressed by the expanding substrate such as silicone encapsulant in this case, and resulting into cracks at the surface that allows moisture to penetrate ultimately.

Therefore, a good candidate for moisture protection of LED package should have the following material properties, namely higher transparency for visible light along with higher elastic modulus and high resistance to moisture penetration at higher stress levels. Also, the transparency is slow to degrade in the presence of moisture so that discoloration will be slow to occur.

CONCLUSION

Moisture is found to be a major cause of LED lumen degradation along with temperature. DLC is used in this work to prevent moisture from penetrating into the LED's internal structure. It is observed that LED encapsulant experiences thermal expansion due to high temperature generation inside the LED package which leads to the stretching of DLC coating. This renders a change of DLC surface from ripple to flat surface and finally cracks generation on the surface, allowing moisture to infiltrate inside the LED structure via encapsulant.

While DLC is not a good candidate to prevent moisture from getting into the LED package, DLC surface also act as barrier for internal moisture evaporating towards the ambient, resulting in higher accumulating moisture inside the LEDs compared to its non- DLC coated counterparts. Consequently, more severe phosphor and die attach degradation for DLC coated samples are observed and ultimately higher lumen degradation when compared with non- DLC samples. Based on the observations from this work, the qualities for a good candidate for moisture protection of LED package are proposed.

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