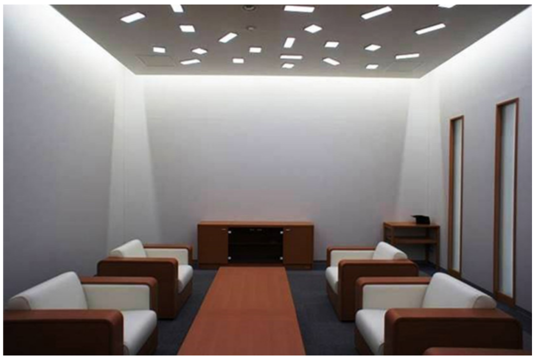
Development and Mass-Production of OLED Lighting Panels with High Luminance, Long Lifetime and High Efficiency



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OLED (organic light-emitting diode) lighting is expected to be new generation electric power saving solid state lighting friendly to human beings and the environment, and has attained a long lifetime superior to fluorescent lamps. Despite being in need of further improvement of luminous efficacy, it is expected to become a light source that has features including thinness, light weight, and eye-friendliness due to surface light emission, allowing for new lighting space design to fulfill various needs.This paper describes its present development progress, issues and future direction, focusing on efficiency improvement, and reports on the development of an OLED lighting panel with high luminous efficacy (40 lm/W) and a long lifetime (40,000 hours) that has attained a sufficient variety of products.

1. Introduction

As the global environment has changed rapidly in recent years, there has been increasing demand for the early creation of earth-friendly natural resource saving and energy saving methods and the immediate establishment of a sustainable society. In the lighting field, conventional lighting such as incandescent bulbs and fluorescent lamps are being replaced with LED lighting to save energy.

OLED lighting is semiconductor lighting that utilizes a luminous principle similar to LED lighting, and its features include energy saving from its high efficiency, long lifetime, high color rendering properties that enable the faithful reproduction of actual colors and the non-existence of ultraviolet light resulting in non-aggressiveness toward the objects being illuminated.

OLED lighting has already been employed for special lighting devices at museums and other facilities[1] because in addition to the advantages above, the features of OLED lighting also include its eye-friendliness, the fact that it is a surface light emission diffusive light source that doesn't cause a local temperature increase, and it has a thin, lightweight design that enables installation anywhere.

This paper describes the successful development of organic light emitting element and light extraction technologies indispensable for further performance improvement, and lighting panels with high luminance, long lifetime and high efficiency attained through the development.

2. Development of OLED lighting panel for high luminance, long lifetime and high efficiency

2.1 P09 series high color temperature (4000 K) type

The P07 series, which was released in February 2013, is a white light (4000 K) panel with a rated luminance of 3000 cd/m^2, a luminous efficacy of 30 lm/W, an LT70 luminance life**1 of 12,000 hours and a higher color rendering index of Ra**2 90. Therefore the P07 series can be used for a wide range of applications including museums and shops where color reproducibility

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is important.

This time, we have developed the P09 series, which has a luminous efficacy as high as 40 lm/W, in order to further improve power saving properties while maintaining the main optical properties required for lighting that the P07 series has attained. The improvement of the power saving properties requires a reduction of the driving voltage or the enhancement of the luminance per unit current (luminous flux). For the fulfillment of this requirement, the improvement of luminous efficacy through the proper selection of luminous dopant and host materials, material selection focusing on the transfer performance of the carrier such as electron/hole mobility, device design focusing on the energy level such as the carrier injection barrier between neighboring organic layers and optical design in consideration of the optical interference in an OLED element are important[2]. The P09 series ensures high color rendering properties through the selection of a light emitting wavelength focusing on efficiency and through optimization of the strength ratios.

In addition, the P09 series has enhanced the luminance to 4000 cd/m^2 through the improvement of efficiency and carrier balance. At the same time, the LT70 at the initial luminance of 3000 cd/m^2 has improved significantly to 40,000 hours, which is comparable to other light sources including LED. In this way, the P09 attains the top level of luminance as an OLED lighting panel while maintaining practical performance.

