OLED Displays

Fundamentals and Applications

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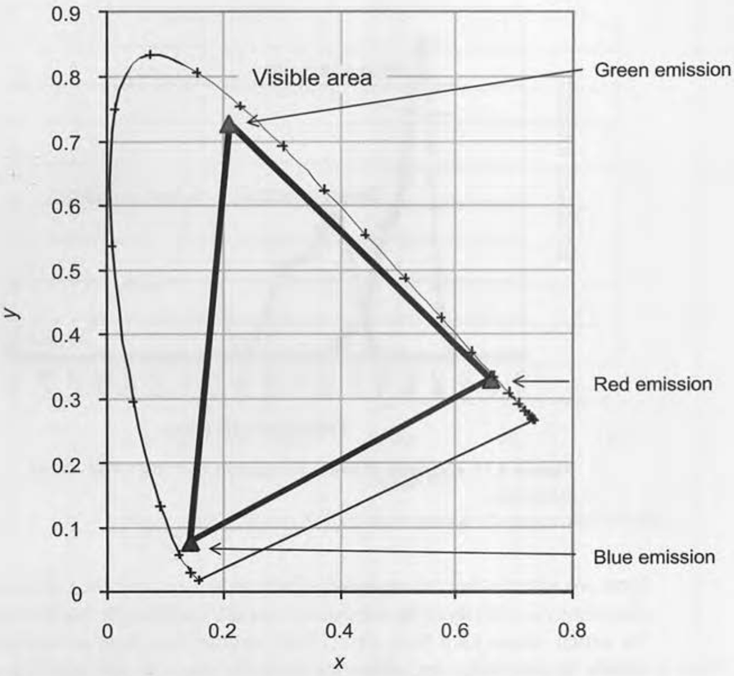

Figure 4.12 Plot of the area reproducible by RGB color mixture.

$$y = \frac{Y}{X+Y+Z} \tag{4.21}$$

This (x, y) value set can be calculated for red, green, and blue, respectively, as (x_R, y_R), (x_G, y_G), (x_B, y_B).

The actual measurement results of an OLED emitter are shown in Fig. 4.12. The color range that can be shown by the combination of these three color primaries is found within the triangle that is made by the three color primaries in the (x, y) coordinate. This area is called the *color gamut*. To determine the color reproduction capability of a display, the metric NTSC% is often used (NTSC = National [US] Television System Committee). It is defined as the ratio of the area of the triangle achievable by the display divided by the area of the standard NTSC triangle, expressed as a percentage. For example, XEL-1, the 11-in. OLED television commercialized in 2007, claimed a color gamut of 110%.

Although NTSC was introduced as a cathode ray tube (CRT) television standard, eventually most CRT fluorescence materials were designed with emission color coordinates close to the European Broadcasting Union (EBU) standard or the Rec709 standard (the international standard for HDTV studios), which are much smaller in area than is the NTSC triangle (Fig. 4.13).

