Lifetime assessment of Bisphenol-A Polycarbonate (BPA-PC) plastic lens, used in LED-based products

M. Yazdan Mehr a,b,*, W.D. van Driel b,c, K.M.B. Jansen d, P. Deeben c, G.Q. Zhang b,c

a Materials innovation institute (M2i), Delft, The Netherlands
b Delft University of Technology, EEMCS Faculty, Delft, The Netherlands
c Philips Lighting, Eindhoven, The Netherlands
d Delft University of Technology, Industrial Design Faculty, Delft, The Netherlands

Abstract

In this investigation, the accelerated optical degradation of two different commercial Bisphenol-A Polycarbonate (BPA-PC) grades under elevated temperature stress is studied. The BPA-PC plates are used both in light conversion carriers in LED modules and encapsulants in LED packages. BPA-PC plates are exposed to temperatures in the range of 100–140 °C. Optical properties of the thermally-aged plates were studied using an integrated sphere. The results show that increasing the exposure time leads to degradation of BPA-PC optical properties, i.e. decrease of light transmission and increase in the yellowing index (YI). An exponential luminous decay model and Arrhenius equation are used to predict the lumen depreciation over different time and temperatures. Accelerated thermal stress tests together with the applied reliability model are used to predict the lifetime of plastic lens in LED lamps in real life conditions.

1. Introduction

Over the last decade, GaN-based light-emitting diodes (LEDs) are developed as good candidates for the high-efficiency light sources for general lighting purposes. LEDs have an intrinsically high reliability compared with conventional light sources (incandescent and fluorescent lamps) since they are semiconductor-based devices. LEDs have much longer lifetime with lower lumen depreciation, compared to incandescent and fluorescent lamps [1], making them good candidates for long-lasting light sources. In LED-based products or systems a blue GaN-based LED chip with an emission wavelength of 450–460 nm is normally used as a light source. The chip is covered with a plastic lens which has the two-fold aim of protecting the lens, and of converting the blue light to white light. Blue light is converted into white light by means of a phosphor layer, which can be either deposited directly on the chip or incorporated into the encapsulating lens.

During service LEDs could fail due to the degradation of each of the components including lens, encapsulant, chip, phosphor layer and interconnects [2–6]. One of the most important degradation mechanisms is the yellowing of the LED plastic lens and encapsulants, which could result in a significant lumen depreciation and change in chromatic properties of the LED. The yellowing of encapsulant/lens could be ascribed to prolonged exposure to short wavelength emission (blue/UV radiation), temperature, and the presence of phosphors, with temperature having a very crucial influence [2]. Temperature increase during service could be due to a combination of junction temperature, ambient temperature and LED self-heating [7]. Narendan et al. [8] showed that light circulation between the phosphor layer and the reflector cup can also increases the temperature. A relatively comprehensive explanation of chemical mechanisms of yellowing of both thermally- and photo-aged BPA-PC without phosphor is given in one of our earlier publications [9].

In addition to the fact that temperature is a very influential degradation factor, it can also be easily controlled and is more commonly used as an input parameter to predict the reliability and the lifetime of plastic encapsulated LEDs. Reliability models for the prediction of LED lifetime is based on standards, developed by Illumination engineering societies (IES) together with the alliance for solid state illumination system and technology (ASISST). IES and ASSIST have developed a standard for lumen measurement method at room temperature or slightly elevated temperatures [10]. Based on this standard, failure in LED light sources is defined as 30% lumen depreciation, since this level of luminous drop is what human eyes can detect. However, performing LED lifetime tests at room temperature necessitates a very long time, which is not acceptable for such a fast growing industry. This means that reliability experiments should be performed in much shorter times. A good approach to reduce the testing time is increasing the temperature in order to accelerate the degradation. An extrapolation can then be used to determine failure rates and...
time-to-failure at real service condition. Reliability models can off course be developed for different components of the system and eventually for the whole LED-based product or system. This study is only devoted to the reliability of the plastic lens and/or encapsulant, since there is not much published information about the reliability of this important component. Plastic materials used in LEDs are mainly silicone, epoxy resins, and/or Bisphenol A Polycarbonates (BPA-PC), with BPA-PC being most widely used in LED-based products, due to its excellent combination of high impact strength, heat resistance and high modulus of elasticity [11]. In our study, two industrial BPA-PC variants with different additives are used for reliability experiments. The degradation rate, acceleration factor and lifetime of these two commercial BPA-PC plates are derived from the developed reliability model.