**1 LT70 luminance life is the time period for which 70% or more of the initial luminance lasts.

**2 Ra is the symbol that represents the general color rendering index, which is the average of the quantified difference between how the test colors lit by the light source to be evaluated are seen and how the reference light is seen. When the color reproducibility is higher, the Ra is closer to 100.

2.2 Low color temperature (3000 K) type - development of next high efficiency panel -

Today we produce the P05 series warm white color panel with low color temperature (3000 K), which has a luminous efficacy of 40 lm/W. For further efficiency improvement, we have developed a new OLED element that has a light extraction structure and attained a luminous efficacy of 60 lm/W.

As the fundamental OLED element structure, the light distribution was designed according to the characteristics of warm white color and the light emitting material was reconsidered. Specifically, a material with a broader light emitting spectrum was used for the improvement of the Ra in order to attain favorable efficiency and color rendering property simultaneously. In addition, even higher efficiency was attained by newly developing a light extraction structure that can efficiently extract waveguide mode light (light confined in an organic thin film), which could not be extracted by conventional optical films. The details of this light extraction structure are described in the next chapter.

Table 1 compares the characteristics of the developed product and the P05 series. The developed product has a practical performance of 60 lm/W at a luminance of 3000 cd/m^2. However, even higher efficiency is required for energy saving, and market demand for even higher luminance and longer lifetime is also increasing. Therefore we are working on the development of the next high efficiency panel that will enable high luminance light emitting. This next high efficiency panel will be released within fiscal 2014.

Table 1 Characteristics comparison of commercialized P05 series panel and developed product

Item	Unit	Warm white color type	
		Commercialized P05 series panel	Developed product*
Luminance	cd/m^2	3000	
Luminous efficacy	lm/W	40	60
Current density	A/m^2	29	20
Voltage	V	8.0	7.6
CCT	K	2800	2700
Color rendering index: CRI	Ra	80	84

*Light emitting size: 30 mm x 40 mm

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3. Further efficiency improvement of OLED lighting panels through the enhancement of light extraction efficiency

3.1 General description and principle of light extraction

For the attainment of more efficient white OLED lighting, the improvement of light extraction efficiency is indispensable. **Figure 1** shows the typical structure of an organic electroluminescence element, and the waveguide and breakdown of the emitted light. The refractive index of each layer is approximately 1.80 for the organic layer (Light emitting layer), 1.90 for the transparent electrode (ITO**3) and 1.52 for the glass substrate. Because the refractive indexes of the organic layer and the transparent electrode are high, there is a component [1] that cannot come out from the transparent electrode to the glass substrate and is confined (waveguide mode: 53%), and another component [2] that cannot come out from the glass substrate to the atmosphere and is confined (substrate mode: 30%), based on the Snell law. As a result, light extracted to the atmosphere is low at just under 17%.

One of the methods for the improvement of light extraction efficiency is to change the direction of the waveguided light. For light contained in the transparent electrode, the waveguide direction can be changed and then the light extraction efficiency can be improved by adding a high-refractive index structure or scattering layer between the transparent electrode and the glass substrate. For light contained in the glass substrate, on the other hand, that can be done by adding to the glass substrate surface a film with a structure or scattering layer.

In this way, it is important for the improvement of light extraction efficiency to change the direction of waveguided light so that the angle of the light ray is changed from a critical angle (total reflection angle) to an angle where the light can be emitted[3].

**3 ITO is the abbreviation for indium tin oxide, which is indium oxide with tin added. ITO constitutes a transparent conductive film.

