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Research

Advanced Materials and Materials Genome—Review

Progress in Understanding Color Maintenance in Solid-State Lighting Systems

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ABSTRACT In this paper, progresses of color maintenance, also known as color shift, in solid-state lighting (SSL) systems are thoroughly reviewed. First, color shift is introduced and a few examples are given from different real-life industrial conditions. Different degradation mechanisms in different parts of the system are also explained. Different materials used as lenses/encapsulants in light-emitting diode (LED)-based products are introduced and their contributions to color shift are discussed. Efforts put into standardization, characterizing, and predicting lumen maintenance are also briefly reviewed in this paper.

KEYWORDS light-emitting diode (LED), color shift, lumen depreciation, lumen degradation

1 General information

1.1 Introduction

Solid-state lighting (SSL) technologies and products are gradually penetrating daily life. An SSL system is composed of a light-emitting diode (LED) engine with an electronic driver or drivers, integrated in a housing that also provides optical functions, thermal management, sensing, and/or other functions. Knowledge of system reliability is crucial, not only for successful business in today's SSL products and applications, but also to gain a deeper scientific understanding that will enable improved products and application design in the future. System malfunction may be induced by the failure and/or degradation of any subsystem or interface. Most SSL system designs, which allow few failures of the subsystem/interface during the application period, can be achieved with significant cost reduction when system reliability is well understood by means of appropriate experimental and simulation techniques.

Color maintenance is a recently-appearing system failure. Color-maintenance problems are insidious, because they are poorly understood, and only appear after many hours of operation. The purpose of this paper is to describe current practice, that is, field issues, test results, and prediction capability, with color maintenance; and to recommend how to address LED color maintenance in our products. This paper presents:

- Examples of color-maintenance issues that have appeared in the field;
- The origins of color shift;
- Current prediction insights; and
- Standardization activities.

1.2 Terms and definitions

"Color maintenance" is analogous to lumen maintenance and is defined as the change in chromaticity of a light source with respect to the chromaticity at the beginning of the lamp's life. It is typically measured as Δxy or as $\Delta u'v'$ in the Commission Internationale de l'Eclairage (CIE) color coordinate systems. The chromaticity coordinates of a source provide a numerical representation of the color of the light. The three most common chromaticity diagrams, with their coordinates, are the CIE 1931 (x, y), the CIE 1960 (u, v), and the CIE 1976 (u', v'). The (x, y) coordinates are the most frequently reported. Every color is represented by unique (x, y) coordinates. The CIE system is the most common method of characterizing the composition of any color in terms of three primaries [1, 2]. Artificial colors, indicated by X, Y, and Z coordinates, also called tristimulus values, can be added ($X + Y + Z = 1$), to produce real spectral colors. The chromaticity coordinates, x, y, and z [1], are the ratios of the X, Y, and Z coordinates of the light to the sum of the three tristimulus values. It is necessary only to consider the quantity of two of the reference stimuli in order to define a color, since the three quantities (x, y, z) are always made to sum to 1. Thus, the (x, y) coordinates are commonly used to represent a color [1, 2].

The (u', v') coordinates are related to the (x, y) coordinates by the following equations:

$$u' = \frac{4x}{-2x \times 12y \times 3} \tag{1a}$$

$$v' = \frac{9y}{-2x \times 12y \times 3} \tag{1b}$$

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Based on Eq. (1), the coordinates $\Delta u'v'$, which define the color shift at any two positions (0 and 1), can be calculated using the following formula:

$$\Delta u'v' = \sqrt{(u'_1 - u'_0) + (v'_1 - v'_0)} \quad (2)$$

Energy Star specifies that color maintenance must not exceed $\Delta u'v'$ = 0.007 on the CIE $u'v'$ diagram, after 6000 h of operation.

"Color consistency" is the variation in chromaticity at the start of a lamp's life among a population of products. For example, a product may be made from LEDs that are binned to fall within three MacAdam steps of a target chromaticity. These LEDs have a color consistency of three steps. Color consistency can also be defined in terms of (x, y) or (u', v'). The color consistency of lamps built from these LEDs may be worse than three steps because of temperature variations, current variations, or other factors.

"Color stability" describes how the entire spectrum changes over time. Although it is closely related to color maintenance, color stability encompasses more detail. The term "color maintenance" will be used in this paper.

2 Examples of color shift

This section describes several examples of field issues in which color shift has been indicated.

