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Sunlight-like organic LED brings natural illumination indoors

Jwo-Huei Jou

A simple layered structure enables organic LEDs with daylight colors and a wide color-temperature span.

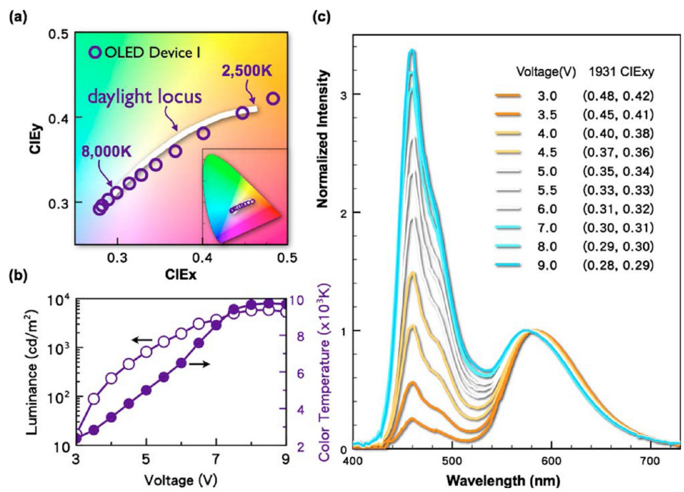

Figure 1. *Emissive color and color-temperature (CT) characteristics of our sunlight-style OLED device I. (a) The emission track on the International Commission on Illumination (CIE) 1931 chromaticity space, which characterizes color, matches closely to the daylight locus between 2500K sunset and 8000K sunlight in a northern country. (b) The CT changes from 2300 to 9700K and brightness from 20 to 5900cd/m^2 as the voltage increases from 3 to 9V. (c) The electroluminescence spectra at various applied voltages. Three peaks, appearing at 460, 495, and 590nm, correspond to the blue, green, and red emitters, respectively.*

Incandescent bulbs and fluorescent tubes provide fundamental lighting needs, but barely satisfy our desire for natural lighting with time-varying color and color-temperature (CT) characteristics[1,2] similar to those of the sun. To get sunlight-style illumination, daylight color emission with a wide CT range is essential. However, current lighting devices give off only daylight color with a fixed CT. The latest white LEDs can be adjusted to a limited extent,[3,4] but there still are unpleasant glare and high-heat problems.

Lately, the focus for organic LEDs (OLEDs) has been on developing devices with higher efficiency and a longer lifespan. Stable lighting color is the basis for developing lighting applications, regardless of whether a pure- or pan-white OLED is used. While color-tunable OLEDs are common, they are not suitable for general lighting purposes. The challenge is to fabricate OLED devices capable of emitting daylight with tunable CT that mimics sunlight.

To fabricate such OLEDs, we applied principles opposite to those for making color-stable OLEDs.[5,6] We found that the emissive color could be changed by varying the applied voltage. However, the color soon deviated from the daylight locus, and we observed only a very limited CT span. So we stretched the CT to a wider range while keeping the emissive color changing along the daylight locus (see Figure 1).

We noticed that the resulting emissive color and CT span of the OLEDs depended on factors like emitter species, efficiency, and number, layer sequence and thickness, and doping concentration. To generate daylight colors matching those of sunlight at all desired CTs, we switched from two daylight-color complementary constituents to three: the red, green, and blue light emitters. We deposited them onto transparent-electrode-coated glass with the blue light-emitting layer adjacent to the transparent cathode side and the red light-emitting layer adjacent to the aluminum anode side, coupling them with a hole-modulating material (see Figure 2). Figure 2(I–V) shows the effect of the layer sequence of blue and red emitters, and the position and thickness of the hole-modulating-layer on the resultant color and CT range of the OLED.[7]

We discovered that the electron was a minor factor given certain device structures. Predominant holes were likely to move and accumulate near the aluminum anode, causing the recombination of the hole with the electron to occur mainly in the red emissive layer and to emit red light in the absence of the hole-modulating layer. On incorporating that layer, especially between the green and red light-emitting layers, a significant portion of holes would be retained in the blue and green layers.

