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Research Article

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Nano-Structures Enabling Sunlight and Candlelight-Style OLEDs

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Abstract

Nano structures enable organic light-emitting diode (OLED) devices to be fabricated with relatively high efficiency and brightness, opening up a new era for high quality displays and lighting, wherein devising a pseudo-natural light is always a must. The uses of incandescent bulbs are the most friendly, electricity-driven lighting sources, lighting measure from the perspectives of human eye protection, melatonin generation, artifacts, ecosystems, the environment, and the night skies due to their intrinsically low blue emission. However, they are phasing out because of the energy wasting. To overcome these difficulties, researchers are focusing on developing a new light with high efficiency, whose emission spectra would also match with those of the natural lights. In 2009, Jou's group invented the world's first electrically powered sunlight-style OLED that yielded a sunlight-style illumination with various daylight chromaticities, whose color temperature ranges between 2,300 and 8,200 K, fully covering those of the entire daylight at different times and regions, and contributed a noteworthy incentive to OLED technology in general lighting. By putting more efforts on this technology, a blue hazard free, low color temperature candlelight-style OLED was developed by employing candlelight complementary emitters, namely orange-red, yellow, green, and sky-blue. The resultant candlelight OLED that exhibits a 1,900 K color temperature is exactly like candles or oil lamps, which is friendly to human eyes, physiologies, ecosystems, artifacts, and night-skies. Specifically, it is at least 10 times safer from the retina protection perspective or 5 times better for melatonin to naturally occur after dusk, as compared with the blue light-enriched white OLED, LED and CFL counterparts. In this article, we discuss the device structure, physics, and engineering behind the serendipity of the pseudo-natural light-style OLEDs.

Keywords

Candlelight-style; OLED; Sunlight-style

Introduction

The new era of an organic light-emitting diodes (OLEDs) begin with the invention by Tang and Van Slyke in 1987 [1]. OLEDs are progressively attracting much attention because of their potential applications and superior performance in the high-quality flat-panel displays, lighting, and optoelectronics [1-4]. In comparison to general lighting and display sources, OLEDs have prominent features like high color purity, high luminance, wide viewing angle, high contrast, high response speed, low power consumption, simple fabrication, ultra-thin structure, light-weight, flexibility, and low cost. [5]. Numerous architectural and fabrication approaches have been introduced to develop a high energy-efficiency and long lifetime OLED devices [3,6]. Over the past few years, OLEDs started to replace the conventional and power consuming light sources, incandescent bulbs and fluorescent lights which are non eco-friendly, contain harmful mercury, and non-disposable. While, OLEDs are self-illuminating, power efficient, and disposable.

Color and color temperature (CT) of light show a strong influence on human physiology and psychology [7]. Long time exposure to light with high color temperature and short wavelength leads to different types of cancer [8]. A good lighting improves alertness, psychomotor vigilance, task performance, morning cortisol level, and sleep quantity [9]. Jou's group contributed remarkable effort in the designing and development of human-friendly light [10-19]. The same group reported both candlelight- and sunlight-style OLED with color-temperature and chromaticity similar to that of the natural lighting source [10-19]. OLED succeeds to make light free from hazardous violet and ultraviolet emission, scorching infrared, unpleasant glare, toxic mercury, and importantly blue hazard [16-19], also succeed to fabricate OLED devices with sunlight style chromaticity and color temperature [10-15]. Combined with high energy-efficiency and high light-quality, all these justifies OLED to be a healthy and good light for lighting to safeguard human health and minimize light pollution.

Types of Natural Light

Natural light includes the light from the sun, stars, fires, bugs, etc. Even though light from the moon is reflected light from the sun, which provides a significant luminance at the full moon. Some glow worms, special kinds of fish, and mushrooms produce light via bio-luminescence [20-27]. Sunlight, light from wood or fires generate a smooth and continuous spectrum over the entire visible range, perfectly matching that of the blackbody radiation at the same corresponding color temperature.

Nature and importance of sunlight

Color temperature of sunlight varies with the time, region, and weather. It is 2,500 K at dawn, 3,250 K at dusk, 5,500 K at noon, or 8,000 K at noon in high-latitude country, and 6,500 K on a cloudy day as shown in Figure 1. High CT induce the production of cortisol, which can enhance the alertness and productive work. The low CT, dusk hue emission is physiologically friendly with the most attractive chromaticity. It influences the migration of birds, the bird's singing at dusk and the mating of crabs and moths [28-34]. The peoples living in northern countries face melancholy or even suicide due to the lack of sunlight during the long winter [7].