2.1 The L Prize LED lamp

Two hundred L Prize lamps were tested for 25 000 h at 45 °C. Testing has continued for 32 of these lamps and test hours now exceed 36 000 h (Figure 1). The L Prize lamps show that LED technology enables color shift (and lumen depreciation) to be quite small [3]. The average lumen maintenance for 200 lamps is over 100%, after 25 000 h. The average lumen maintenance at 36 000 h is 96.5% with respect to the maximum light output, which occurred after about 2000 h of operation. The average color maintenance, $\Delta u'v'$, is slightly above 0.001, or about one MacAdam step [3], both at 25 000 h and 36 000 h, as shown in Figure 2. (Two light sources observed simultaneously cannot be distinguished from each other by an average viewer, if the colors are within one MacAdam step of each other.)

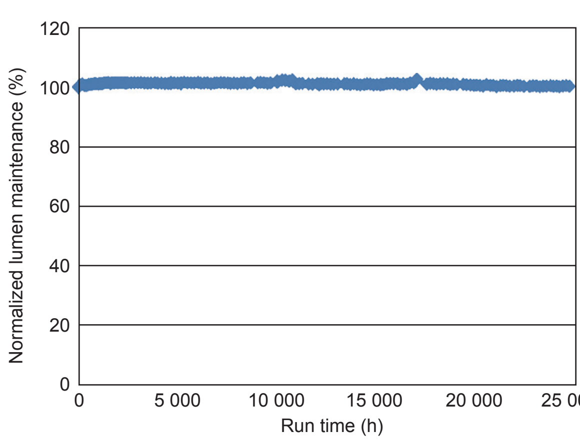

Figure 1. L Prize test results: Normalized lumen maintenance [3]. L Prize average lumen maintenance, as of 2013-04-29.

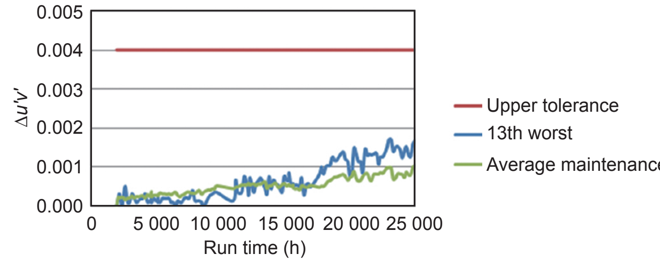

Figure 2. L Prize test results: Color shift. Chromaticity maintenance: 13th worst performing lamp.

Controlling color shift in an L Prize lamp was particularly complicated, because two LED colors were used (red and blue) in addition to a remote phosphor. When two colors of LEDs are used, they will have different temperature dependence and different degradation rates. Both of these factors will cause color maintenance to be poorer than for a light source made from a single LED color. Still, it is possible to create a stable light source, as shown in the figures above. In some cases, color-maintenance issues appear after several years of lamp service. Because the market has the impression that LED lamps "live forever," failures like color shift are particularly irksome.

2.2 Reports from the Smithsonian Institution

At the US Department of Energy (DOE) R&D workshops in 2011 and 2013, Scott Rosenfeld, a curator at the Smithsonian Institution, reported color-consistency (2011) and color-maintenance (2013) problems with LED lamps [4, 5]. Clear color change can be observed in Figure 3. Reported color shifts at the museum were as large as $\Delta u'v'$ = 0.027 (27 steps), after only 10 000 h of operation! Some of the reported color shifts are too large to comply with the Energy Star specification that color shift should be less than 0.007 at 6000 h of operation.

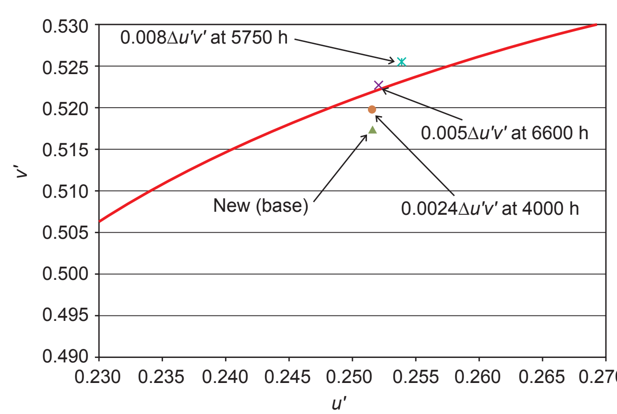

Figure 3. Results from the Smithsonian Institution [4, 5]. PAR30/3000K with CREE XPE chip and Themistor, manufacture #1, lamp types A and B.

2.3 Pacific Northwest National Laboratory

DOE-funded project at the Pacific Northwest National Laboratory (PNNL) [6–8] gives an excellent overview of color maintenance. A gateway project conducted at the Smithsonian Institution, involving several lamps from six different