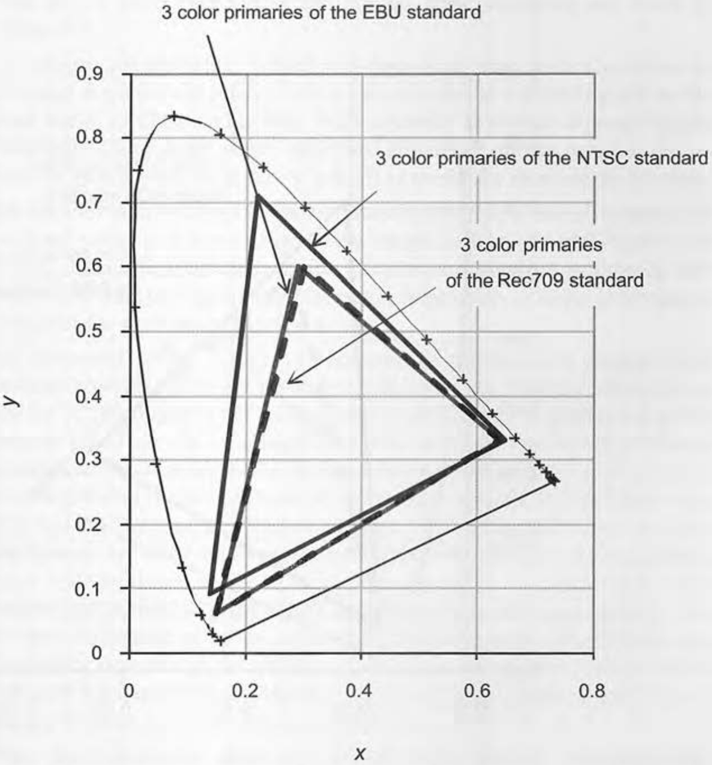

Figure 4.13 Graphical representation of the three color standards applied in television manufacture.

On the other hand, digital cameras and computers often use the s-RGB standard, which is shown in Fig. 4.14 (it has the same color coordinates as EBU and Rec709). The Joint Photographic Experts Group (JPEG) standard also normally uses the s-RGB color coordinate standard; however, as the s-RGB triangle is not large enough to reproduce high fidelity colors, a new header standard EXIF2.2 has introduced the s-Ycc standard, which uses an extended dynamic range with grayscale values that extend from negative values to values greater than 255, while normal s-RGB uses 0 to 255 to express gray scales. The newer header standard EXIF2.21 can also handle the Adobe-RGB standard, which is popular in the publishing industry (Fig. 4.14).

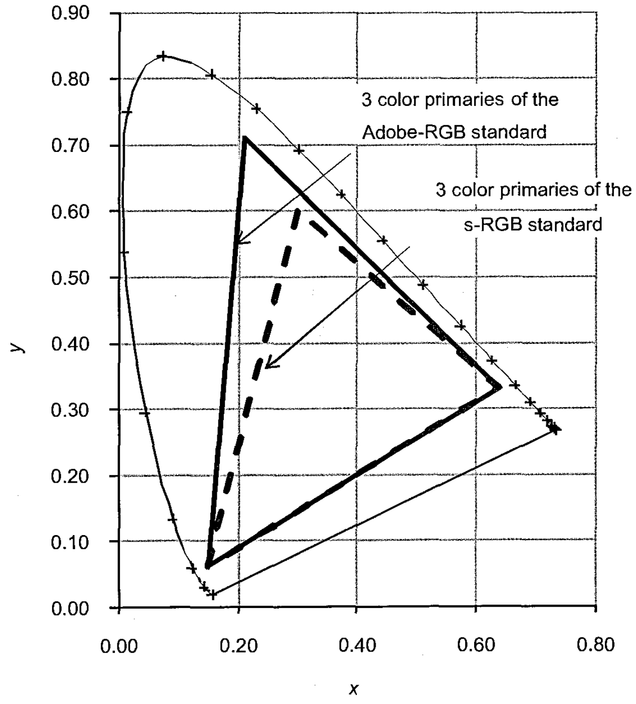

Figure 4.14 Graphical representation of the three color standards applied in digital camera manufacture.

TABLE 4.2 (*x*, *y*) Coordinate of Color Primaries for Each Standard

Standard	Red	Green	Blue
NTSC	(0.67,0.33)	(0.21,0.71)	(0.14,0.08)
Rec-709(HDTV)	(0.64,0.33)	(0.30,0.60)	(0.15,0.06)
EBU	(0.64,0.33)	(0.29,0.60)	(0.15,0.06)
s-RGB	(0.64,0.33)	(0.30,0.60)	(0.15,0.06)
Adobe-RGB	(0.64,0.33)	(0.21,0.71)	(0.15,0.06)

The (x, y) color coordinates for four of these standards are listed in Table 4.2.

