White Paper

OLED ASSOCIATION

Continued Advances in OLED Technologies and Materials Accelerate the Emergence of New High Performance Displays and Lighting Products

While the prudent were right to expect continued ‘coming soon’ messages on larger OLED TVs since LG’s Samsung’s and Sony’s demos shown at last year’s CES, even the optimists have been surprised by the influx of small- and medium-sized OLED displays into handheld devices in the last 12 months. Who would have predicted that at CES 2010 Google would introduce its own handset with a large, high-resolution OLED display? And, almost concurrently, that Osram would introduce a commercial OLED lighting product? With the progress of the past year, 2010 looks to be an even more exciting year for OLEDs in both the display and lighting arenas.

It’s no secret that OLED displays, especially TVs, look great. They offer high contrast, sharpness, and bright, eye-popping color that take high-definition imagery to new peaks. Their fast refresh rates also make them extremely attractive for the emerging 3D TV market. With improved manufacturing and higher volume production, even the price of OLED TV’s can soon be in line with the incumbents. For lighting, white OLEDs offer a greener alternative to fluorescent lighting and are meeting lifetime and efficiency goals in Europe, Asia and North America. With continued research in OLED technology and materials, even higher performing products can be expected in both display and lighting markets.

The current performance of OLEDs and their continued potential create new reference points to compare with LCDs and inorganic LEDs in their respective display and lighting markets. For example, the luminance of an LCD is strictly a function of the output of the backlight, limited by the display efficacy (the amount of light that flows through the display), which is typically 2% to 5% of the source. The amount of light appearing on the LCD is then a function of the LED backlight performance, the display efficacy and the image. In an OLED, the efficacy of the material largely controls the luminance, so the light output is a function of the image and the material efficacy - now in the range of 25% to 30%.

Viewing angle is another measure that is defined differently. For an LCD, the viewing angle is considered acceptable if the contrast ratio (CR) is >10:1, regardless of the head-on CR. For OLED displays, the requirement has been set more stringently. Its viewing angle is acceptable *only* if the CR is the same at any angle. Another difference is the ability of OLED displays to track the gray scale, perfectly from fully to <10% of saturation. LCDs do not track the gray scale accurately and can be off by 80% to 90% at the lowest levels.

Also, power consumption is measured differently. LCD power consumption is the same whether the image is fully black or fully white, while OLED display power consumption is dependent on the specific image being shown - with black or very dark content being close to zero and white images consuming the most power.

Key Factors in Power Consumption and OLED Progress

With the continued trend toward portability, in combination with the increase in energy costs and desire for environmental 'greenness', reducing the power consumption of displays and lighting have become industry priorities. Largely through the development of phosphorescent technology and materials, OLEDs offer a real and exciting solution to meet these power consumption requirements.

1) While LCDs depend on the performance of the backlight, i.e., cold cathode fluorescent lights (CCFL) or inorganic LEDs, OLEDs depend on the performance of the organic material.

    a) Each year OLED material makers have been reporting improvements in their capability to convert electrical energy into optical energy.
    b) The key ingredients in the performance of OLEDs from the perspective of power consumption are brightness, efficiency and lifetime. These factors remain the same for displays and lighting.

2) The key measures of OLED performance are luminous efficiency (in candelas/Amp (cd/A)), which measures the light output for a given current; operating lifetime, which is a measure of how many hours (hr) it takes to reach 50% of the original luminance and power efficiency (in lumens per Watt (lm/W)), which is a measure of the light output per power input as used in lighting. Yet another measure is the color gamut, which is a measure of how close the saturated red, green and blue come to color standards, as portrayed in the CIE diagram (refer to Appendix for additional information). An additional measure for lighting is its color temperature, as determined by comparing its chromaticity with that of an ideal black-body radiator. Higher color temperatures (5,000K or more) are cool (bluish white) colors, and lower color temperatures (2,700–3,000K) are warmer (yellowish white through red) colors. Generally, for room lighting the warm colors are more desirable. Color Rendering Index (CRI) is another measure of the quality of color light. The higher the CRI the closer the light source replicates the colors that would be rendered by the sun. Lighting sources have CRI's that range from very low for a source like a low-pressure sodium vapor lamp, which is monochromatic, to close to one hundred, for a source like an incandescent light bulb.