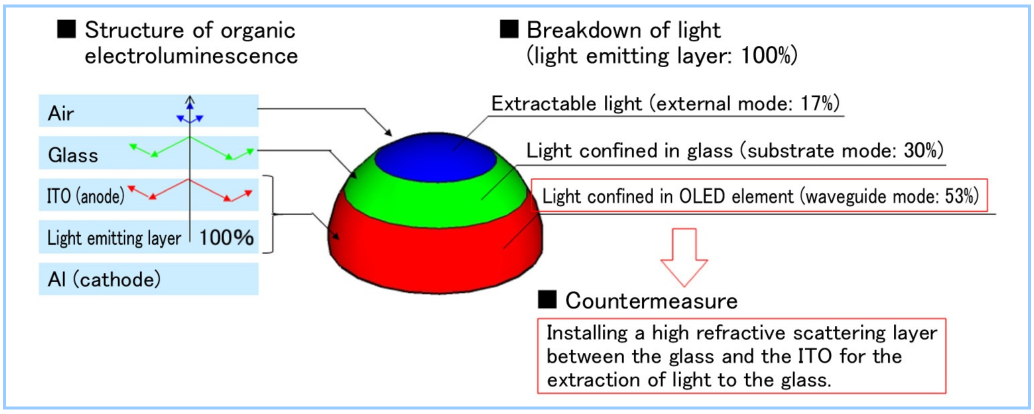

Figure 1 Breakdown of emitting light from typical organic electroluminescence element

3.2 Simulation of light extraction

Figure 2 shows the calculation results of the relationship between the refractive indexes and light intensity distribution. When there is no difference in the refractive indexes, the light spreads concentrically. On the other hand, when there is a difference in the refractive indexes in the layers (the direction of progression is from a higher refractive index to a lower refractive index), the light returns and does not enter the layer with the lower refractive index because total reflection occurs at the boundary face. **Figure 3** shows the simulation results of the installation of a scattering layer between the transparent electrode and the glass substrate to allow light to enter the layer.

When there is no scattering layer between the transparent electrode and the glass substrate, light with a critical angle or greater angle becomes returning light that is waveguided between the light emitting layer and the ITO layer, which results in light that cannot come out to the glass substrate. On the other hand, when there is a scattering layer, the light angle changes in the scattering layer and the light can enter the glass substrate. The amount of light that can enter increases by 20% to 30% depending on the structure of the scattering layer. Based on the results above, we made a trial model of an OLED lighting panel using a light extraction substrate.

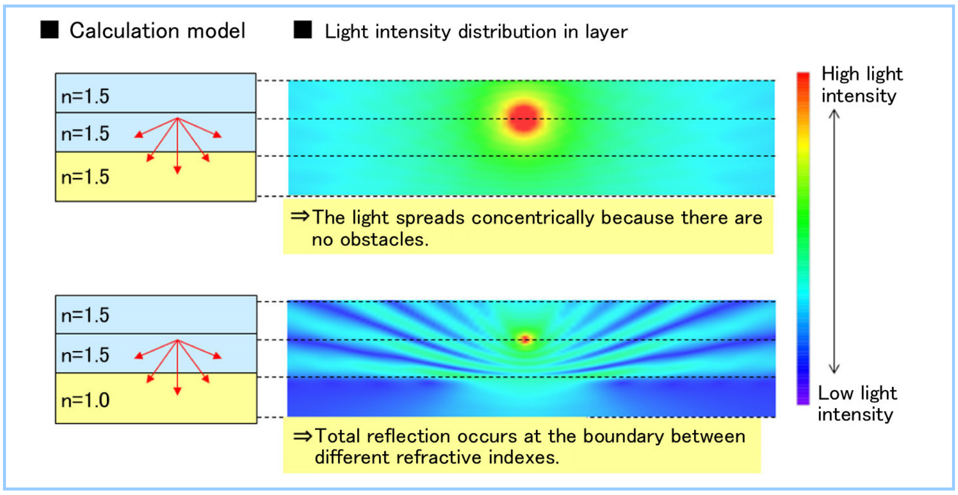

Figure 2 Simulation results of relationship between refractive indexes and light intensity distribution