To ensure color fidelity, s-RGB can reproduce most colors realistically because there are not many vivid colors outside the s-RGB triangle in the real world, as illustrated in Figs. 6.28 and 6.29. However, although highly saturated colors rarely occur, they have an intense impact on a viewer, so a color gamut wider than that of s-RGB is useful for showing such colors.

In the television industry, the image boosting technique, which converts an original image into a more impressive image, such as one with more vivid colors, by means of graphic engine IC chips or a graphics processing unit (GPU), is often used to enhance the image impression. A wider color gamut is useful for such an application as well.

As discussed earlier, the (x, y) coordinate is popular as a display color metric; however, there are problems with using the standard. Distance in the (x, y) coordinate is not proportional to differences in perception of the human visual system, so a larger area does not always mean better display capability. Figure 4.15 shows 10 times the perception limits of the human eye in different regions of the (x, y) color space reported by McAdam et al. [2]; this is known as the "McAdam ellipse." As it is an ellipse, not a circle, the human eye does not have the same sensitivity for the x axis and the y axis. Also as shown in Fig. 4.15, the human eye is very sensitive to blue colors (left bottom of graph) but is less sensitive to red (right bottom) and is very insensitive to green colors (top). This illustrates that human eye sensitivity depends on the location on the (x, y) coordinate. Therefore it is not very meaningful to discuss the area to judge the display capability on the basis of an (x, y) coordinate system.

The issues discussed above explain why many display companies and research institutes have used (u', v') color coordinates to express display capability. The CIE1976 color space coordinates (u', v') can be expressed as

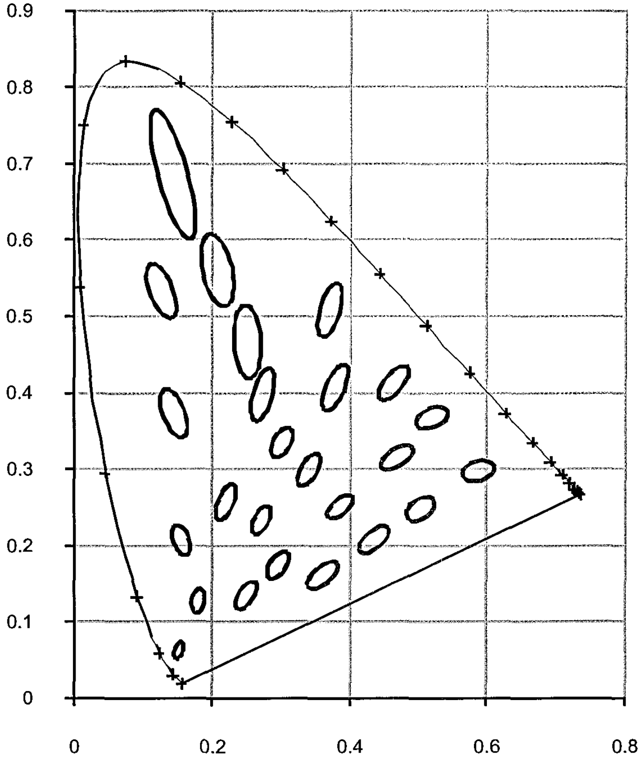

Figure 4.15 *Graphical representation of McAdam ellipse, showing the human eye's perception limit (at 10× magnification).*

$$u' = \frac{4x}{(-2x+12y+3)} = \frac{4X}{(X+15Y+3Z)} \tag{4.22}$$

$$v' = \frac{9y}{(-2x+12y+3)} = \frac{9Y}{(X+15Y+3Z)}. \tag{4.23}$$

Performance comparisons using the (u', v') color coordinates indicate how a color display color can actually be perceived by the human eye.

Also, uniform color space is sometimes factored into any discussion of display capability or color boosting because the defective criteria (such as the luminance variation limit or the image burning limit according to lifetime test discussed in Section 2.2.4, uniformity criteria discussed in Section 5.4.4, or the metal bus design discussed in Section 5.4.3) should be determined according to the limit of human perception.