3) State of Small Molecule and Polymer OLEDs

    The efficacy of small molecule OLED materials' red, green and blue at the beginning of 2009 and 2010 are shown in Table 1, and those for polymeric OLEDs on similar scale are shown in Table 2. *Given the current efficacy at the beginning of 2009 for small molecule OLED materials, a 3.5-inch display operating at 250 cd/m^2, would have a lifetime of ~50,000 hr and power consumption of 300 mW. With the improvement achieved over the past year, the same 3.5-inch display at 250 cd/m^2*

would use only 200 mW and would have a lifetime of 70,000 hrs, or at 50,000 hr could operate at 400 cd/m^2, at the same power of 300 mW.

Table 1 Small Molecule Performance (@ 1000 cd/m^2)

Jan. 2009	Lifetime (hr to 50%)	Efficacy (cd/A)
Red (phosphorescent)	80 – 500k	21 - 28
Green (phosphorescent)	100 – 250k	58 - 67
Blue (fluorescent)	15K – 25k	2.5

Jan. 2010	Lifetime (hr to 50%)	Efficacy (cd/A)
Red (phosphorescent)	120 – 500k	22 - 28
Green (phosphorescent)	150 – 500k	63 - 69
Blue (fluorescent)	25K – 50k	3.3

Table 2 Polymer Performance (@ 1000 cd/m^2)

Jan. 2009	Lifetime (hr to 50%)	Efficacy (cd/A)
Red (Fluorescent)	89k	10
Green (Fluor / Phos)	79k / 30k	15 / 50
Blue (Fluorescent)	21k (0.21)	7.5 (0.21)

Jan. 2010	Lifetime (hr to 50%)	Efficacy (cd/A)
Red (Fluor / Phos	200k / 350k	11 / 31
Green (Fluor / Phos)	200k / 83k	28 / 50
Blue (Fluorescent)	26k (0.21), 7.8k (0.14)	8.0 (0.21), 7.5 (0.14)

OLED material performance is improving rapidly. 3.5-inch OLED displays have the potential to reach 100 mW of power consumption at 400 cd/m^2 in the foreseeable future. A 40-inch TV operating at 500 cd/m^2 may achieve power consumption under 75W and lifetimes in excess of 100k hours. This compares to the most efficient LCD TVs today with over 100W and more typically closer to 200W.

In the case of large screen OLED TV's, both materials performance and manufacturing costs remain key challenges to the commercial introduction of products. A current trend in large (>20") OLED TV manufacturing technology is to print materials into pixels, rather than evaporate, in order to bring manufacturing yields higher and costs lower. Despite their current lower performance than small molecule OLEDs, polymer and solution-processible OLEDs with their printing potential make for an exciting technology competition which will serve to benefit the consumer.

In the case of OLED lighting, the key parameters are luminance (measured in lumens), power consumption (lm/W), color temperature, measured in degrees Kelvin (K), Color Rendering Index (CRI) measured as a percentage of incandescent performance and lifetime at 70% of initial luminance (T_{70}). The recent announcement by Osram of their commercially-available Orbeos, a 6-inch diagonal OLED lighting panel defines the state of the art. It provides 1,000 cd/m^2 (or 73 lumens of light), a warm color temperature of

2,800 K, a CRI of 80, with power consumption of 23 lm/W and a lifetime of 5,000 hr. Moreover, this mass-produced OLED lighting panel also now provides a very exciting design feature to the lighting community. With a 2 mm thin form factor, OLED lights have the potential to be used in a variety of novel ways and places. Moreover, a number of research activities have demonstrated results white OLEDs with 70 to 100 lm/W, providing a strong developmental pathway to future higher-performing products. *With such improvements, white OLED product specifications are likely to go up to 3,000 cd/m*^{2} *(>200 lm), CRI >80, lifetimes of >10,000 hr fairly soon.*

With the tremendous progress in OLED technology and materials over the past few years, OLEDs are now established in the marketplace. 2010 will see a continued increase in the use of OLED displays in handheld devices, TV's and other display applications as well as the emergence of additional OLED lighting products.