Nature and importance of candlelight

Candles are physiologically friendly light source due to the low color temperature and less blue emission. Candlelight exhibits a CT around 1,900 K, which can create a romantic atmosphere during dinner time. This pleasant sensation may be due to the production of melatonin, which regulates the sleep, wakefulness and helps people relax. The main drawbacks of conventional candlelight are energy

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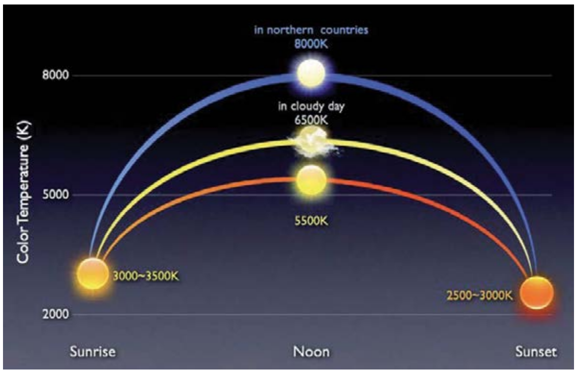

Figure 1: Color temperature of sunlight at different regions, times, and weathers [11].

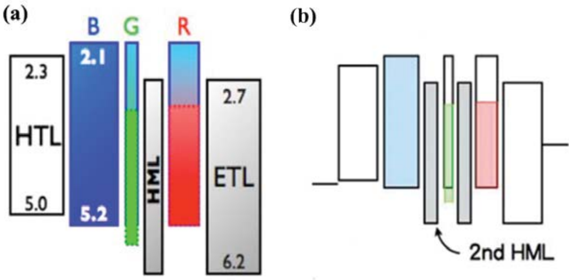

Figure 2: Sunlight-style OLED with a) single carrier modulation layer and b) double carrier modulation layers [10,11].

waste (0.1-0.3 lm/W), flickering, glare, obtrusiveness, burning problems, potential fire hazards, high heat due to intens infrared radiation, and unpleasant smoke due to incomplete burning. Indoor applications of candles may consume oxygen and generate greenhouse gases [35].

Theoretical

Spectral resemblance index (SRI)

Jou's group introduced that the spectral resemblance index for calculating the light quality of a given light [36]. The calculation is based on the direct comparison of a light source's lumen spectrum with the natural light counterpart having the same color temperature.

$$SRI = \frac{\int L(\lambda,T)d\lambda}{\int L_{BR}(\lambda,T)d\lambda} \times 100\% \tag{1}$$

where L_{BR} (λ,T) is the luminance spectrum of the blackbody-radiation, and L (λ,T) is the overlapping area between the luminance spectrum of the considered light source and its corresponding blackbody-radiation.

Maximum permissible exposure-limit (MPE)

Maximum permissible exposure-limit (MPE) with a unit of second (sec) is the highest power or energy density a light source, which is safe to human eyes. MPE is represented by "t". The value of "t" can be determined according to the IEC 62471 standard [37], $t=100/E_B$ where E_B is defined as the blue-light weighted irradiance,

$$E_B = \sum_{300}^{700} E_\lambda \times B(\lambda) \tag{2}$$

where B(λ) is the blue-light hazard function [38] and E_λ is the spectral irradiance.

Melatonin suppression sensitivity (MSS)

One method of expression of melatonin suppression sensitivity is in photon quanta [39]

$$S_{PQ} = 10^{(\lambda r - \lambda)/C} \tag{3}$$

Where, S_{PQ} suppression power per photon quanta of a given monochromatic light, λ relative to that of the reference light, λ_r, and C is a fitting constant.

Another method of expression of melatonin suppression sensitivity in lux (lx), for general illumination purpose. Therefore the above formula becomes [39],

$$S_L(\lambda) = \frac{\lambda S_{PQ}(\lambda)}{V(\lambda)} \tag{4}$$

Where, $S_L(\lambda)$ is the action spectrum of MLT suppression per lux, V(λ) is the photopic luminosity function, which converts photo quanta into illuminance in terms of lx.