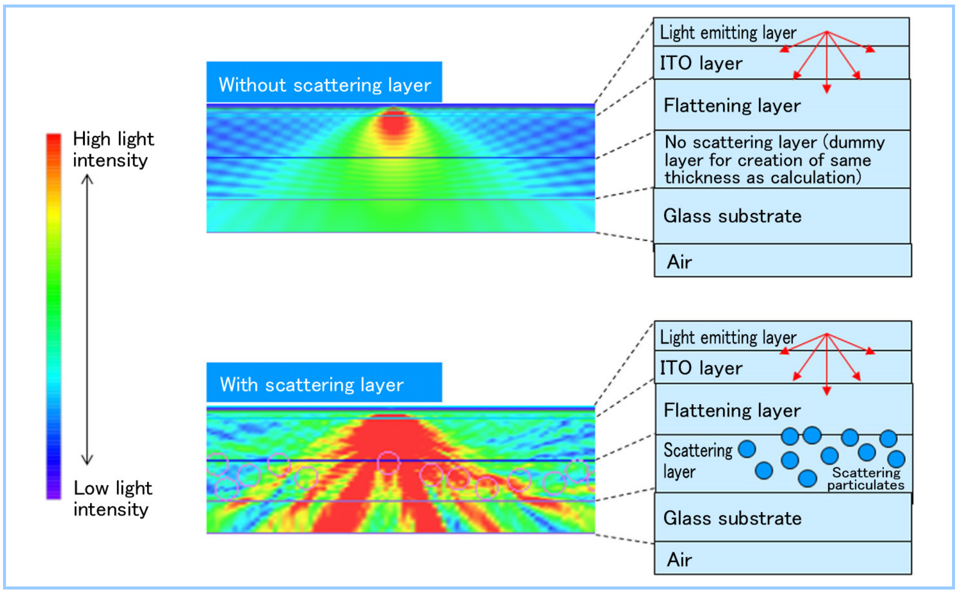

Figure 3 Simulation results of relationship between existence of scattering and light intensity distribution

3.3 Evaluation of trial model of light extraction substrate for the improvement of efficiency

Figure 4 shows the structure of the light extraction substrate developed by Lumiotec Inc. The light extraction substrate consists simply of the glass substrate, the high refractive index scattering layer formed on it and the ITO layer laminated on them as a transparent conducting layer. The requirements for the high refractive index scattering layer are as follows:

- A refractive index that allows light generated by the light emitting layer to enter without total reflection at the boundary face between the scattering layer and the ITO layer
- A light scattering property that changes the direction of the entered light to an angle that does not reflect on the glass boundary face (critical angle)
- Surface flatness equivalent to the ITO layer formed directly on the glass substrate

For the realization of the above requirements, the light extraction substrate produced by Lumiotec Inc. employs a two-layer structure and has a scattering layer on the glass substrate side. In addition, a high refractive index layer (flattening layer) is formed on the ITO layer side in order to maintain the flatness.

Figure 5 compares the refractive indexes of the flattening layer and the ITO layer. Light can be taken in efficiently because the refractive index of the flattening layer is higher than that of the ITO layer in a wide range of the entire region of visible light.

For the maximization of the light extraction efficiency, the structure can be optimized for the further improvement of efficiency by matching the OLED element design based on the light distribution obtained by the simulation results shown in the preceding section. The combination of this light extraction substrate and an all-phosphorescent white OLED element obtained a luminous efficacy exceeding 60 lm/W at a luminance of 3000 cd/m^2. This result indicates that practical luminance as a lighting device and practical energy saving property for the environment are attained.