Appendix
OLED Specification Definitions

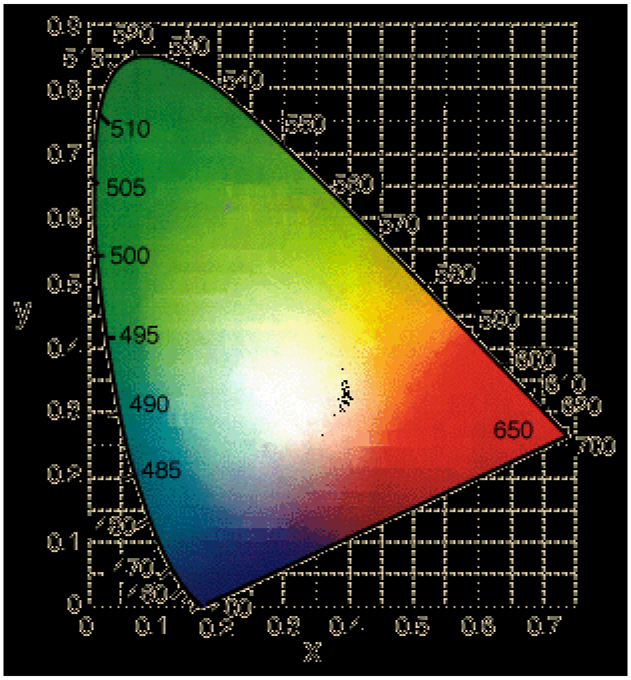
1. **Efficacy – Cd/A** -- The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 _ 10^{12} Hz and that has a radiant intensity in that direction of $^{1}/_{683}$ Watt per steradian. In radiometry, radiant intensity is a measure of the intensity of electromagnetic radiation. It is defined as power per unit solid angle. The candela is sometimes still called by the old name *candle,* such as in *foot-candle* and the modern definition of *candlepower*. If a source emits a known intensity (in candelas) in a well-defined cone, the total luminous flux in lumens can be calculated by taking the number of candelas, and dividing it by the number in the table below that corresponds to the *radiation angle* of the lamp (the full vertex angle of the emission cone). See MR16 for emission angles of some common lamps. Radiation angle Divide by 5° 167.2 10° 41.82 15° 18.50 20° 10.48 25° 6.714 30° 4.671 35° 3.439 40° 2.639 45° 2.091 50° 1.699 55° 1.409 60° 1.188 65° 1.016 70° 0.8800 75° 0.7702 80° 0.6803 85° 0.6058 90° 0.5434 95° 0.4906 100° 0.4455 105° 0.4068 110° 0.3732 115° 0.3440 120° 0.3183 If the source emits light uniformly in all directions, the flux can be found by multiplying the intensity by 4п: a uniform 1 candela source emits 12.6 lumens.

2. **Lumen/W** – Luminous efficacy is a figure of merit for light sources. It is the ratio of luminous flux (in lumens) to power (usually measured in Watts). Depending on context, the power can be either the radiant flux of the source's output, or it can be the total electric power consumed by the source.[Which sense of the term is intended must usually be inferred from the context, and is sometimes unclear. The former sense is sometimes called luminous efficacy of radiation (LER), and the latter luminous efficacy of a source (LES). Artificial light sources are usually evaluated in terms luminous efficacy of a source, also sometimes called *overall luminous efficacy*. This is the ratio between the total luminous flux emitted by a device and the total amount of input power (electrical, etc.) it consumes. It is also sometimes referred to as the wall-plug luminous efficacy or simply wall-plug efficacy. The overall luminous efficacy is a measure of the efficiency of the device with the output adjusted to account for the spectral response curve (the "luminosity function"). When expressed in dimensionless form (for example, as a fraction of the maximum possible luminous efficacy), this value may be called overall luminous efficiency, wall-plug luminous efficiency, or simply the lighting efficiency. The main difference between the luminous efficacy of radiation and the luminous efficacy of a source is that the latter accounts for input energy that is lost as heat or otherwise exits the source as something other than electromagnetic radiation. Luminous efficacy of radiation is a property of the radiation emitted by a source. Luminous efficacy of a source is a property of the source as a whole.