For polychromatic light, the following expression is used.

$$S_{LC}(\lambda) = \frac{\int \lambda S_{PQ}(\lambda)\lambda S_I(\lambda)d\lambda}{\int V(\lambda)\lambda S_I(\lambda)d\lambda} \tag{5}$$

Where, S_{LC} (λ) is the correlated suppression power per lux and $S_I(\lambda)$ is the power spectrum of the studied light.

Sunlight OLEDs

The color temperature of light influences the human health and work performance. Drowsiness has been observed under low color temperature lighting. To have high-quality lighting, emission with a daylight chromaticity and a color temperature span covering that of sunlight is essential, especially considering its strong effect on human psychology. To have a high-quality sunlight-style illumination, emission with daylight chromaticity and a wide color-temperature span from 2,000 to 6,000 K is necessary. A good lighting can improve alertness, psychomotor vigilance, task performance, morning cortisol level and sleep quantity. In 2009, Jou's group reported the first single device with sunlight-style emission [10].

Device architecture

The sunlight-style OLED has a relatively simple design, consisting of various color-emitting materials, electron transporting layer, carrier modulation layer, and electron injection layer with few nanometers of thickness. Jou's group examined the influence of both single and double carrier modulation layers (CML) in sunlight-style OLED (Figure 2).

The first reported sunlight-style OLED consisted of fluorescent emissive materials and later it was replaced by phosphorescent materials for improving the device efficacy [10]. Jou's group also reported the dusk-hue chromaticity OLED by using four blackbody radiation-complementary emitters (Figure 3) [11].

Device characteristics

The color temperature of the device was regulated by varying the applied voltage and insertion of CML. The sunlight-style OLED showed a relatively high degree of similarity in the emissive spectrum with that of the sunlight (Figure 4).

Using a 3 nm CML, the OLED device produced 2,500 K sunset hue at 3.5 V, 3,250 K dawn light at 4 V, 5,500 K sunny noon daylight at

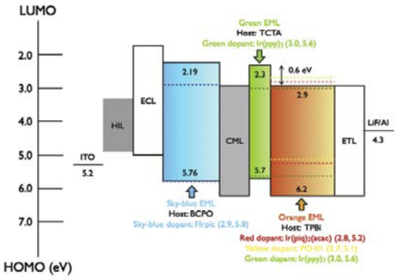

Figure 3: Energy level schematic illustration of the OLED devices comprising four black body radiation complementary emitters, namely red, yellow, green, and sky-blue, dispersed in three emissive layers with a nano-scale carrier modulating layer [17].

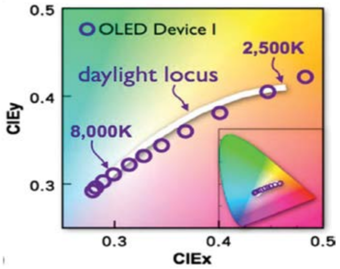

Figure 4: The color temperature of sunlight-style OLED matches with daylight locus [10].

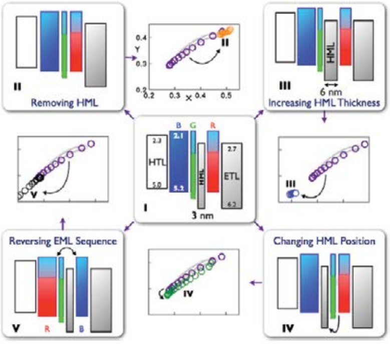

Figure 5: Schematic representation of the influence of CML on device performance [10].

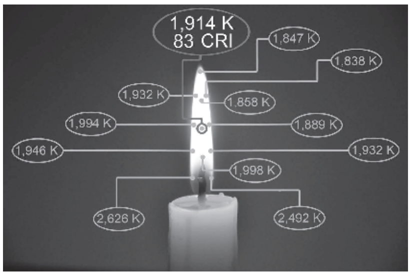

Figure 6: Candle shows different color temperatures at different flame positions. The color temperature varies from 1,847 to 2,626 K for the white candle studied. To represent this most effectively, the color temperature of the brightest spot is chosen, which is 1,914 K [16].