2. Materials and modelling approach

Two commercial 3 mm-thick BPA-PC plates, hereafter named A and B, with some differences in the amount/type of additives, are used in this study. Normal additives, used in plastic lens in LED applications, contain optical brightener, scatter agent, flame retardant, and heat stabilizer. The samples are manufactured by injection moulding. The specimens are kept in a furnace at 100, 120, and 140 °C up to 3000 h at air atmosphere. Testing temperatures for accelerated lumen depreciation test is determined in such a way that the temperature does not exceed the glass transition temperature of the plastics. Glass transition temperature (Tg) of BPA-PC is 150 °C, so the accelerated temperatures are chosen at least 10 °C below Tg, which is believed to be safe. Optical properties of thermally-aged plates, were studied at room temperature. Spectral power distribution (SPD) of BPA-PC plates and the yellowing index (YI) of thermally-aged plates were measured by Integrated-Sphere. Integrated-Sphere is an optical component consisting of a hollow spherical cavity with its interior covered with a diffuse white reflective coating, with small holes for entrance and exit ports. Uniform scattering or diffusing effect is a main property of Integrated-Sphere. It is typically used with some light source and a detector for optical power measurement. The yellowing index (YI) is calculated according to ASTM D1925 [12] with the following equation:

\[
YI = \frac{100 \times 1.28X - 1.6Z \text{ CIE}}{Y \text{ CIE}}
\]

where \(X\) and \(Y\) are the tristimulus values in (CIE) standard.

The reliability model is based on an exponential luminous decay equation to calculate time-to-failure as given in by [11]

\[
\phi(t) = \beta \exp(-\alpha t)
\]

where \(\phi(t)\) represents the lumen output, \(\alpha\) is the rate of reaction or depreciation rate parameter, \(t\) is time and \(\beta\) is a pre-factor. Obviously when lumen output, \(\phi_t\), is equal to 70%, \(t\) is time-to-failure. The rate of reaction, \(\alpha\), is related to the activation energy of the reaction and to the ageing temperature as follows [13]

\[
\alpha = A \exp\left(-\frac{E_a}{kT}\right)
\]

where \(A\) is a pre-exponential factor, \(E_a\) is the activation energy (eV) of the degradation reaction, \(k\) is a bortzmann constant (eV K\(^{-1}\)), and \(T\) is the absolute temperature (K).

3. Results

Stress at high temperature levels can induce thermal ageing and consequently a strong optical power lowering and depreciation of light output, as is shown in Fig. 1 for the case of thermal ageing at 140 °C (as an example). Reduction of light output with increasing thermal ageing time for samples, aged at 100 and 120 °C, show the same trend in both variants.

Fig. 2 shows the yellowing index (YI) of variants A and B recorded after 3000 h as a function of ageing temperature, at 100, 120, and 140 °C. Obviously, the higher the temperature the higher YI is.

The evolution of YI of BPA-PC plates at 140 °C as a function of thermal ageing time for both plates A and B is shown in Fig. 3. As it is seen, there are two stages in the discoloration of thermally-aged samples. The first stage is the so-called induction period in which there is no major change in the value of YI and the rate of yellowing is very slow, followed by the second yellowing regime, where the yellowing is accelerated and the rate of yellowing is comparatively faster. It is shown that the main reason of chem-
ical degradation in BPA-PC plates is the thermal-oxidation of plates and the forming of cyclic anhydrides and aromatic ketone [9]. The intensities of cyclic anhydrides and aromatic ketone bands of thermally-aged specimens follow the same two-stage trend, inferring that thermal oxidation could be considered as the main reason of the yellowing [9].

Fig. 4 depicts the colour shift of the specimens (Duv) at different loading conditions. The variation of colour shift is similar to that of YI. Similar to YI, there is no major colour shift during the incubation stage, whereas the colour shift during the degradation stage is linearly proportional to the testing duration.