3. **Color**
   3.1. **Color Coordinates** – The CIE system characterizes colors by a luminance parameter Y and two color coordinates x and y which specify the point on the chromaticity diagram. This system offers more precision in color measurement than do the Munsell and Ostwald systems because the parameters are based on the spectral power distribution (SPD) of the light emitted from a colored object

and are factored by sensitivity curves which have been measured for the human eye. Based on the fact that the human eye has three different types of color sensitive cones, the response of the eye is best described in terms of three "tristimulus values". However, once this is accomplished, any color can be expressed in terms of the two color coordinates x and y. The colors that can be matched by combining a given set of three primary colors (such as the blue, green, and red of a color television screen) are represented on the chromaticity diagram by a triangle joining the coordinates for the three colors. The diagram given here is associated with the 1931 CIE standard. Revisions were made in 1960 and 1976, but the 1931 version remains the most widely used version.

Figure 1 1931 CIE Standard



Approximate colors can be assigned to areas on the CIE Chromaticity Diagram. These are rough categories, and not to be taken as precise statements of color. The boundaries and the color names are adapted from Brand Fortner, "Number by Color," Part 5, *SciTech Journal* 6, p32, May/June 1996.

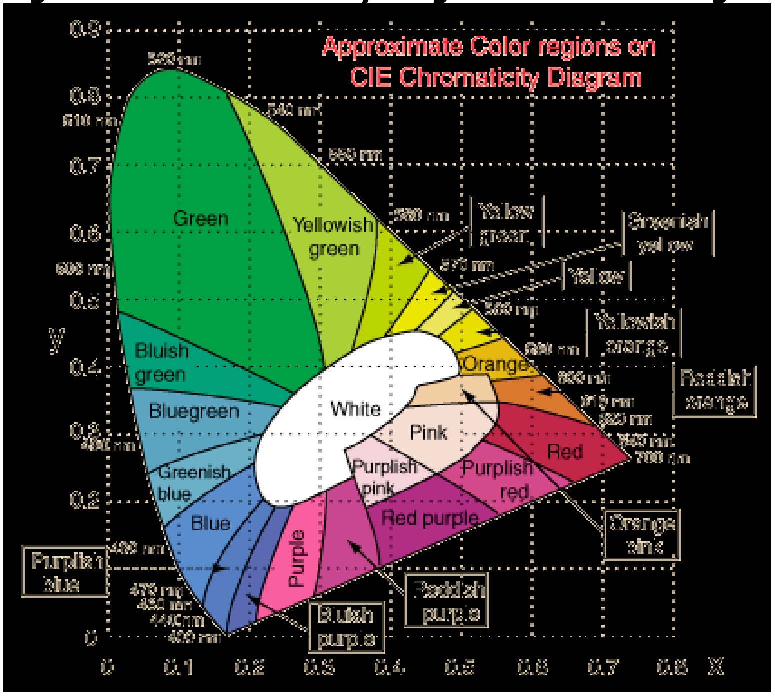
Any attempt to depict the gamut of human color vision on a computer monitor must be accompanied by numerous qualifications and exceptions. In the first place, you cannot display the range of human color perception on an RGB monitor - the gamut of normal human vision covers the entire CIE diagram while the gamut of an RGB monitor can be displayed as a triangular region within the CIE diagram. Another qualification is that the hue and saturation associated with a given color name can vary over a considerable range. Add to that the variations with different kinds of display monitors, and you rightly conclude that an accurate rendition is impossible. With all those excuses, however, it still might be instructive to provide a rough idea of the regions of the CIE Diagram associated with common color names.

The display here was created by choosing representative RGB values for the color regions from a rendition of the 1976 CIE Chromaticity Diagram provided by Photo Research, Inc. Note that one representative value in about the middle of the hue and saturation ranges was chosen for each section of the diagram. The point chosen was just a visual judgment of a representative color in the range. The RGB values obtained are listed in the table at right. A different observer would likely have chosen different points to represent the color names, but at least these values might provide a starting point for preferred variations.

One characteristic of the commonly used 1931 CIE Chromaticity Diagram that is evident even from this crude portrayal is that the green takes up far too much of the landscape compared to the number of visually different colors in the region. That was one of the shortcomings that the 1960 and 1976 revisions sought to address.