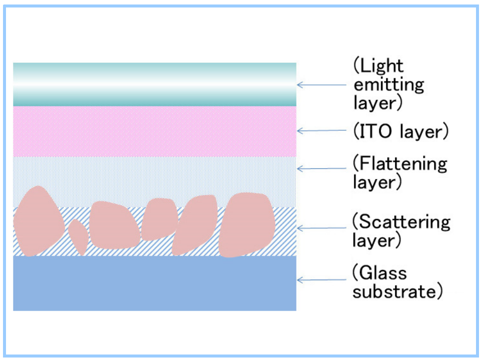

Figure 4 Structure of light extraction substrate

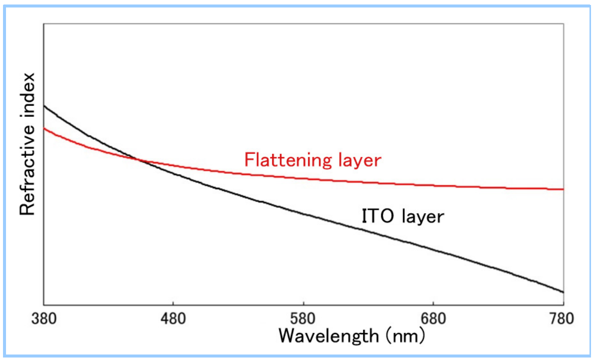

Figure 5 Refractive indexes of flattening layer and ITO layer

3.4 Mass production of developed product

For the formation of the scattering and flattening layers on the light extraction substrate, an application method with high material utilization efficiency and past mass production results for large size substrates including liquid crystal panels are employed. Similarly to conventional panels, this method forms transparent electrodes on the substrate on which the scattering and flattening layers are formed. As a result, a light extraction substrate with a simple structure is realized while keeping the cost low.

Lumiotec Inc. was able to efficiently proceed with the panel design by incorporating the simulation technologies of the light extraction structure. In addition, we worked on the extension of the light emitting area by reconsidering the design tolerance of the panel in the manufacturing process and design rules. As a result, the light emitting area on a panel with external dimensions of 145 mm x 145 mm could be increased by approximately 6% without the external dimensions being changed. The developed P09 series OLED lighting panel was exhibited at Lighting Japan 2014 (**Figure 6**) and gained a good reputation for the simultaneous attainment of practical luminance and long lifetime. **Table 2** compares the P09 series and the existing P07 series. The P09 series OLED lighting panel will be released in mid fiscal 2014.

Figure 6 P09 series OLED lighting panel (panel external dimensions: 145 x 145 mm)

Table 2 Comparison of P09 series and existing P07 series (panel external dimensions: 145 x 145 mm)

Item	Unit	Performance: P07 series (Existing model)		Performance: P09 series (New model*)
CCT	K	4000		4000
Luminance	cd/m^2	3000	→	4000
Total luminous flux	lm	140	→	200
Luminous efficacy	lm/W	30	→	40
CRI	Ra	90	→	85
Life-time (LT_{70}, 3000 cd/m^2)	h	12000	→	40000

* The product is available in the near future.

4. Application examples of OLED lighting panel

As the performance of OLED lighting panels has steadily improved, panel development has tended to focus on characteristics such as color rendering property and therefore there are an increasing number of application examples that utilize the features of organic electroluminescence as a thin diffusive surface light source.

Current domestic application examples include employment for museums based on features such as the high color rendering property, low heat generation and no harmful ultraviolet or infrared ray emissions. **Figure 7** shows an example of use for lighting of a national treasure display at the Tokyo National Museum. **Figure 8** shows an example of use in ceiling light devices in a meeting room for lighting the entire room. In this case, sufficient illumination can be ensured only by OLED lighting. **Figure 9** shows an example of use in pendant light devices for a restaurant. OLED lighting is attracting attention in the design industry as lighting that is different from existing forms. Among the many lighting devices produced, an example of use in an innovative, commercialized desk light product is shown in **Figure 10**.