The effects of thermal stress on the performance of the lens materials are shown in Fig. 5, which depicts the degradation kinetics of commercial variants A and B. It is noticeable that the degradation rate shows a significant dependence on the stress temperature level; the higher the ageing temperature, the higher the degradation kinetics. The experiments were performed up to 10% reduction in light output (solid lines in Fig. 5). However, as is already explained, based on the ASSIST standard, lifetime of LEDs is defined as time to reach 70% of its initial lumen output [11]. Therefore the extrapolation of experimental data is needed. Given that the reaction rate is assumed to be constant for each temperature, \( a \) at temperature \( T \) is calculated as follows:

\[
a(T) = \frac{-\ln \left( \frac{T}{t} \right)}{t}
\]

In order to calculate \( a \) at each temperature, \( t \) is taken equal to the time when lumen decays to 0.9, which is obtained experimentally. Having the reaction rate for each temperature, one can easily calculate the time for 70% lumen decay at each temperature. The calculated \( a \) can obviously be used to extrapolate the lumen decay till 70% for each temperature (see dashed lines in Fig. 5). Table 1 illustrates the calculated values for the reaction rate for each temperature for both samples. Obviously, by increasing the temperature, the reaction rate becomes larger, meaning that lumen depreciation takes place at shorter time.

The activation energy of the degradation reaction in LEDs depends on the materials and the working conditions. The activation energy can be calculated from Eq. (2). In order to obtain the activation energy, the natural logarithm of the reaction rates is plotted against the inverse of the absolute temperature, see Fig. 6. The slope is multiplied by the negative of the gas constant to obtain the activation energy, \( E_a \), in the eV. Activation energies for both samples A and B are between 0.3 and 0.4, which are in agreement with previous reported values [12,13].

### 3.1. Prediction of time-to-failure at low temperatures

The real working temperature of LDEs is much lower than the applied temperatures [12]. Therefore, the kinetics of lumen depreciation to 30% of its initial value by using exponential luminous decay model and Arrhenius equation should be extrapolated to temperatures lower than 100 °C. This can be done using Eq. (1) by equating \( z \) to 0.7, knowing that \( a \) can be obtained from Eq. (2). The values of \( a \), calculated for 40, 60 and 80 °C, are given and shown in Table 2, as it is seen that the higher the temperature the faster the lumen depreciation is.

Fig. 7 illustrates time-to-failure (70% lumen decay) of both variants A and B, calculated at different temperatures. It is seen that sample B has a longer life time compared to the sample A; i.e. at 40 °C the light output from lens A reduces to 70% of its initial value after 100khrs, while for variant B time-to-failure is 140 k h. This slight difference in lifetime of these two LED lens materials is due to the difference in the type and amounts of additives.

### 3.2. Acceleration factor

By using Arrhenius equation one can calculate the acceleration factor of the tests at different temperatures. Acceleration factor is a measure of how much the test is accelerated at testing condition, compared to normal behaviour at real working condition. Obviously the higher the acceleration factor, the faster and more effi-
cient (in terms of needed time for the experiment) the experiments. This factor is defined by following equation:

\[ A = \frac{E_a}{k(T_1 - T_2)} \]  

(5)

when \( T_1 \) is the working temperature, which is assumed to be around 40°C, and \( T_2 \) is the testing temperature. The acceleration factors of variants A and B at ageing temperatures 100, 120 and 140°C have been given in Table 3. As it is expected, the higher the temperature the higher the acceleration factor.

4. Discussions

Many studied has been done on the reliability of LEDs [14–18] in which temperature is used as a very significant controlling parameter. When LEDs are exposed to high temperature levels the optical properties of the package and of the material used for the encapsulation can severely degrade [3–5]. This can result in a significant reduction in the luminous flux, emitted by the devices. Hsu et al. [18] have shown that in addition to the reliability of the material properties of the plastic lens, the lens shape may also have an influence on the reliability of the high-power LED modules. LED-based products encapsulated with hemispherical-shaped lens exhibited the better life time due to better thermal dissipation than those in cylindrical and elliptical-shaped lenses. This study is however more focused on the plastic lens itself and the effects of geometry are not taken into consideration.