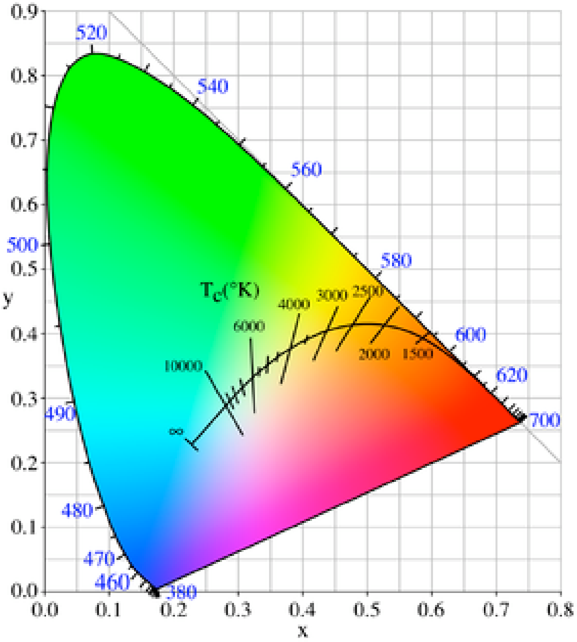
Light Sources – Many light sources, such as fluorescent lamps, emit light primarily by processes other than raising the temperature of a body. This means the emitted radiation does not follow the form of a black-body spectrum. These sources are assigned what is known as a correlated color temperature (CCT), the color temperature of a black body radiator which to human color perception most closely matches the light from the lamp. Because such an approximation is not required for incandescent light, the CCT for an incandescent light is simply its unadjusted temperature, derived from the comparison to a black body radiator.

Figure 2 CIE Chromaticity Diagram with Color Regions



5. **Color Temperature** –A characteristic of visible light that has important applications in lighting, photography, videography, publishing, manufacturing, and other fields. The color temperature of a light source is determined by comparing its chromaticity with that of an ideal black-body radiator. The temperature (usually measured in kelvin, K) at which the heated black-body radiator matches the color of the light source is that source's color temperature; for a black body source, it is directly related to Planck's law and Wien's displacement law. Higher color temperatures (5,000K or more) are cool (bluish white) colors, and lower color temperatures (2,700–3,000K) warm (yellowish white through red) colors. In physics, a "black body" is an idealized object that absorbs all electromagnetic radiation that falls on it. No electromagnetic radiation passes through it and none is reflected. Because no light (visible electromagnetic radiation) is reflected or transmitted, the object appears black when it is cold. However, a black body emits a temperature-dependent spectrum of light. This thermal radiation from a black body is termed "black-body radiation." At room temperature, black bodies emit mostly infrared wavelengths, but as the temperature increases past a few hundred degrees C, black bodies start to emit visible wavelengths, appearing red, orange, yellow, white, and blue with increasing temperature. By the time an object is white, it is emitting substantial ultraviolet radiation. Black-body emission gives insight into the thermal equilibrium state of a continuous field. In classical physics, each different Fourier mode in thermal equilibrium should have the same energy, leading to the theory of ultraviolet catastrophe that there would be an infinite amount of energy in any continuous field. Black bodies could test the properties of thermal equilibrium because they emit radiation which is distributed thermally. Studying the laws of the black body historically led to quantum mechanics.

Figure 3. CIE Chromaticity Diagram with While Color Temperature (K)



6. **The Color Rendering Index** (CRI), is a measure of the quality of color light, devised by the International Commission on Illumination (CIE). It generally ranges from zero for a source like a low-pressure sodium vapor lamp, which is monochromatic, to one hundred, for a source like an incandescent light bulb, which emits essentially blackbody radiation. It is related to color temperature, in that the CRI measures for a pair of light sources can only be compared if they have the same color temperature. A standard "cool white" fluorescent lamp will have a CRI near 62. CRI is a quantitatively measurable index, not a subjective one. A reference source, such as blackbody radiation, is defined as having a CRI of 100 (this is why incandescent lamps have that rating, as they are, in effect, blackbody radiators), and the test source with the same color temperature is compared against this. Both sources are used to illuminate several standard samples. The perceived colors under the reference and test illumination (measured in CIE 1931 form) are compared using a standard formula, and averaged over the number of samples taken (usually eight) to get the final CRI. Because eight samples are usually used, manufacturers use the prefix "octo-" on their high-CRI lamps.

   The standard formula consists of taking the color differences _E_i, between the test color and the eight samples, on the 1964 W*U*V* uniform color space (which is now obsolete). The CRI is calculated for each of the eight samples: $R_{I=}$100-4.6_E_i, which gives the color rendering index with respect to each sample. The general color rendering index Ra is then the average of these eight separate indices."