Figure 7 Lighting for display case in museum (Tokyo National Museum, National Institutes for Cultural Heritage)

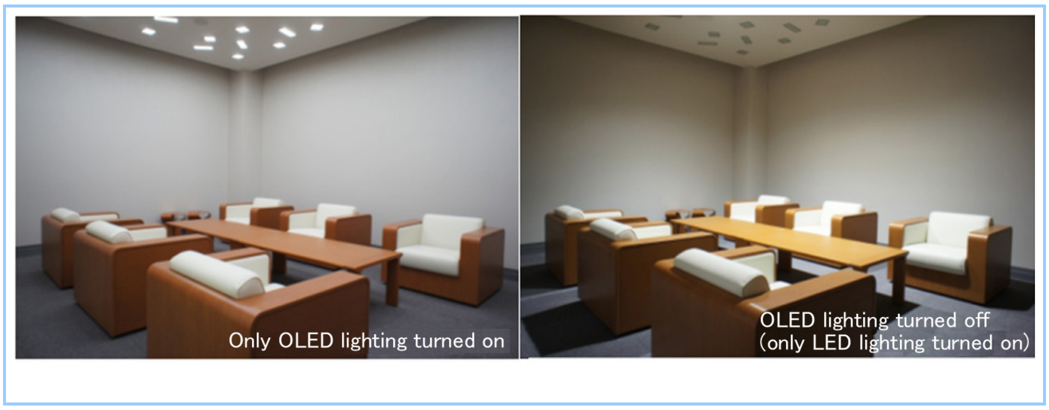

Figure 8 Main lighting for meeting room (Nissin Pharmaceutical Co., Ltd.)

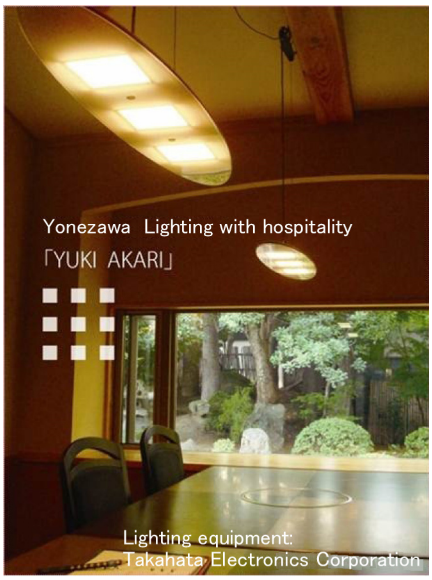

Figure 9 Pendant light used in restaurant (Yonezawagyu Sankairyouri Yoshitei)

Figure 10 Desk light (design office Feel Lab)

At the present moment, OLED lighting is commercialized mainly in a relatively limited number of applications including lighting for museums and design lighting devices. However, its usage is expected to expand to a wide range of surface lighting including general lighting applications through performance improvement and cost reduction in the future.

In addition, an increasing number of trial products that utilize features unique to organic electroluminescence have been produced, including a lighting device that uses an ITO transparent electrode instead of a typical metal electrode using an aluminum film, and then realizes a transparent appearance when not in use, as well as flexible lighting equipment that uses a resin or very thin glass substrate on which an organic electroluminescence element is formed. It is expected that OLED lighting can create new value by producing unprecedented lighting, despite various challenges.

5. Conclusion

Lumiotec Inc. has attained top-class high performance in OLED lighting with the P09 series, featuring a luminance of 4000 cd/m^2 (equivalent to a fluorescent lamp) and the long lifetime of 40,000 hours (equivalent to LED lighting) through the steady development of OLED element and mass production technologies. The company is now working on the further improvement of OLED device performance while developing a flexible panel using super thin glass substrates and a high luminous quantity large panel with dimensions of 300 mm x 300 mm intended for use as main lighting equipment, in order to further utilize the features of OLED lighting panels, which are lightweight and thin. In addition, cost reduction is also an important issue for entry to the general lighting market, and therefore research on the next panel structure and production facilities suitable for mass production has been begun. We would be happy if we could contribute to the improvement of the global environment by spreading OLED lighting panels, which are known as front runners alongside LED lighting.

References

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