5.5 V, 6,500 K noon daylight on a cloudy day, and greater than 8,000 K noon daylight in high-latitude countries at 7 V or above [10]. The power efficiency was 7.0 and 2.2. lm/W at 100 and 1000 cd/m^2, respectively. Applying double CML and phosphorescent emissive materials enhanced the power efficacy to 9.0 lm/W at 2,400 K and 0.9 lm/W at 18,000 K. Insertion of two CML improved the device efficacy and color temperature span compared to the device with one CML [10,11]. By varying the red dye concentration, the color temperature span tuned from 1,875-6,030 K to 3,100-18,800 K. The SRI for the devices with blackbody radiation-complementary emitters was 90, showing a high resemblance to black-body radiation.

The function of nano-layer(s) of carrier modulation materials

The hole is a faster carrier than the electrons, which may enhance the recombination in an emissive layer near to cathode. Insertion of the carrier modulating layer (CML) or hole modulating layer (HML) in between the emissive layers tuned the hole mobility and recombination zone in the device. CML thickness and position of CML layer influences the color, color temperature and color temperature span of the device. The device without CML showed an orange emission with a low CT, 330 K. The CML with optimum thickness inserted in between emissive layers (Figure 5) modulated the flux of holes and produced sunlight-style emission [10].

A higher thickness of CML leads to a high threshold voltage and showed a hypsochromic shift with high CT, 19,000 K. Changing the position of the CML also affects the sunlight-style emission, the entire emission, from 3.5 to 9.5 V shifts away from the daylight locus. Insertion of double CML layers also enhanced the power efficacy and color temperature span by controlling the hole mobility.

Candlelight OLED

Candles emit low blue emission and color-temperature (CT) that minimizes the all kinds of blue-hazards. It also owns a continuous emission spectrum, free of ultraviolet radiation, and high in color rendition (CRI) as shown in Figure 6 [16]. In addition, candle light is able to create a romantic atmosphere, and a pleasant sensation may originate from the naturally occurring melatonin secretion, which helps people relax. Hence, there is an urgency to a lighting source that avoids all the aforementioned drawbacks and matches the visible spectrum of a candle.

In 2013, Jou's group demonstrated the first environment-friendly, energy efficient, high spectrum resemblance index (SRI), and high-quality candlelight-style OLED for indoor and outdoor illumination [16]. Candlelight-based, blue-hazard free lighting sources are physiologically-friendly to the human eye, museum artifacts, ecosystems, and night sky (Figure 7).

Device structure

The candlelight-style OLEDs had comparatively simple architecture, consisting of multiple layers of complementary organic emitters, hole-injection, and hole-transport as shown in Figure 8. A candlelight-style OLED mainly consists of four organic electro-phosphorescence dyes, namely red, green, yellow, and sky-blue. These organic dyes are dispersed in engineered host materials coupled with a cross-linkable hole transporting layer and then dispersed in different emissive layers separated by a nano-interlayer to harvest the ultimate color rendering index [16].

Device characteristics

The devices are designed to maximize the emission of the employed red light-emitting dye and minimize that of the blue counterpart

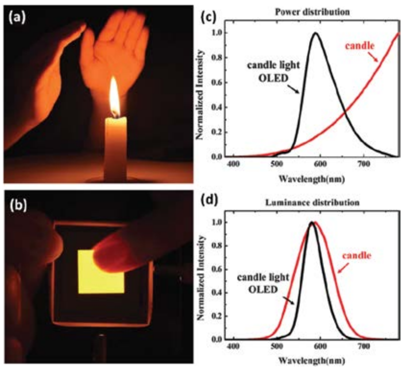

Figure 7: Photographs of (a) the hydrocarbon-burning candle with scorching heat and (b) electricity-driven non-scorching candlelight OLED. Comparison of the (c) spectral power and (d) luminosity distributions of the candlelight OLED with the candle. The candlelight-style OLED shows a 60% similarity with the candle as comparing their spectral luminance distributions that are obtained by convoluting the power spectra with the luminosity function [19].