4.2.4 Uniform Color Space

CIE-LAB and CIE-UV are two well-known uniform color spaces. On these uniform color spaces, lightness and color can be treated equally so that the length = 1 on the color space is almost equal to the human eye perception limit.

In CIE-LAB uniform color space (Fig. 4.16), lightness $L*$ is defined as

$$L^* = 116 f \frac{Y}{Y_n} - 16$$

$$a^* = 500\left(f \frac{X}{X_n} - f \frac{Y}{Y_n}\right)$$

$$b^* = 200\left(f \frac{Y}{Y_n} - \frac{Z}{Z_n}\right)$$

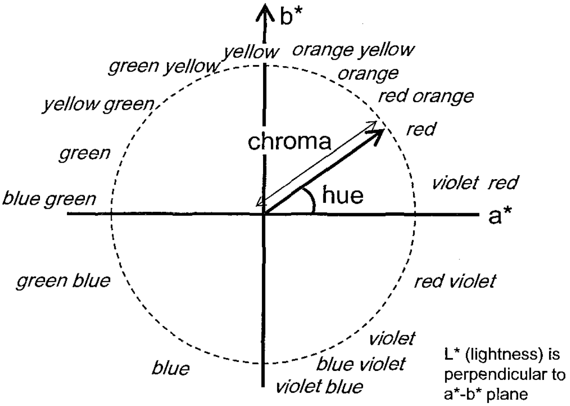

Figure 4.16 CIE-LAB uniform color space.

In the case of $t > \left(\frac{6}{29}\right)^3$, $f(t) = t^{1/3}$. In other cases, $f(t)$ is $\frac{1}{3}\left(\frac{29}{6}\right)^2 t + \frac{4}{29}$.

Plotting a^*, b^*, and L^* on a three-dimensional graph, the angle of the line made by the plotted point and the original point in plane a^*–b^* shows the hue, and the distance between the plotted point and the original point in plane a^*–b^* is the chroma, as in the Munsell color system widely used in color science. In this color space, the color difference (including lightness difference) is defined as ΔE_{ab} by the following equation:

$$\Delta E_{ab} = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}}$$

For CIE-LUV uniform color space, the (u^*, v^*) coordinate is defined by the following equations:

$$u^* = 13L^*(u - u'_n)$$

$$v^* = 13L^*(v - v'_n)$$

Color difference can be expressed as follows for CIE-LUV uniform color space:

$$\Delta E_{uv} = \sqrt{\Delta L^{*2} + \Delta u^{*2} + \Delta v^{*2}}$$

Color difference $\Delta E = 1$ is known to be close to the human perception limit and is a useful criterion for determining parameters for display design, such as

- Acceptable display white point variation
- Acceptable lifetime and viewing angle
- Acceptable image sticking level.

4.2.5 White Point Determination

To display a white image, all red, green, and blue subpixels need to emit light. The white color changes the impression of a display quite a bit. The color should be selected according to the purpose of the display.

When tristimulus values of red, green, and blue are (X_R, Y_R, Z_R), (X_G, Y_G, Z_G), (X_B, Y_B, Z_B) respectively, then

$$X_{\text{white}} = X_R + X_G + X_B \tag{4.24}$$

$$Y_{\text{white}} = Y_R + Y_G + Y_B \tag{4.25}$$

$$Z_{\text{white}} = Z_R + Z_G + Z_B \tag{4.26}$$

Then the (x,y) coordinate of the white emission can be calculated as follows:

$$x_{\text{white}} = \frac{X_{\text{white}}}{X_{\text{white}} + Y_{\text{white}} + Z_{\text{white}}} \tag{4.27}$$

$$y_{\text{white}} = \frac{Y_{\text{white}}}{X_{\text{white}} + Y_{\text{white}} + Z_{\text{white}}}. \tag{4.28}$$

The white coordinate (white point) is expressed by the CIE coordinates as well as by the blackbody radiation temperature.