Spectral power distribution (SPD) method is used to study the effect of high temperature stress test on the optical degradation of BPA-PC plastic lens. The aim was to investigate the effect of temperature on the acceleration of optical degradation in LEDs, to determine the effect of yellowing of BPA-PC lens on the lumen depreciation of LED-based products, and to develop an accelerated test method and a reliability model for LED plastic lens. An exponential luminous decay model and Arrhenius model were used to predict the lumen depreciation over different times and temperatures. It is shown that the lumen depreciation rate (\( a \)) for sample A is larger than that in sample B, due to the slight differences in their chemical compositions. The lower the depreciation rate, the better the performance a plastic lens could have.

The results also show that there is a direct relation between the temperature and acceleration factor. One can see that the acceleration factor is maximum at 140°C for both samples A and B. The obtained acceleration factors are, however, not as large as what one could expect from a fast and efficient reliability test. Other stresses, like short wavelength irradiation or possibly changing the composition, should obviously be used to have acceleration factors in the range 10–20, which will be more efficient for LED reliability experiments. Koh et al. [13] showed that expected lifetimes, defined as 30% lumen depreciation at 40°C, for a range of different commercial LEDs are around 35 k h. What is obtained in this study for the lifetime of just the plastic lens is more than 100 k h, indicating that other failure modes are contributing to the degradation of LED package (i.e. phosphor and irradiation). The effect of phosphor, will be addressed in our future work.

As is already explained, in LEDs plastic lens is layered with phosphor. The phosphorous layer is used for the conversion of blue light into white light. Recent reports [17–21] have indicated that the package/phosphors system can also significantly degrade during the LED lifetime. This can result in a significant decrease in LED efficiency.

Table 1

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Sample A</th>
<th>Sample B</th>
</tr>
</thead>
<tbody>
<tr>
<td>100°C</td>
<td>2.5E–05</td>
<td>2.0E–05</td>
</tr>
<tr>
<td>120°C</td>
<td>4.5E–05</td>
<td>4.0E–05</td>
</tr>
<tr>
<td>140°C</td>
<td>7.0E–05</td>
<td>6.5E–05</td>
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Table 2

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Sample A</th>
<th>Sample B</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>3.29E–06</td>
<td>1.97E–06</td>
</tr>
<tr>
<td>60</td>
<td>7.06E–06</td>
<td>4.73E–06</td>
</tr>
<tr>
<td>80</td>
<td>1.36E–05</td>
<td>1.03E–05</td>
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</table>

Table 3

<table>
<thead>
<tr>
<th>Sample ()</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>373 K</td>
<td>2.8</td>
<td>2.2</td>
</tr>
<tr>
<td>393 K</td>
<td>3.5</td>
<td>2.6</td>
</tr>
<tr>
<td>413 K</td>
<td>4.3</td>
<td>3.1</td>
</tr>
</tbody>
</table>

Fig. 6. Plot of ln (a) vs E/KT for samples (a) A and (b) B.

Fig. 7. Time-to-failure (70% lumen decay) of both variants A and B at different temperatures.

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5. Conclusions

The accelerated optical degradation of two different commercial Bisphenol-A Polycarbonate (BPA-PC) plates, under elevated temperature stress, is studied. The BPA-PC plates are used both in light conversion carriers in LED modules and encapsulants in LED packages. BPA-PC plates are exposed to temperature in the range of 100–140°C. Exponential luminous decay model and Arrhenius equation are used to predict the lumen depreciation the lifetime of plastic lens in LED lamps in real service conditions. The following conclusions can be drawn from this study:

- Increasing the exposure time is associated with the discolouration, decrease in the relative radiant power value, and increase in the yellowness index (YI) of PC plastic lens.
- The higher the temperature the higher the YI is.
- By increasing the temperature, the reaction rate becomes larger, meaning that lumen depreciation takes place at shorter time. The reaction rate follows the Arrhenius acceleration law.
- The acceleration factors of variants A and B at ageing temperatures of 140°C are calculated to be around 4.
- The lifetime of the plastic lens, defined as 30% lumen depreciation at 40°C, is around 100 k h for the commercial grades tested.

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References