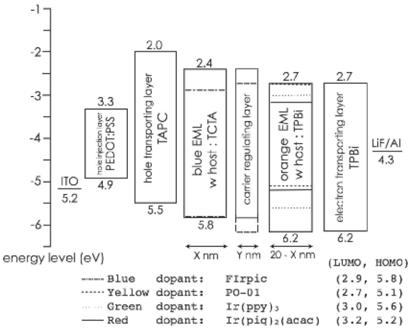

Figure 8: Schematic energy-level diagram of the candle light-style OLED device [16].

accordingly. However, in a candlelight-style OLED, the color temperature can be easily tuned lower by diminishing the melatonin suppression sensitive blue emission, also has no emission beyond the infrared region [16-19]. The candlelight-style OLEDs efficacy roll-off may be attributed to numerous factors, including concentration quenching, exciton quenching, imbalance carrier injection, and ineffective carrier confinement. To improve this, employing much-diluted emitter, multiple emission layers, improving the injection of a minor carrier to balance the carriers, and incorporating effective electron and/or hole confinement layers [16].

In 2013, Jou's group has reported the first wet processed low color temperature candlelight-style illumination source to reduce melatonin suppression based on a four blackbody-radiation complementary dye spectrum OLED. The OLED exhibits a candlelight-style yellowish orange chromaticity with an efficacy of 29 lm/W at 100 cd m^{-2}, CIE$_{xy}$ (0.52, 0.43) with a respective CRI of 87 and color temperature of 2,050 K, closely matching the (0.52, 0.42) and 1,914 K of a white candle [19]. They sandwiched the emissive layer by two thin layers of light-emitting auxiliary materials to facilitate the transport of carriers and further sandwiched by the two additional carrier injection layers to minimize the interfacial barrier between the organic molecules and electrodes.

In 2016, Jou's group again demonstrated a human-eye friendly and melatonin-secretion friendly candlelight-style OLED via a wet process. The resultant candlelight OLED is 57 and 17 times safer in terms of retinal protection and melatonin generation respectively, as compared with the 5,000 K white LED, CFL, and OLED. In addition, the efficacy is 100 times that of a candle (0.3 lm/W) and 3 times that of an incandescent bulb. The devices were fabricated of organic electro-phosphorescent dyes with red, yellow, and green the resultant chromaticity of yellowish-orange with a CIE$_{xy}$ of (0.56, 0.44), an efficacy of 33 lm/W, and CT of 1,918 K. A candlelight OLED with better performance from either a power efficiency or an EQE perspective, the enhancements to the HTL possessing an effective electron-confining function to prevent the overflow of the electrons from the emissive layer. Moreover, much better light quality, in terms of SRI, is also obtainable provided slightly greater emissions in the green and orange regions [19]. In respect of melatonin suppression sensitivity (MSS), the candlelight-style OLED is 4 times safer than a candle. From the perspective of the human eye protection, the candlelight-style OLED permit a 28,410 s (8 h) maximum permissible exposure limit (MPE) before causing permanent damage to the retina, it is 11 times safer than candlelight whose MPE is 2,616 s (44 min) [19].

Future Scope and Commercialization

The global demand for energy is increasing very fast, whereas the fossil (petroleum and coal) energy resources are draining rapidly. Furthermore, the International Energy Agency's 2006 reported that lighting consumes about 20% of the total generated electric energy, in which 30 to 40% of total energy consumption in residential buildings, hospitals, offices, and industrial buildings. Although a notable development has been made in lighting and display technology, there are still massive challenges to realize healthy, physiologically-friendly, long lifespan, highly visual-quality, and high efficiency. OLED is one future technology with an enormous potential to supply an alternative clean energy source, which is projected to reach a higher profitability at a lower level cost of electricity. In recent years, candlelight-style and sunlight-style OLED have gained widespread attention due to their numerous superlative features, such as eco-friendly, energy-saving, low cost, roll-to-roll fabrication, blue hazards free emission and tunable optical properties. The possibility of using sunlight and candlelight-style OLEDs to replace many present lighting technologies, especially when aiming for ultimate lighting quality for indoors and at night. Our future research will involve improving the energy savings of the OLED and performing collaborative studies into the impact of such light on human-psychology.

Concluding Remarks and Outlooks

Considering the growing importance of energy saving and environment friendliness, eco-friendly solid-state lighting is emerging as a highly competent and viable alternative to the existing lighting technologies. Candlelight- and sunlight- style OLED serve as a starting point for future innovations in research and development of human-friendly lighting sources with feasible commercialization. These lighting sources are more reliable, less obtrusive, or more "glare free" than a candle, providing its users more options in designing more human-friendly lighting fixtures; by doing so, this may lead them to a brighter future. These OLEDs strongly reveal that this technology has the potential to transform the way we light our world and it is going to emerge within the next few years.

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