To express the color of white emission, a blackbody temperature is often used. Radiant intensity from a black object having temperature T at wavelength between λ and $d\lambda$ can be expressed as (Planck radiation law)

$$P(\lambda) = \frac{8\pi hc^2}{\lambda^5} \cdot \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

(P, total radiant intensity from a black object toward all direction; c, speed of light; h, Planck constant; k_B, Boltzmann constant. It is necessary to pay attention to a potentially confusing definition. "Warm" color temperature, which normally means a color coordinate closer to red, has a low color temperature, while "cold" color temperature, normally a color coordinate closer to blue, has a high color temperature.)

Fig. 4.17 shows the spectrum of the radiant intensity for various color temperatures.

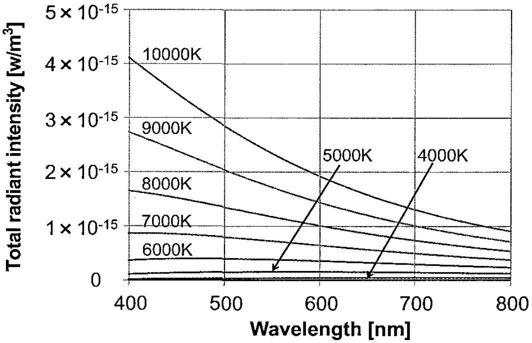

Figure 4.17 Black body emission spectrum for each color temperature.

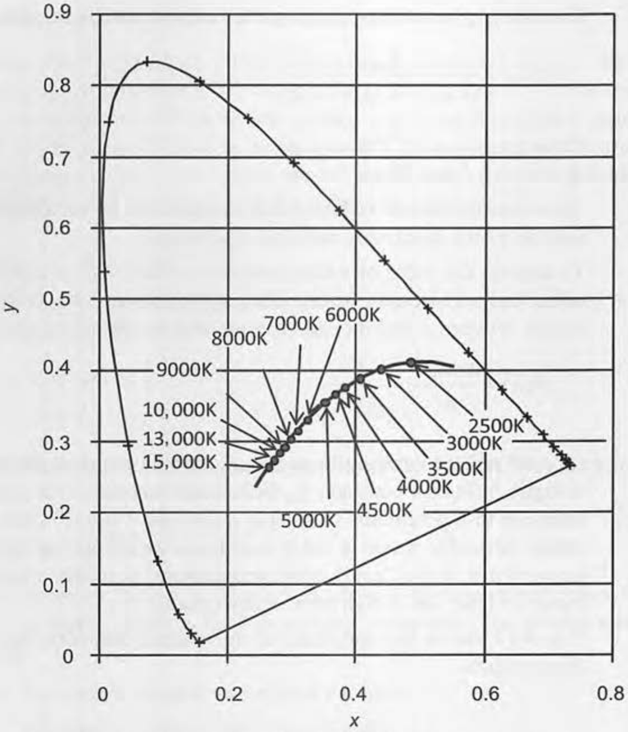

Figure 4.18 Graphical representation of blackbody versus color temperatures.

Figure 4.18 shows the CIE coordinate of each blackbody temperature. (The line that the color coordinate follows when temperature is changed is called Planckian locus or blackbody locus.)

In television applications, a temperature of 6500 K (designated as D65) is used to display the white point, which has been introduced by the SMPTE-170M standard in the United States and many other countries. On the other hand, Asian countries such as Japan are using high-temperature color points. For example, Japan is using 9300 K (D93) as a target, which was introduced by NHK, a Japanese broadcasting organization. D65 is $(x,y) = (0.3127, 0.3290)$ and D93 is $(x,y) = (0.283, 0.297)$ on the CIE coordinate. For computer