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10.1117/2.1200910.1767 Page 2/3

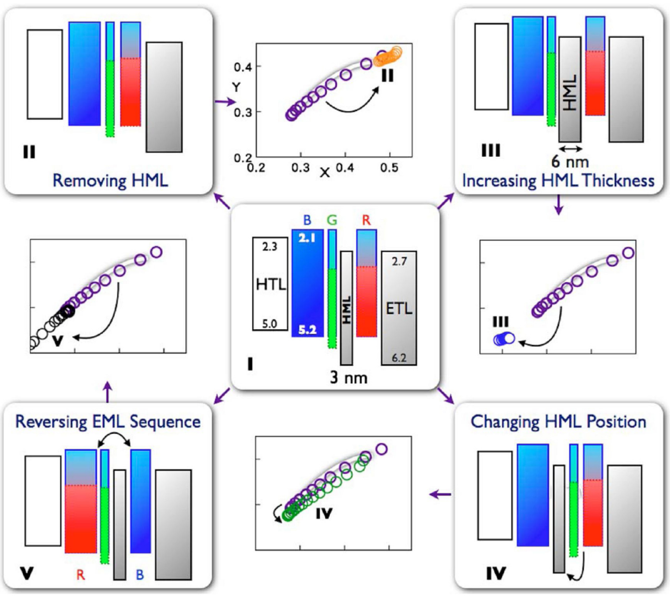

Figure 2. *Effects of the hole-modulating layer (HML), the electron-transport host material TPBi—1,3,5-tris-(N-phenylbenzimidazole-2-yl)-benzene—and sequence of the multi-emitting layers (EML) on the CT and CT span of a sunlight-style, CT-tunable OLED. The effects are indicated by the emission track, against the daylight locus, on the CIE chromaticity space. Also shown are the energy-level diagrams of our device I and counterpart devices II–V for comparison. ETL is the electron-transport layer, and HTL is the hole-transport layer.*

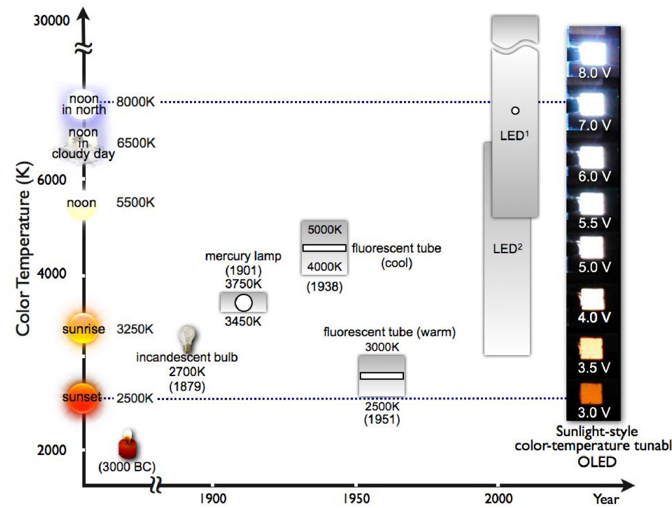

Figure 3. *Sunlight-style OLED with CT span from 2300 to 9700K, compared to the CT and/or CT span exhibited by candles as well as typical electricity-driven lighting devices. The OLED device exhibits, at 3.0V, an orange emission of 2400K; at 5.5V, a pure-white emission of 6500K; and at 8.0V, a bluish-white emission of 9700K.*

At low applied voltage, a small portion of electrons were injected into the blue and green emissive layers to recombine with the retained holes to emit blue and green light. They then mingled with the dominant red light to yield an orange-white light. As the voltage was increased, increasing electrons injected into the blue and green emissive layers formed a comparatively stronger blue and green light. That, consequently, shifted the emission from orange to pure-white and even blue-white.

Using a 3nm hole-modulating layer, the OLED device emitted 2500K sunset hue at 3.5V, 3250K dawn light at 4V, 5500K sunny noon daylight at 5.5V, 6500K noon daylight on a cloudy day, and greater than 8000K noon daylight in high-latitude countries at 7V or above (see Figure 3).

To conclude, we have demonstrated[7] the first single lighting device composed of a simple OLED structure capable of yielding tunable daylight color with CT ranging from 2300 to 9700K, matching that of sunlight. Our method offers advantages when coupled with the many superior properties of OLEDs, such as planarity, flexibility, energy savings, and environmental friendliness. The OLEDs are also easy to design molecularly and can be synthesized from sustainable materials. Our method offers the possibility of using 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.

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10.1117/2.1200910.1767 Page 3/3

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